ATTACHMENT 9.2

DOCUMENT 7



State of the Global Climate 2021

Key Messages....3
Foreword....4
Global Climate Indicators....4
Baselines....4
Greenhouse gases....5
Temperature....6
Ocean....8
Cryosphere....16
Stratospheric ozone....25
Drivers of short-term variability....26
High impact events in 2021....28
Heatwaves and wildfires....28

Cold spells and snow....29
Precipitation....30
Flood....31
Drought....33
Tropical cyclones....34
Severe storms....35
Attribution....35
Risks and impacts....36
State of disasters....36
Food Security....37
Population Displacement....39
Climate impacts on ecosystems....41
Contributors....43
Data sets and methods....44

Key Messages

Atmospheric concentrations of the major greenhouse gases, carbon dioxide, methane and nitrous oxide, continued to increase in 2020 and 2021. The growth rate of all three greenhouse gases in 2020 was above the average for the last decade despite a 5.6% drop in fossil fuel CO_2 emissions in 2020 due to restrictions related to the COVID-19 pandemic.

Global mean temperature in 2021 (January to September) is around 1.08 ±0.13 °C above the 1850-1900 pre-industrial average and the year is likely to be between the 5th and 7th warmest year on record. 2021 is cooler than recent years owing to La Niña conditions early in the year.

The rate of global sea level rise has increased since satellite altimeter measurements began in 1993, reaching 4.4 mm/yr between 2013 and 2021. Global mean sea level reached a new record high in 2021.

Ocean heat content reached new record highs in 2019 and then 2020, the latest year for which a comprehensive analysis is available. Ocean warming rates show a particularly strong increase in the past two decades.

Changes in the global cryosphere in 2021 were consistent with recent multi-decadal trends, with below-normal Northern Hemisphere spring snow cover and end-of-summer Arctic sea ice area, negative mass balances on mountain glaciers and the Greenland and Antarctic Ice Sheets, and near-normal Antarctic sea ice cover.

The summer heat wave in western North America took a toll on the region's mountain glaciers, with exceptional mass losses in the Cascade, southern Coast, and Rocky Mountains. Mass loss at some glaciers in southwestern British Columbia was the greatest in the instrumental record (1965-2021).

Greenland experienced an exceptional mid-August melt event which included temperatures above 0 °C and rainfall at Summit Station, the highest point on the ice sheet. This is the first time that rain has been observed at Summit, and marks the third time in the last nine years that the Summit has experienced melting conditions. Ice core records indicate that only one such melt event occurred in the 20th century.

Exceptional heatwaves affected western North America on several occasions during June and July. Lytton, in south-central British Columbia, reached 49.6 °C on 29 June, breaking the previous Canadian national record by 4.6 °C. 569 heat-related deaths were reported in British Columbia alone between 20 June and 29 July.

Death Valley, California reached 54.4 °C on 9 July, equalling a similar 2020 value as the highest recorded in the world since at least the 1930s.

Extreme heat affected the broader Mediterranean region on several occasions during the second half of the Northern Hemisphere summer. The most exceptional heat was in the second week of August. On 11 August, an agrometeorological station near Syracuse in Sicily reached 48.8 °C, a provisional European record.

The most significant hurricane of the North Atlantic season was Ida. Ida made landfall in Louisiana on 29 August with sustained 1-minute winds of 240 km/h, the equal-strongest landfall on record for the state, with major wind damage and storm surge inundation. The system continued on a northeast track over land with significant flooding, especially in the New York City area. In total, 72 direct and 43 indirect deaths were attributed to Ida in the United States and Venezuela, with economic losses in the United States estimated at US$63.8 billion.

Extreme rainfall hit Henan Province of China from 17 to 21 July. On 20 July, the city of Zhengzhou received 201.9 mm of rainfall in one hour (a Chinese national record), 382 mm in 6 hours, and 720 mm for the event as a whole, more than its annual average. The city experienced extreme flash flooding with many buildings, roads and subways inundated. 302 deaths were attributed to the flooding, and economic losses of US$17.7 billion were reported.

Western Europe experienced some of its most severe flooding on record in mid-July. The worst-affected area was western Germany and eastern Belgium, where 100 to 150 mm fell over a wide area on 14-15 July over wet ground. The highest daily rainfall was 162.4 mm at Wipperfürth-Gardenau (Germany). Numerous rivers experienced extreme flooding, with several towns inundated, and there were also several landslides. 179 deaths were reported in Germany and 36 in Belgium, with economic losses in Germany exceeding US$20 billion.

Foreword

TBD

Global Climate Indicators

Global climate indicators[1] provide a broad view of climate change at a global scale, encompassing the composition of the atmosphere, energy changes largely caused by the accumulation of greenhouse gases, and the response of the land, ocean, and ice. These indicators are closely inter-related. For example, the rise in CO_2 and other greenhouse gases in the atmosphere leads to warming of the atmosphere and ocean. Warming of the ocean leads in turn to rising sea levels, which is added to by the melting of ice on land in response to increasing atmospheric temperatures. The global indicators draw on a wide range of data sets that are listed at the end of the report and show a consistent picture of a warming world.

The connections between global climate indicators and the Sustainable Development Goals were highlighted in "Climate Indicators and Sustainable Development: Demonstrating the Interconnections"[2]. The report demonstrates the linkages and feedback loops amongst the key climate indicators as a physical system and the resulting cascading risks to nearly all of the 17 Sustainable Development Goals, including those affecting environmental, social, and economic systems. Monitoring the global climate indicators, as well as their related risks and impacts, is therefore of critical importance for achieving the Sustainable Development Goals by 2030.

Baselines

Baselines are fixed periods, usually spanning one or more decades, that are used as a fixed point against which current conditions can be compared. A variety of baselines are used in this report and these are specified in the text and figures where appropriate.

Where possible the WMO climatological standard normal, 1981-2010, is used as a baseline for consistent reporting[3]. For some indicators however, it is not possible to use this baseline due to a lack of measurement during the whole period or because a longer period is needed to calculate representative statistics.

[1] https://journals.ametsoc.org/view/journals/bams/102/1/BAMS-D-19-0196.1.xml
[2] https://library.wmo.int/index.php?lvl=notice_display&id=21953
[3] 1981-2010 is used in preference to 1991-2020 for consistency with climate reports from WMO members not all of whom have yet transitioned to using the more recent period.

There are two notable exceptions. Firstly, for global mean temperature, a baseline of 1850-1900 is used. This is the baseline used in recent IPCC reports (AR6 WG1[4], SR15[5]) as a reference period for pre-industrial temperatures and is relevant for understanding progress relative to the long term goal of the Paris Agreement. For more details of how this is calculated see Global Temperature data. Secondly, for greenhouse gases, atmospheric concentrations can be estimated much further back in time, using gas bubbles trapped in ice cores. The year 1750 is used in this report to represent pre-industrial greenhouse gas concentrations.

Greenhouse gases

Atmospheric concentrations of greenhouse gases reflect a balance between emissions from human activities, natural sources and sinks in the biosphere and ocean. Increasing levels of greenhouse gases in the atmosphere due to human activities are the major driver of climate change since the mid-20th century. Global average mole fractions of greenhouse gases are calculated from in situ observations made at multiple sites in the Global Atmosphere Watch (GAW) Programme of WMO and partner networks.

In 2020, greenhouse gas concentrations reached new highs (Figure 1), with globally averaged surface mole fractions for carbon dioxide (CO_2) at 413.2 ± 0.2 parts per million (ppm), methane (CH_4) at 1889 ± 2 parts per billion (ppb) and nitrous oxide (N_2O) at 333.2 ± 0.1 ppb, respectively, 149%, 262% and 123% of pre-industrial (1750) levels. The increase in CO_2 from 2019 to 2020 was slightly lower than that observed from 2018 to 2019, but higher than the average annual growth rate over the last decade. This is despite the approximately 5.6% drop in fossil fuel CO_2 emissions in 2020 due to restrictions related to the COVID-19 pandemic[6]. For CH_4 and N_2O, the increase from 2019 to 2020 was higher than that observed from 2018 to 2019 and also higher than the average annual growth rate over the last decade.

Real-time data from specific locations, including Mauna Loa (Hawaii) and Cape Grim (Tasmania) indicate that levels of CO_2, CH_4 and N_2O continued to increase in 2021.

Atmospheric methane increase is an issue for concern because it is not only a powerful greenhouse gas but it also has, as a precursor of tropospheric ozone, implications for human health, agriculture and ecosystems[7]. The mean annual increase of CH_4 decreased from approximately 12 ppb yr^{-1} during the late 1980s to near zero between 1999 and 2006. Since 2007, atmospheric CH_4 has been increasing, and in 2020 it increased by 11 ppb over 2019 levels. Studies using GAW CH_4 measurements indicate that increased CH_4 emissions from wetlands in the tropics and from anthropogenic sources at the mid-latitudes of the Northern Hemisphere are the likely causes of this recent increase[8]. These studies also have pointed to the short-term climate benefits and cost-effectiveness of mitigating CH_4 emissions. Such mitigation measures were presented in the United Nations Environment Programme (UNEP) methane assessment[7] and address major emitting sectors, namely oil and gas, agriculture and waste management.

[4] AR6 Climate Change 2021: The Physical Science Basis https://www.ipcc.ch/report/ar6/wg1/
[5] IPCC Special Report: Global Warming of 1.5 °C https://www.ipcc.ch/sr15/
[6] https://public.wmo.int/en/resources/united_in_science https://library.wmo.int/index.php?lvl=notice_display&id=21946
[7] https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions
[8] Nisbet, E.G., M.R. Manning et al., 2019: Very strong atmospheric methane growth in the 4 years 2014–2017: Implications for the Paris Agreement. Global Biogeochemical Cycles, 33, 318–342, https://doi.org/10.1029/2018GB006009

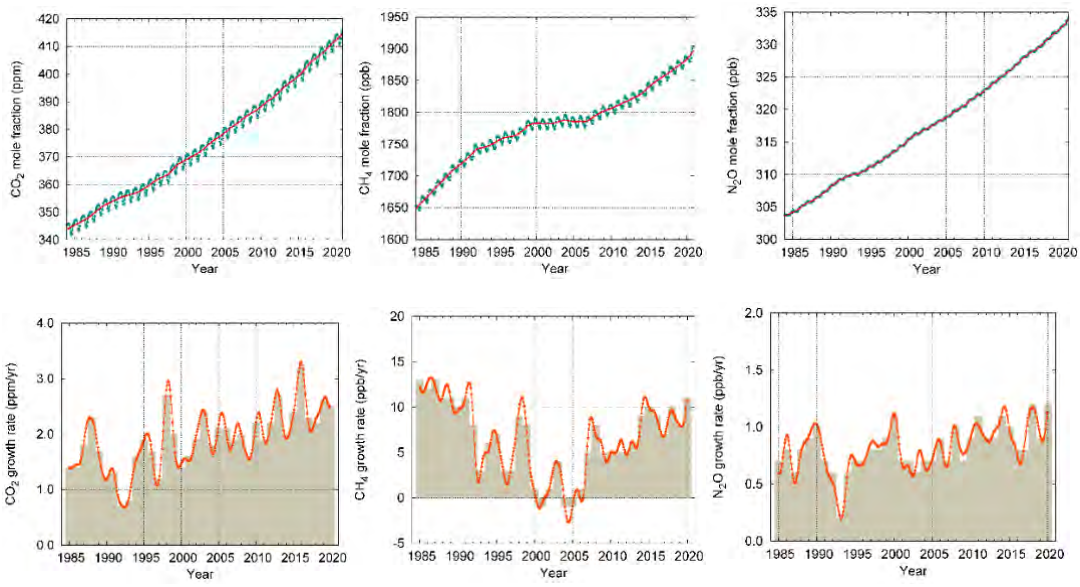


Figure 1: Top row: Globally averaged mole fraction (measure of concentration), from 1984 to 2020, of CO_2 in parts per million (left), CH_4 in parts per billion (centre) and N_2O in parts per billion (right). The red line is the monthly mean mole fraction with the seasonal variations removed; the blue dots and line show the monthly averages. Bottom row: the growth rates representing increases in successive annual means of mole fractions for CO_2 in parts per million per year are shown as grey columns (left), CH_4 in parts per billion per year (centre) and N_2O in parts per billion per year (right) (Source: WMO Global Atmosphere Watch).

Temperature

The global mean temperature for 2021 (based on data from January to September) was 1.08 ± 0.13°C above the 1850-1900 average (Figure 2). Currently, year-to-date averages from all data sets used in the analysis would place 2021 as the 6th (NOAAGlobalTemp) or 7th (all others) warmest year on record globally. However, three months of the year remain, and the ranking is liable to change. It is nevertheless likely that 2021 will be between the 5th and 7th warmest year on record and therefore likely that the most recent seven years, 2015 to 2021, will be the seven warmest years on record.

2021 is cooler than recent years due to the influence of a moderate La Niña at the start of the year (see Drivers of short-term variability). La Niña has a temporary cooling effect on the global mean temperature, which is strongest in the year following an event. Aside from the weak La Niña of 2018, the last significant La Niña event was in 2011. 2021 is around 0.18 to 0.26 °C warmer than 2011. As the 2020-21 La Niña has waned, monthly global temperatures have increased. However, conditions have approached La Niña thresholds again as of October. The year 2016, which started during a strong El Niño, remains the warmest year on record in most of the data sets surveyed.

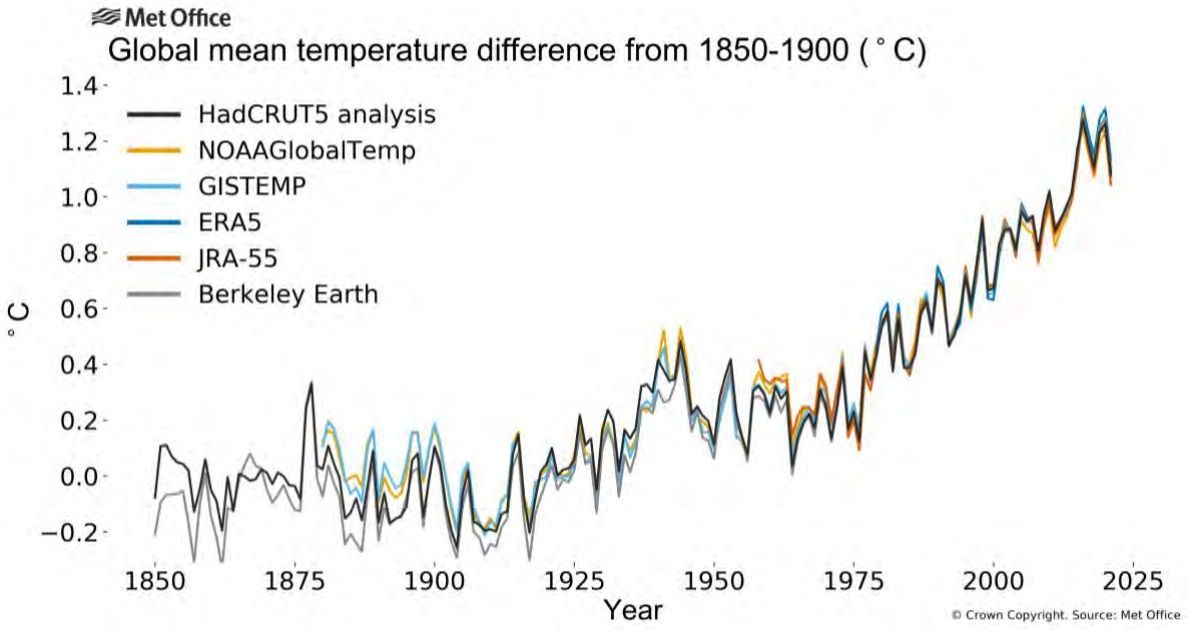


Figure 2: Global annual mean temperature difference from preindustrial conditions (1850–1900) for six global temperature data sets. For details of the datasets and processing see Data sets and methods.

The calculation of global temperature anomalies relative to the 1850-1900 baseline has been updated from previous State of the Global Climate reports. The new method uses the assessment of temperature change and its uncertainties from the IPCC Sixth Assessment Report (AR6) as a foundation for estimating changes since 1850-1900. Details are given in the section on Global Temperature data.

The Paris Agreement[9] aims to "*strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by … Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*".

Assessments of changes in climatological averages refer to long-term changes, in this case in the global mean temperature, and not to the temperature of a single year. In IPCC AR6 WG1 SPM, long-term change was assessed using a 20-year average. For the period, 2001-2020 the average was estimated[10] to be 0.99 [0.84-1.10] °C. The provisional 20-year average for the period 2002-2021, based on the average of the six data sets, was 1.01 ± 0.12 °C above the 1850-1900 average.

Near surface air temperatures for the first nine months of 2021 (Figure 3) were above the 1981-2010 average across a broad swath of North America and Greenland, northern and tropical Africa, the Middle East and southern Asia. Areas with below average temperatures included parts of northern Asia, Australia, southern Africa, northwest North America, and the southern central United States. The imprint of La Niña can clearly be seen in the tropical Pacific. Cooler conditions in southern Africa, India, and eastern Australia are characteristic of La Niña. The cooler-than-average area in northern Asia stands in contrast to 2020 which saw exceptionally high temperatures in the region, this is

[9] https://unfccc.int/sites/default/files/english_paris_agreement.pdf
[10] IPCC AR6 WG1 Summary for Policymakers A.1.2. The IPCC average was based on four data sets: HadCRUT5, NOAAGlobalTemp interim, Berkeley Earth and Kadow et al.

partly associated with the different phases of the Arctic Oscillation in early 2020 (strongly positive) and early 2021 (strongly negative, see the section on AO Arctic Oscillation).

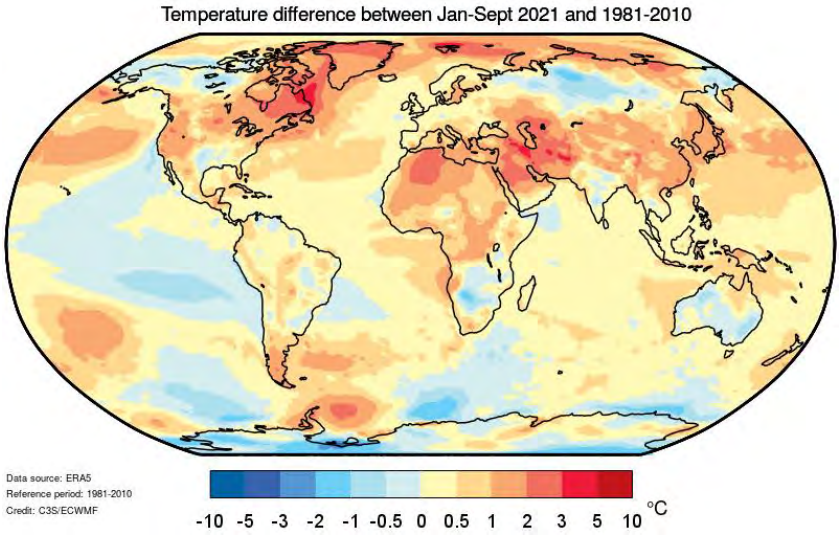


Figure 3: Near-surface air temperature differences from the 1981-2010 average for January to September 2021. Data are from the ERA5 reanalysis product. Source: Copernicus Climate Change Service/ECMWF

Ocean

Most of the excess energy that accumulates in the Earth system due to increasing concentrations of greenhouse gases is taken up by the ocean. The added energy warms the ocean, and the consequent thermal expansion of the water leads to sea level rise, which is added to by melting land ice. The surface layers of the ocean have warmed more rapidly than the interior, which can be seen in the rise of global mean sea-surface temperature and also in the increased incidence of marine heatwaves. As the concentration of CO_2 in the atmosphere increases, so too does the concentration of CO_2 in the ocean. This affects ocean chemistry, lowering the average pH of the water, a process known as ocean acidification. All these changes have a broad range of impacts in the ocean and coastal areas. Note that with reporting delays, the most recent data for some of these indicators are from 2020.

Ocean heat content

Increasing human emissions of CO_2 and other greenhouse gases cause a positive radiative imbalance at the top of the atmosphere – the Earth Energy Imbalance (EEI) – leading to an accumulation of energy in the form of heat in the Earth system which is driving global warming[11,12,13]. Around 90% of this accumulated heat in the Earth system is stored in the ocean, which is measured through Ocean Heat Content (OHC). A positive EEI signals that the Earth's climate system is still responding to the current forcing[14] and that more warming will occur even if the forcing does not increase further[15]. This in turn is reflected in a continued increase of ocean heat content. IPCC AR6 Working Group 1 (WG1) concluded that it is unequivocal that human influence has warmed the atmosphere, ocean

[11]Hansen, J. et al. (2011). Earth's energy imbalance and implications. Atmospheric Chemistry and Physics. https://doi.org/10.5194/acp-11-13421-2011
[12] Rhein, M. et al. 2013. Climate change 2013: The physical science basis.
[13] von Schuckmann, K. et al. (2016). An imperative to monitor Earth's energy imbalance. In Nature Climate Change. https://doi.org/10.1038/nclimate2876
[14] Hansen, J. et al. (2005). Earth's Energy Imbalance: Confirmation and Implications. Science, 308(5727), 1431 LP – 1435. https://doi.org/10.1126/science.1110252
[15] Hansen, J. et al. (2017). Young people's burden: requirement of negative CO2 emissions. Earth Syst. Dynam., 8(3), 577–616. https://doi.org/10.5194/esd-8-577-2017

and land, and that it is extremely likely that human influence was the main driver of the ocean heat increase observed since the 1970s[16].

Historical measurements of subsurface temperature back to the 1940s mostly rely on shipboard measurement systems, which constrains the availability of subsurface temperature observations at a global scale and at depth[17]. With the deployment of the Argo network of autonomous profiling floats, which first achieved near-global coverage in 2006, it is now possible to routinely measure OHC changes down to a depth of 2000m[18,19].

Various research groups have developed estimates of global OHC, and all results show continued ocean warming (Figure 4). Differences between the estimates at annual to decadal scale arise from the various statistical treatments of data gaps, the choice of climatology and the approach used to account for instrumental biases[20,21]. A concerted effort has been established to provide an international view on the global evolution of ocean warming[22] up to the year 2020.

The upper 2000m depth of the ocean continued to warm in 2019 reaching a new record high, and it is expected that it will continue to warm in the future[23,24]. A preliminary analysis based on seven global data sets suggests that 2020 exceeded that record (Figure 4). All data sets agree that ocean warming rates show a particularly strong increase in the past two decades. Ocean warming rates for the 0-2000m depth layer reached 1.0 (0.6) ± 0.1 Wm^{-2} over the period 2006-2020 (1971-2020). For comparison, the values for the upper 700m depth amount to 0.6 (0.4) ± 0.1 Wm^{-2} over the period 2006-2020 (1971-2020). Below 2000m depth, the ocean also warmed albeit at the lower rate of 0.07 ± 0.04 Wm^{-2} from 1991-2018[25].

[16] IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [MassonDelmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

[17] Abraham, J. P. et al. (2013). A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. Reviews of Geophysics, 51(3), 450–483. https://doi.org/10.1002/rog.20022

[18] Riser, S. C. et al. (2016). Fifteen years of ocean observations with the global Argo array. Nature Climate Change, 6(2), 145–153. https://doi.org/10.1038/nclimate2872

[19] Roemmich, D. et al. (2019). On the Future of Argo: A Global, Full-Depth, Multi-Disciplinary Array. In Frontiers in Marine Science (Vol. 6, p. 439). https://www.frontiersin.org/article/10.3389/fmars.2019.00439

[20] Boyer, T. et al. (2016). Sensitivity of Global Upper-Ocean Heat Content Estimates to Mapping Methods, XBT Bias Corrections, and Baseline Climatologies. Journal of Climate, 29(13), 4817–4842. https://doi.org/10.1175/JCLI-D-15-0801.1

[21] von Schuckmann, K. et al. (2016). An imperative to monitor Earth's energy imbalance. In Nature Climate Change. https://doi.org/10.1038/nclimate2876

[22] von Schuckmann, K. et al. (2020). Heat stored in the Earth system: Where does the energy go? The GCOS Earth heat inventory team. Earth Syst. Sci. Data Discuss., 2020, 1–45. https://doi.org/10.5194/essd-2019-255

[23] IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

[24] IPCC, 2021: Summary for Policymakers

[25] Update from Purkey, S. G., and G. C. Johnson, 2010: Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets. J. Climate, 23, 6336–6351, https://doi.org/10.1175/2010JCLI3682.1

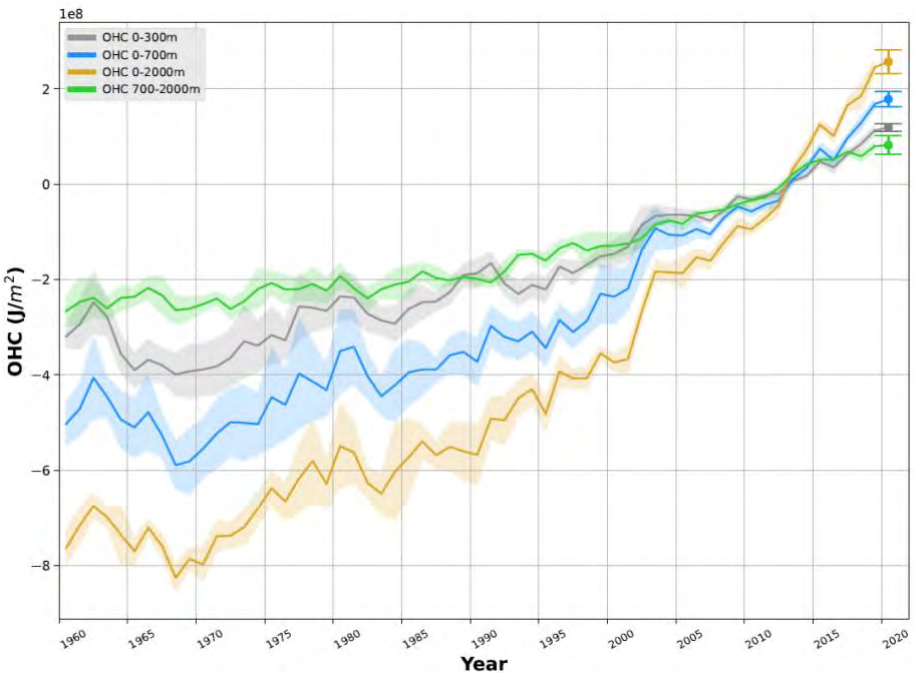


Figure 4: 1960-2020 ensemble mean time series and ensemble standard deviation (2-standard deviations, shaded) of global ocean heat content (OHC) anomalies relative to the 2005-2017 average for the 0-300m (grey), 0-700m (blue), 0-2000m (yellow) and 700-2000m depth layer (green). The ensemble mean is an outcome of a concerted international effort, and all products used are listed in von Schuckmann et al., 2020. Note that values are given for the ocean surface area between 60°S-60°N, and limited to the 300m bathymetry of each product. Updated from von Schuckmann et al. (2020). The ensemble mean OHC (0-2000m) anomaly (relative to the 1993-2020 average) has been added as a cross, together with its ensemble spread, and is based on the 7 products listed in Ocean heat content data.

Sea level

Global mean sea level (GMSL) is one of the key global climate indicators. It integrates changes occurring in many components of the climate system; on interannual to multidecadal time scales, GMSL changes result from ocean warming via thermal expansion of sea water, melting of land ice and exchange of water with water bodies on land. Measured since the early 1990s by high precision altimeter satellites, the mean GMSL rate was 2.1 mm yr^{-1} between 1993 and 2002 and 4.4 mm yr^{-1} between 2013 and 2021, an increase by a factor of 2 between the periods, mostly due to the accelerated loss of ice mass from the ice sheets[26]. In 2021, GMSL reached a new record high. Compared to previous El Niño and La Niña years (e.g., in 1997-1998, 2010-2011, 2015-2016), during which the GMSL displayed temporary positive or negative anomalies of several millimetres, 2021 was marked by an increase of the GMSL that was close to the long-term trend (Figure 5).

[26] WCRP Global Sea Level Budget Group: Global sea-level budget 1993–present, Earth Syst. Sci. Data, 10, 1551–1590, https://doi.org/10.5194/essd-10-1551-2018, 2018.

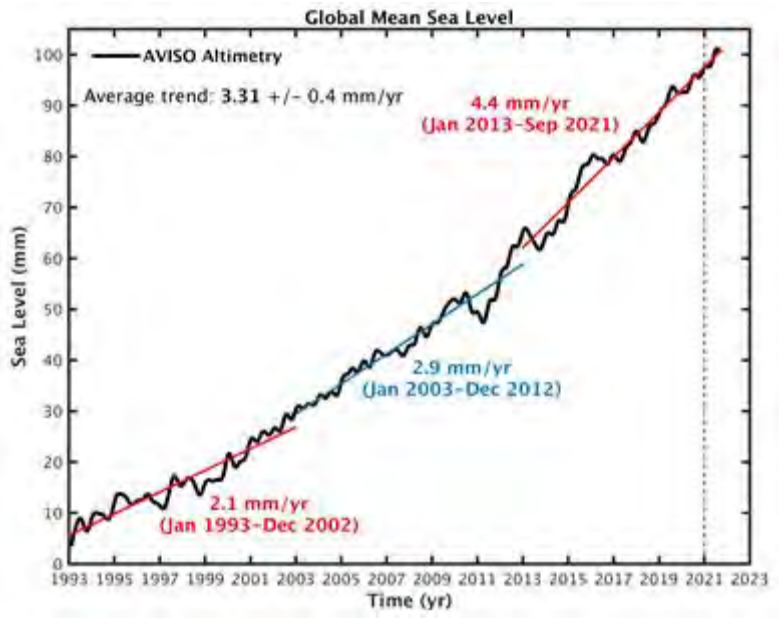


Figure 5: Global mean sea level evolution from January 1993 to September 2021 (black curve) based on high precision satellite altimetry. The coloured straight lines represent the average linear trend over 3 successive time spans (January 1993-December 2002; January 2003-December 2012; January 2013-September 2021). The thin vertical dashed line separates 2021 from previous years. Data source: AVISO altimetry (https://www.aviso.altimetry.fr)

Although sea level has risen almost everywhere since 1993, sea level has not risen equally everywhere. Regional patterns of sea level change are dominated by local changes in ocean heat content and salinity. Several regions continue to be affected by a rate of sea level rise substantially faster than the global mean (see Figure 6, which shows the difference between local and global sea level). This is particularly the case in the western tropical Pacific east of the Philippines and New Guinea, the southwest Pacific east of Australia and New Zealand, the north Pacific, the southwest Indian ocean east of Madagascar, and the south Atlantic. In other regions, local sea level has risen more slowly than the global mean e.g., around Greenland and south of Iceland, and in the Southern Ocean around Antarctica. The patterns of trends in sea level have only varied a little over the last 30 years of the altimetry era, and changes from one year to another are small.

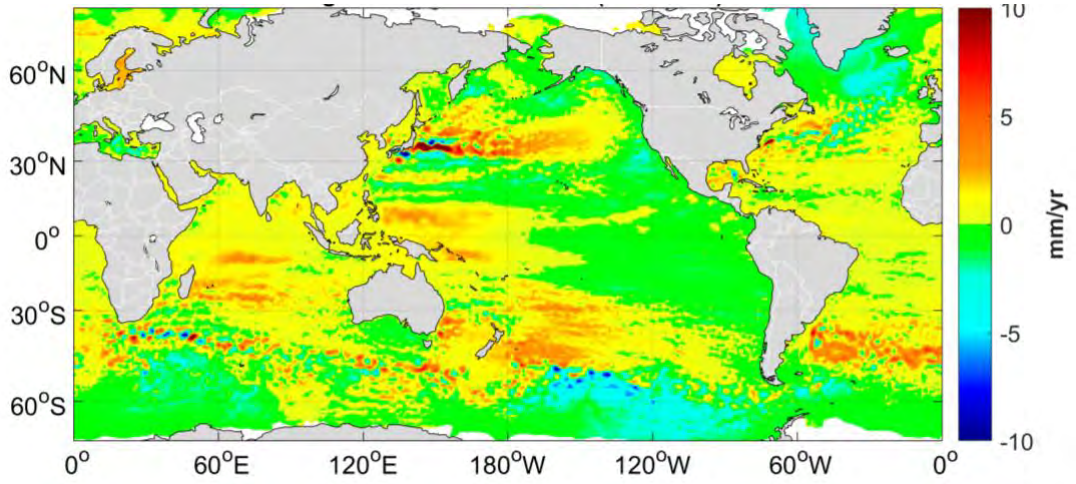


Figure 6: Regional trend patterns in sea level after the global mean trend has been removed, over 1993-2020 based on satellite altimetry. Unit: mm/yr. Data source: Copernicus Climate Change Service (https://climate.copernicus.eu). Note that the actual sea level has increased almost everywhere.

Marine heatwaves and cold spells

In analogy with heatwaves and cold spells on land, Marine Heat Waves (MHW) and Marine Cold Spells (MCS) are prolonged periods of extreme heat or cold that affect the near-surface layer of the ocean. They can have a range of consequences for marine life and dependent communities[27] and MHWs have become more frequent over the 20th Century. Satellite retrievals of sea-surface temperature are used to monitor MHWs and MCSs, categorized here as moderate, strong, severe, or extreme (for definitions, seeMarine heatwave and marine cold spell data).

Much of the ocean experienced at least one 'strong' MHW at some point in 2021 (to 14 October, Figure 7). MHWs were conspicuously absent in the eastern equatorial Pacific Ocean – linked to below average sea-surface temperatures associated with La Niña – and much of the Southern Ocean – one of the few areas in which MCSs are increasing in duration. The Laptev and Beaufort Seas experienced "severe" and "extreme" MHWs from January to April 2021. In 2021, almost all MCSs were 'moderate', except in areas of high variability such as the poleward extension of the Gulf Stream. The eastern equatorial Pacific Ocean experienced almost no MHWs in 2021 and was one of the few non-polar regions of the global ocean to see broad MCS coverage.

MHWs in 2021 (to 14 October) showed an average daily coverage of 13%, which is less than the record of 17% in 2016 and 16% in 2020. Nearly 25% of MHWs were classified as 'strong', another 25% as 'moderate', and 55% of the ocean surface experienced at least one MHW during 2021 (Figure 7c) – less than the record of 65% in 2016 and 63% in 2020.

The average daily coverage of the global ocean by MCSs in 2021 (to 14 October) was 3% (Figure 8b) – a lower value than the record high in 1982 (7%) and less than 2020 (4%). MCSs in 2021 were predominantly classified as 'moderate' (17%) and 'strong' (3%). In total, 22% of the ocean surface experienced at least one MCS during 2021 (Figure 8c), which is lower than 2020 (25%) and 1985 (63%).

[27] Smale, D. A., Wernberg, T., Oliver, E. C., Thomsen, M., Harvey, B. P., Straub, S. C., ... & Moore, P. J. (2019). Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nature Climate Change, 9(4), 306-312.

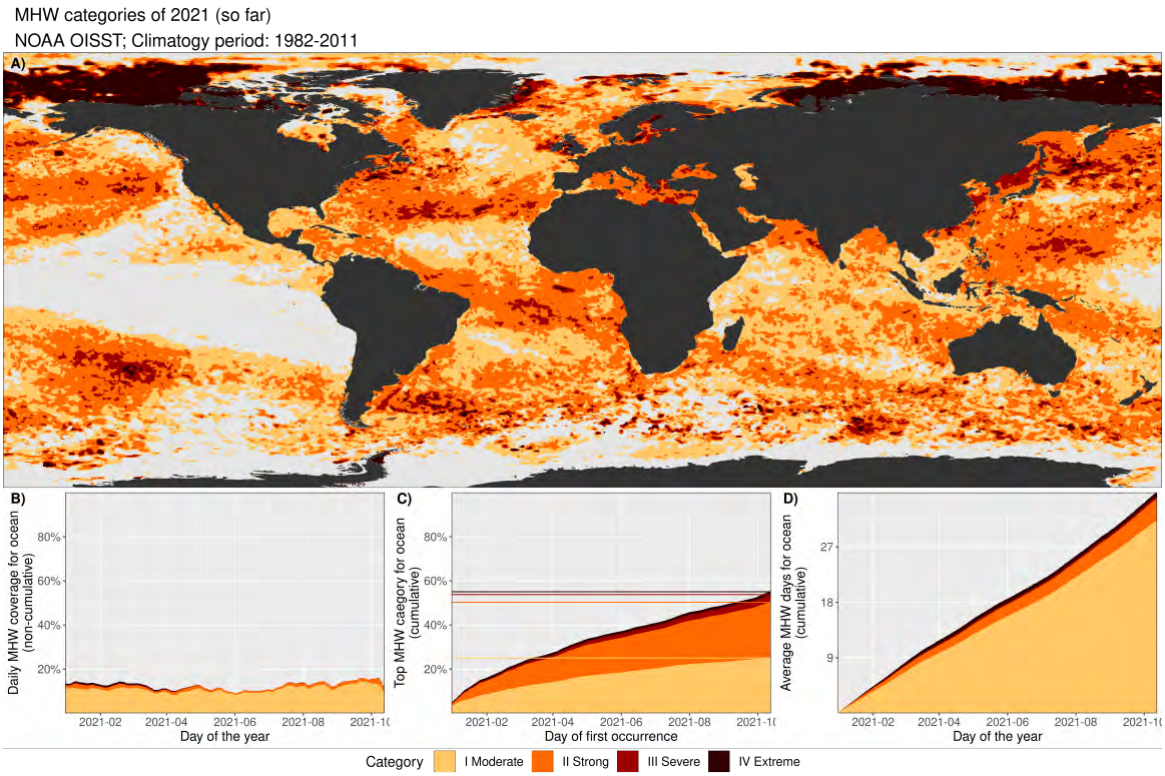


Figure 7: (a) Global map showing the highest MHW category (for definitions, see Marine heatwave and marine cold spell data) experienced at each pixel from 1 January to 14 October 2021 (reference period 1982–2011). Light grey indicates that no MHW occurred in a pixel over the entire year; (b) Stacked bar plot showing the percentage of the surface of the ocean experiencing an MHW on any given day of the year; (c) Stacked bar plot showing the cumulative percentage of the surface of the ocean that experienced an MHW over the year. Note: These values are based on when in the year a pixel first experienced its highest MHW category, so no pixel is counted twice. Horizontal lines in this figure show the final percentages for each category of MHW; (d) Stacked bar plot showing the cumulative number of MHW days averaged over the surface of the ocean. Note: This average is calculated by dividing the cumulative sum of MHW days per pixel weighted by the surface area of those pixels. Data are from NOAA OISST. Source: Robert Schlegel

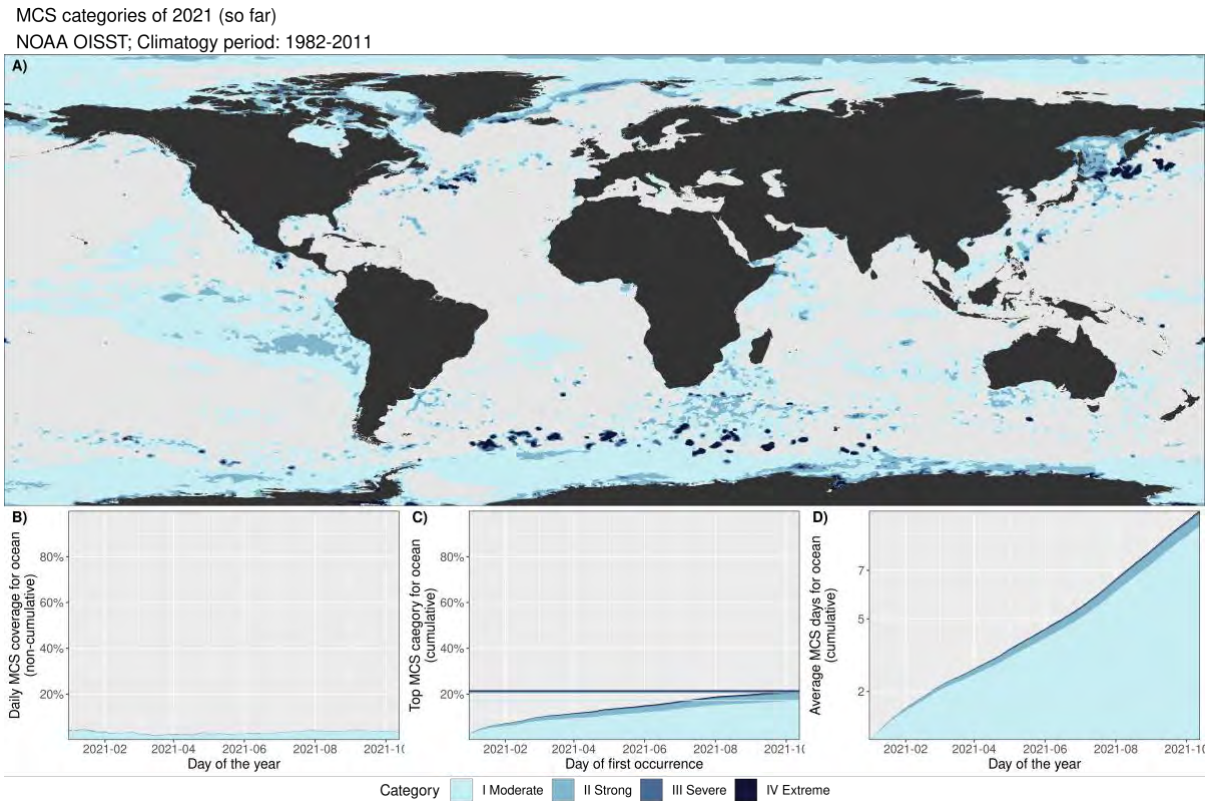


Figure 8: as for Figure 7 but showing Marine Cold Spells rather than Marine Heat Waves. Data are from NOAA OISST. Source: Robert Schlegel

Ocean acidification

The ocean absorbs around 23% of the annual emissions of anthropogenic CO_2 to the atmosphere[28,29], while this slows the rise of atmospheric concentration of CO_2[30] and the related warming, the costs to the ocean are high. CO_2 reacts with seawater and reduces the pH of the ocean[31], a process known as ocean acidification. The current global rate of ocean acidification (Figure 9) exceeds, by at least an order of magnitude, the rates inferred for the Paleocene-Eocene Thermal Maximum (PETM), which occurred around 56 million years ago and was associated with large perturbations of the global carbon cycle[32]. The IPCC AR6 concluded that "*there is* very high confidence *that open ocean surface pH is now the lowest it has been for at least 26 kyr and current rates of pH change are unprecedented since at least that time*". As the pH of the ocean decreases, its capacity to absorb CO_2 from the atmosphere also declines[33].

Ocean acidification threatens organisms and ecosystem services, and hence food security, tourism and coastal protection. Local and regional acidification is of great relevance to marine organisms and

[28] IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].
[29] https://library.wmo.int/index.php?lvl=notice_display&id=21620
[30] Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., et al. (2018). Global carbon budget 2017. Earth Syst. Sci. Data 10, 405–448. doi: 10.5194/essd-10-405-2018
[31] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.
[32] IPCC AR6 WG1 Chapter 2, section 2.3.3.5 Ocean pH
[33] Middelburg, J. J., Soetaert, K., &Hagens, M. (2020). Ocean alkalinity, buffering and biogeochemical processes. Reviews of Geophysics,58,e2019RG000681. https://doi.org/10.1029/2019RG000681

biological processes. However, there is high variability in coastal areas due to a range of factors affecting CO_2 levels.

National datasets of ocean acidification observations submitted towards the Sustainable Development Goal (SDG) 14.3 and the associated SDG Indicator 14.3.1 ("Average marine acidity (pH) measured at agreed suite of representative sampling stations",

Figure 10) highlight the need for sustained, repeated observation and measurement of ocean acidification along the coastlines and in the open ocean to improve understanding of its consequences, enable modelling and predictions of change and variability. While there are currently still gaps in the global coverage, capacity building efforts increase the capability of many nations to measure, manage and report ocean acidification data, as confirmed by the growing number of countries participating in data collection towards the SDG Indicator 14.3.1.

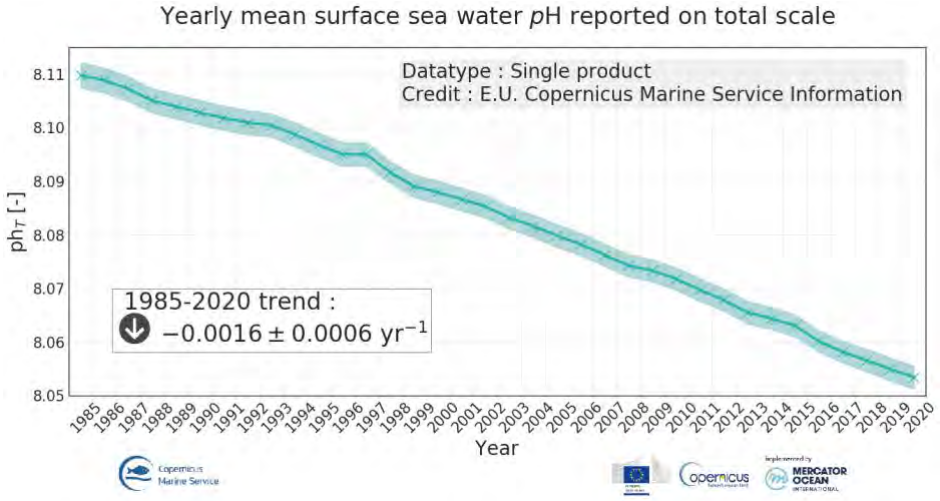


Figure 9: Global mean surface pH 1985 to 2020 from E.U. Copernicus Marine Service Information (blue). The shaded area indicates the estimated uncertainty.

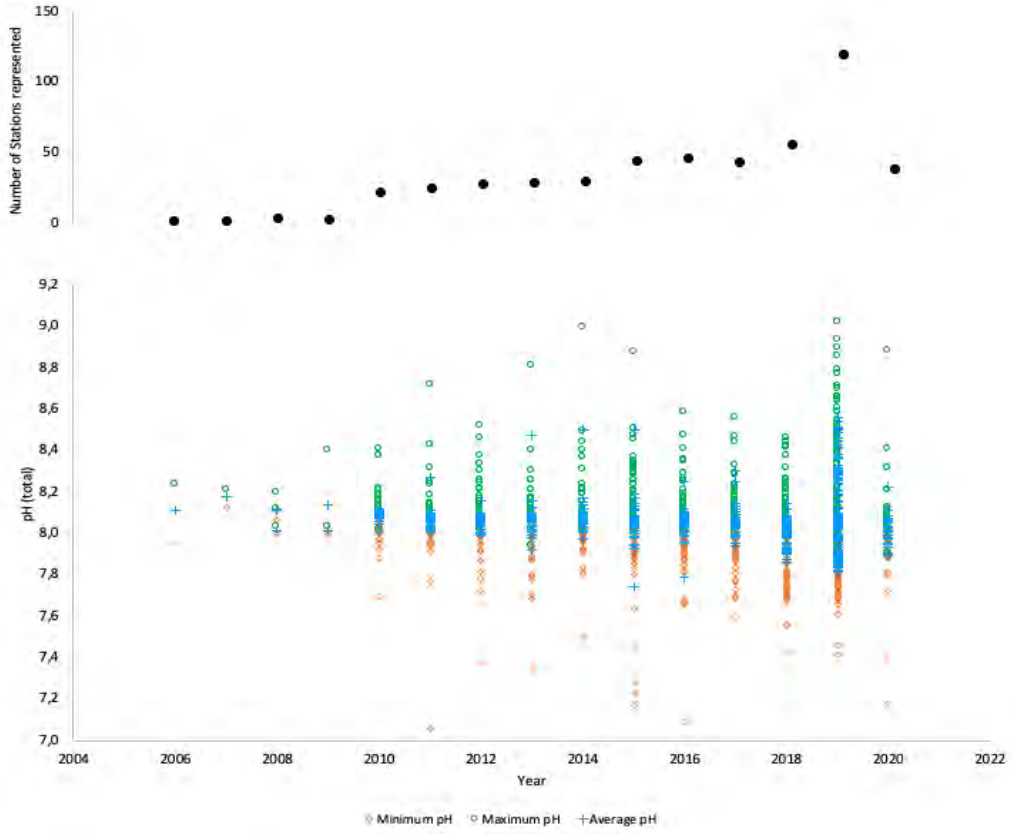


Figure 10: (left) Calculated surface pH values based on ocean acidification data submitted to the 14.3.1 data portal (http://oa.iode.org). Top panel: Black dots – number of stations represented per year. Bottom panel: Blue crosses – average annual pH reported from quality assured measurements; orange diamonds – annual minimum pH values reported for each station; green circles – annual maximum pH values reported for each station.

Cryosphere

The cryosphere comprises the frozen parts of the earth. This includes sea ice, glaciers, ice sheets, snow, and permafrost, all of which are covered in this report. Note that with reporting delays, the most recent data for some of these indicators are from 2020.

Sea ice

Arctic sea ice

The 2020-2021 Arctic winter saw anomalously high sea-level pressure over the central Arctic Ocean. The resulting anticyclonic wind pattern drove thicker multiyear ice into the Beaufort Sea[34]. The maximum Arctic sea-ice extent for the year was reached[35] on 21 March, at 14.8 million km^2. March 2021 was the 9th or 10th lowest extent on record (1979-2021), depending on the data source. For more details on the data sets used, see Sea ice.

Melt rates were close to the 1981-2010 average early in the melt season. However, sea-ice extent decreased very rapidly in June and early July in the Laptev Sea and East Greenland Sea regions. As a result, the Arctic-wide sea-ice extent was record low in the first half of July. The monthly July average was the 2nd to 4th lowest on record (tied with 2012 and 2019), with strong regional contrasts[36] (Figure 12). More ice than normal (1981-2010) was found in the Beaufort and Chukchi

[34] Mallett, R.D.C., Stroeve, J.C., Cornish, S.B. et al. (2021). Record winter winds in 2020/21 drove exceptional Arctic sea ice transport. Commun Earth Environ 2, 149 https://doi.org/10.1038/s43247-021-00221-8

[35] https://nsidc.org/arcticseaicenews/2021/03/arctic-sea-ice-reaches-uneventful-maximum

[36] https://climate.copernicus.eu/sea-ice-cover-july-2021

Seas, but the Siberian and European sectors (Laptev Sea and East Greenland Sea) had much less sea ice than normal. One exception was the Eastern Kara Sea, where some sea ice persisted for the whole season. Conditions shifted rapidly after July, with a sustained period of colder weather across the Arctic Ocean. This slowed the sea-ice melt and August 2021 ended-up with the 10th lowest extent on record, possibly also related to thicker multiyear ice in the Beaufort Sea that resisted melting.

Assisted by the August slowdown in melt, the minimum September extent was greater than in recent years but still well below the 1981-2010 average, representing the 12th lowest minimum ice extent in the 43-year satellite record (Figure 11). The 2021 minimum extent was observed[37] on 16 September at 4.72 million km^2 while the mean September ice extent was 4.92 million km^2, significantly below the 1981-2010 average. Sea-ice extent in the East Greenland Sea was a record low by a large margin.

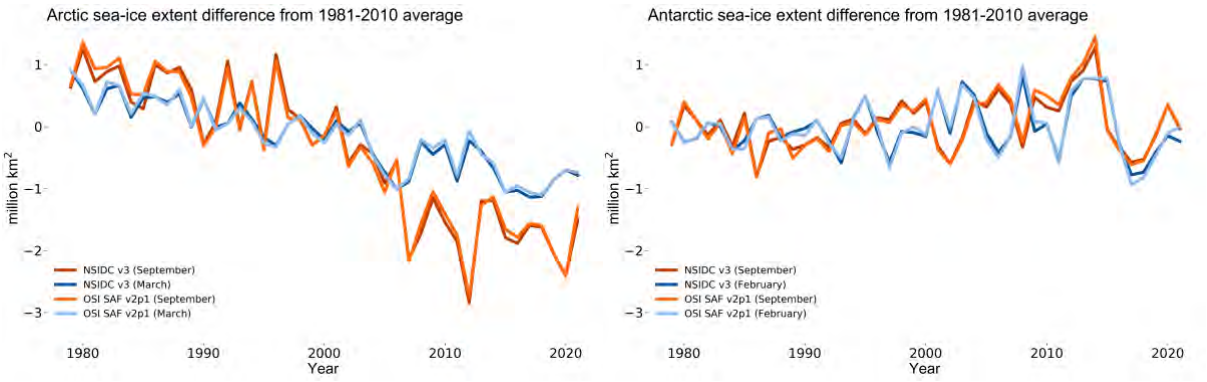


Figure 11: Sea-ice extent difference from the 1981–2010 average in the Arctic (left) and Antarctic (right) for the months with maximum ice cover (Arctic: March; Antarctic: September) and minimum ice cover (Arctic: September; Antarctic: February). Source: Data from EUMETSAT OSI SAF v2p1 and National Snow and Ice Data Centre (NSIDC) v3 (Fetterer et al., 2017) (see reference details in Sea-ice data).

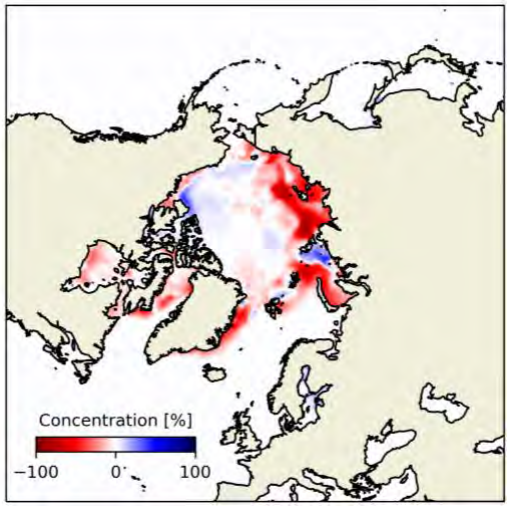


Figure 12: Arctic sea-ice concentration anomaly for July 2021 (difference from the 1981-2010 average). Red represents areas with less ice than normal, blue means more ice. Source: EUMETSAT OSI SAF data with research and development input from ESA CCI.

[37] https://nsidc.org/arcticseaicenews/2021/09/arctic-sea-ice-at-highest-minimum-since-2014

Antarctic sea ice

Sea-ice extent across the Southern Ocean during the first 9 months of 2021 was generally below the 1981–2010 mean, with a relatively low February minimum but near- average conditions during the summer melt season. There was an exceptionally early maximum ice extent at the end of August.

The minimum in the 2021 annual cycle occurred on 19 February, when sea ice covered 2.60 million km^2, the 15th lowest extent in the record (1979-present). The extent of ice at the annual minima began to increase in magnitude in the early 1990s, reaching a maximum of 3.68 million km^2 in 2013, before dropping sharply to 2.08 million km^2 in 2017, the lowest ice extent in the record. Since then, the extents at the annual minima have increased slowly. In February, most Antarctic sea ice is found in the Weddell Sea and therefore the sea-ice extents at the annual minima reflect regional changes in that area.

Antarctic sea ice reached its maximum annual extent of 18.80 million km^2 on 30 August 2021. This was close to the average magnitude in terms of extent and the 22nd largest in the 43 years of data. However, this was the 2nd earliest maximum, with only one other maximum having occurred in August (that of 2016). During July and August both the Amundsen Sea Low to the west of the Antarctic Peninsula and the Lazarev Sea Low close to the Greenwich Meridian were deeper than normal, leading to stronger than average offshore flow that led to positive sea ice anomalies in the Amundsen and Ross Seas, and between the northeast Weddell Sea and 90˚ E.

Glaciers

Glaciers are formed from snow that has compacted to form ice, which can deform and flow downhill to lower and warmer altitudes where it melts. If the glacier terminates in a lake or the ocean, ice loss also occurs through melting where ice and water meet or by calving of the glacier front to form icebergs. Glaciers are sensitive to changes in temperature, precipitation, and sunlight, as well as other factors such as changes in basal lubrication, warming ocean waters, or the loss of buttressing ice shelves.

Over the period 2000-2019, global glaciers and ice caps (excluding the Greenland and Antarctic Ice Sheets) experienced[38] an average mass loss of 267 ± 16 Gt yr^{-1}. Mass loss increased to 298 ± 24 Gt yr^{-1} from 2015-2019. Glaciers in several mid-latitude regions thinned at more than double the global average (0.52 ± 0.03 m yr^{-1}) from 2015-2019, e.g., -1.52 m yr^{-1} in New Zealand, -1.24 m yr^{-1} in Alaska, -1.11 m yr^{-1} in Central Europe, and -1.05 m yr^{-1} in western North America (not including Alaska).

According to the World Glacier Monitoring Service, in the hydrological year 2019-2020, the 40 or so glaciers with long-term observations experienced an average mass balance of -0.98 m water equivalent (m w.e[39]. Figure 13), less than in the record years 2018 and 2019, but still ranking as the 5th most negative mass balance year on record, for the period 1950-2020. Despite the global pandemic, mass balance observations were collected for most glacier monitoring sites worldwide, although some data gaps will be inevitable. Preliminary results for 2021 are only available for a few selected regions at this time, including for southwestern Canada and the Swiss Alps.

[38] Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F. and Kääb, A., 2021. Accelerated global glacier mass loss in the early twenty-first century. Nature, 592 (7856), 726-731.

[39] Metres water equivalent is the depth of water you would get if the lost ice were melted and spread across the surface area of the glacier.

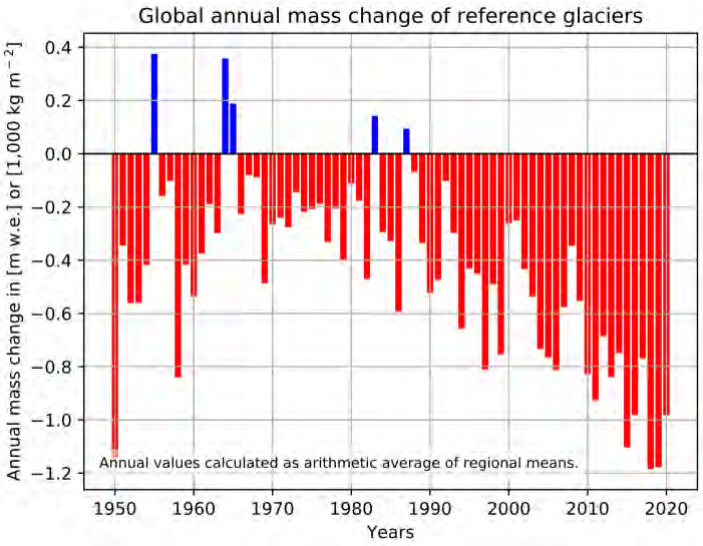


Figure 13: Global glacier mass balance, 1950-2020, from a subset of around 40 global reference glaciers. Units are m w.e. which is the depth of water that would be obtained from melting the lost ice and distributing it evenly across the glaciers. Data and image curated by the World Glacier Monitoring Service, http://www.wgms.ch.

Exceptional Glacier Mass Loss in Western Canada:

Mass loss from North American glaciers accelerated over the last two decades. Glacier mass loss in western North America increased from 53 ± 13 Gt yr^{-1} for the period 2000-2004 to 100 ± 17 Gt yr^{-1} for 2015-2019[38].

An exceptionally warm, dry summer in 2021 (see Heatwaves and wildfires) exacerbated mass loss for most glaciers in southern British Columbia, Alberta and the US Pacific Northwest. In the Coast Mountains of British Columbia, Place and Helm glaciers lost more mass during the period 2020-2021 than in any year since measurements began in 1965 (Figure 14a). In the Canadian Rocky Mountains, mass loss from Peyto Glacier was the second greatest since 1965, after the strong El Niño year of 1998 (Figure 14b). Repeat LiDAR surveys[40] indicate mass balances of -2.66, -3.30, and -1.95 m w.e. on Place, Helm, and Peyto glaciers, respectively. This represents roughly twice the mean regional rate of thinning from 2015-2019.

Little snow remained on most of the mountain glaciers in this region by mid-August, and many of these glaciers have lost their firn zone, where multi-year snow undergoes the transformation from snow to glacial ice. Particulate deposition – including soot and ash – from extensive regional wildfire activity in summer 2021 meant that the surfaces of the glaciers were unusually dark in July and August and absorbed more sunlight than usual, contributing to the extreme mass loss. Kokanee Glacier, British Columbia, lost 5-6% of its total volume in 2021, while Columbia Icefield, the largest icefield in the Rocky Mountains (210 km^2), lost about 0.34 Gt of ice (Figure 14c).

[40] Pelto, B. M., Menounos, B., and Marshall, S. J., 2019. Multi-year evaluation of airborne geodetic surveys to estimate seasonal mass balance, Columbia and Rocky Mountains, Canada. The Cryosphere, 13, 1709–1727, https://doi.org/10.5194/tc-13-1709-2019.

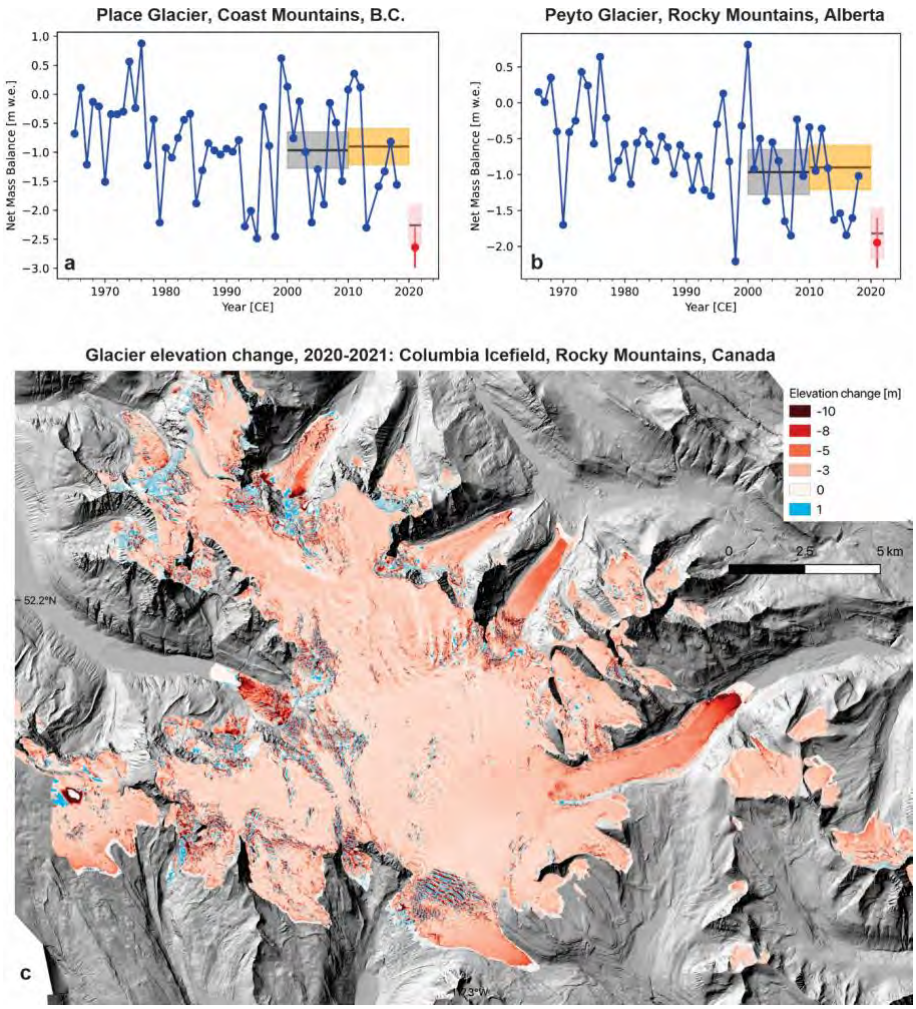


Figure 14: Glacier mass balance records from (a) Place Glacier, British Columbia, and (b) Peyto Glacier, Alberta from 1965 to 2021. Data for 1965-2019 are from the World Glacier Monitoring Service and 2021 mass balance estimates are from LiDAR surveys, with firn-density corrections after Pelto et al. (2019). The blue and yellow horizontal bars indicate decadal mean values for the region from Huggonet et al. (2021). Data from 2021 indicate the uncertainty (pink bar), the mass balance calculation using the contemporaneous LiDAR-derived glacier area (red circles), and the specific mass balance calculated from the Randolph Glacier Inventory glacier areas/outlines as used by Huggonet et al. (2021) (black crosshairs). (c) LiDAR-derived elevation change on the Columbia Icefield, Canadian Rocky Mountains, for the 2020-2021 mass balance year.

Reduced Glacier Melt Rates in the Swiss Alps:

Glaciers in the Swiss Alps suffered significantly less ice loss than in the previous years due to substantial snow in winter and a cool and rainy summer season. Nevertheless, in 2021 none of the monitored glaciers showed mass gain, and ice losses averaged around 0.5 m w.e., corresponding to a reduction of glacier ice volume in Switzerland of 0.8%.

Ice sheets

Ice sheets are expanses of glacial ice that cover an area larger than 50 000 km^2. In the current climate, there are two ice sheets, found on Greenland and Antarctica.

Greenland ice sheet

Changes in the total mass balance of the Greenland ice sheet reflect the combined effects of: surface mass balance, defined as the difference between snowfall and meltwater runoff from the ice sheet; the marine mass balance, which is the sum of mass losses at the periphery from the calving of icebergs and the melting of glacier tongues on contact with the ocean; and the basal mass balance,

which consists of basal melting due to geothermal heat, frictional heat generated by sliding at the base of the glacier and by deformation of the ice.

For Greenland[41], the total mass balance in 2020-2021 (1 September 2020 – 31 August 2021) was -166 Gt, which is close to the average for the period 1987-2021. This was the 25th year in a row with a negative mass balance. Over the period September 1986 to August 2021, for which we have daily data, the Greenland Ice Sheet lost a total of 5 511 Gt of ice. Cumulative mass loss was 4 261 Gt from April 2002 to June 2021, the period covered by observations from the GRACE satellites.

The GRACE and GRACE-FO satellites can measure changes in the amount of ice using the minute variations they cause in the gravitational field. This provides an independent measure of the total mass balance. Based on this data, the Greenland ice sheet for the same period as above (April 2002 to June 2021) has lost about 4 473 Gt. This ice loss contributed to a sea level rise of about 1.2 cm.

The surface mass balance for the 2020-2021 mass balance season in Greenland was +357 Gt, which is slightly above the 35-year average 1986-2020 of +326 Gt. However, estimated ice loss due to iceberg calving and glacier tongue melting, the marine mass balance, of -500 Gt, was the highest of the period. The basal mass balance is small (~ -23 Gt) and does not show an obvious trend. The Greenland surface mass balance record is now three and a half decades long and, although it varies considerably from one year to another, there has been an overall decline in the average surface mass balance and total mass balance over time.

Greenland Ice Sheet melt extent was close to the long-term average through the early summer, but temperatures and meltwater runoff were well above normal in late July and August 2021 (Figure 16), the latter event was associated with a major incursion of warm, humid air in mid-August. This air mass moved in from Baffin Bay and covered much of southwestern and central Greenland. On August 14, rain was observed for several hours at Summit Station, the highest point on the Greenland Ice Sheet (3 216 m), and air temperatures remained above freezing for about nine hours[42]. There is no previous report of rainfall at Summit, and this is the latest date in the year that above-freezing temperatures have been recorded at this location. Melt events at Summit were also observed in 1995, 2012, and 2019. Ice core records indicate that prior to 1995, the last time melting occurred at Summit was in the late 1800s.

[41] Based on the average of three regional climate and mass balance models. See Mankoff, K. D., X. Fettweis, P.L. Langen, M. Stendel, K.K. Kjeldsen, N.B. Karlsson, B. Noël, M.R. van den Broeke, W. Colgan, S.B. Simonsen, J.E. Box, A. Solgaard, A.P. Ahlstrøm, S.B. Andersen and R.S. Fausto, 2021: Greenland ice sheet mass balance from 1840 through next week. Earth Syst. Sci. Data, https://doi.org/10.5194/essd-2021-131, accepted.

[42] NSIDC (2021), http://nsidc.org/greenland-today/2021/08/rain-at-the-summit-of-greenland/

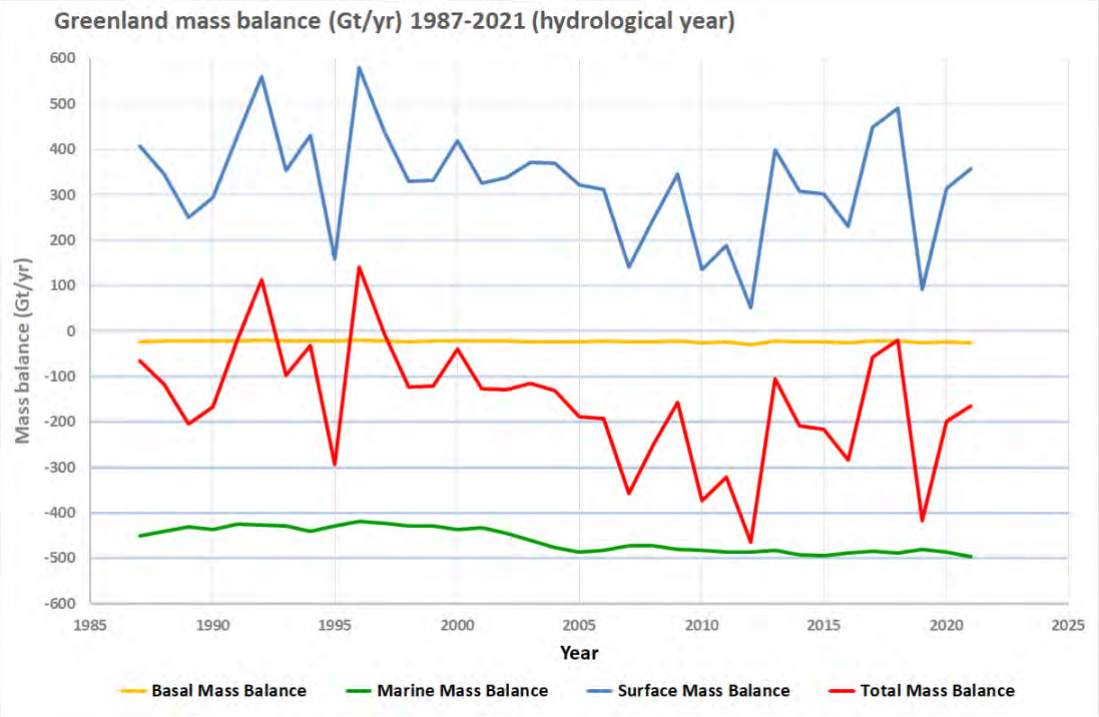


Figure 15: Components of the total mass balance of the Greenland Ice Sheet 1987-2021. Blue: Surface mass balance SMB, green: marine mass balance MMB (also referred to as discharge), orange: basal mass balance BMB, red: total mass balance TMB, the sum of SMB, MMB and BMB[43].

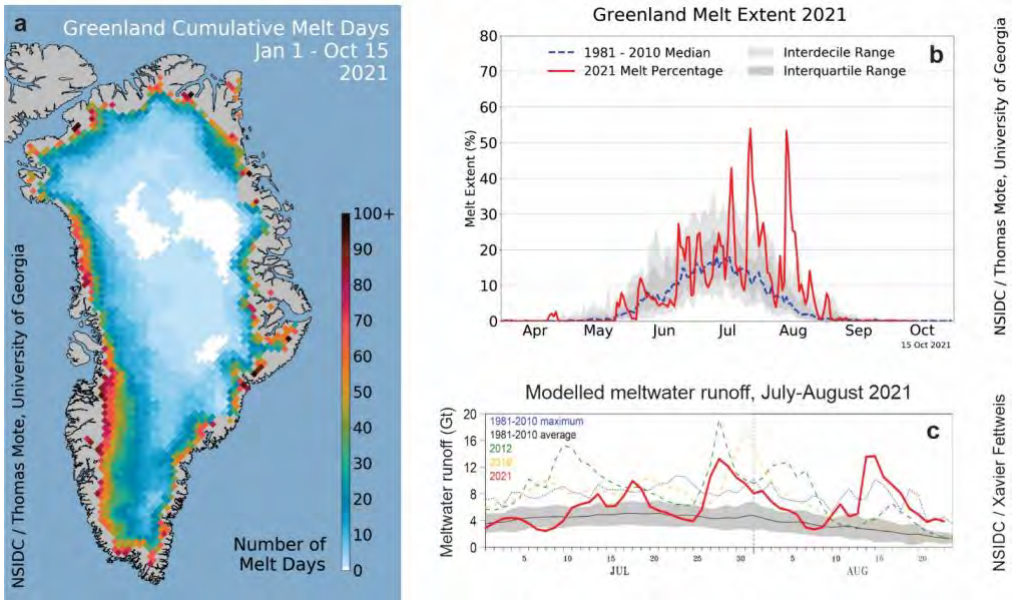


Figure 16: (a) Cumulative melt days on the Greenland Ice Sheet, 2021, indicating melt impacts over most of the ice sheet in summer 2021. (b) Melt extent (%) over the ice sheet through the 2021 melt season on Greenland, relative to the median melt extent from 1981-2010. (c) Greenland meltwater runoff through July-August 2021 relative to the recent extensive melt seasons of 2012 and 2019, indicating the record amount of late-season ice sheet melting associated with the mid-August rainfall event at Summit. All images are courtesy of the U.S. National Snow and Ice Data Center http://nsidc.org/greenland-today/, with thanks to Ted Scambos and the Greenland Ice Sheet Today. Analysis in (a) and (b) is from Thomas Mote, University of Georgia and meltwater runoff in (c) is estimated from the regional climate model MARv3.12, courtesy of Xavier Fettweis, University of Liège, Belgium.

[43] Mankoff, K D., X. Fettweis, P.L. Langen, M. Stendel, K.K. Kjeldsen, N.B. Karlsson, B. Noël, M.R. van den Broeke, W. Colgan, S.B. Simonsen, J.E. Box, A. Solgaard, A.P. Ahlstrøm, S.B. Andersen and R.S. Fausto, 2021: Greenland ice sheet mass balance from 1840 through next week, Earth Syst. Sci. Data, https://doi.org/10.5194/essd-2021-131, accepted.

Antarctic ice sheet

The Antarctic Ice Sheet so far experiences negligible surface melt compared to Greenland, but some melt typically occurs on the Antarctic Peninsula between November and February, as well as on some of the low-lying ice shelves and in coastal zones. The summer 2021 melt season in Antarctica was moderate and was below average for 1990-2020 (Figure 17)[44]. The northern Filchner Ice Shelf in the Weddell Sea experienced a strong but brief melt event in mid-December 2020. The summer melt season in Antarctica concluded in mid-February 2021. The strongest positive melt anomalies of the year were over the remnant Larsen B and C ice shelves on the Antarctic Peninsula; most other locations experienced near-normal melt extent relative to the mean 1990-2020 conditions.

Despite near-normal surface melting in Antarctica in summer 2021, GRACE-FO satellite gravity data indicate that the Antarctic Ice Sheet continued to lose mass in early 2021 (Figure 18), associated with calving and marine ice sheet melting in the Amundsen Sea sector of West Antarctica. Antarctic Ice Sheet mass loss since 2010 is largely driven by thinning and grounding-line retreat of Thwaites Glacier, triggered by ocean warming in this sector of the ice sheet[45].

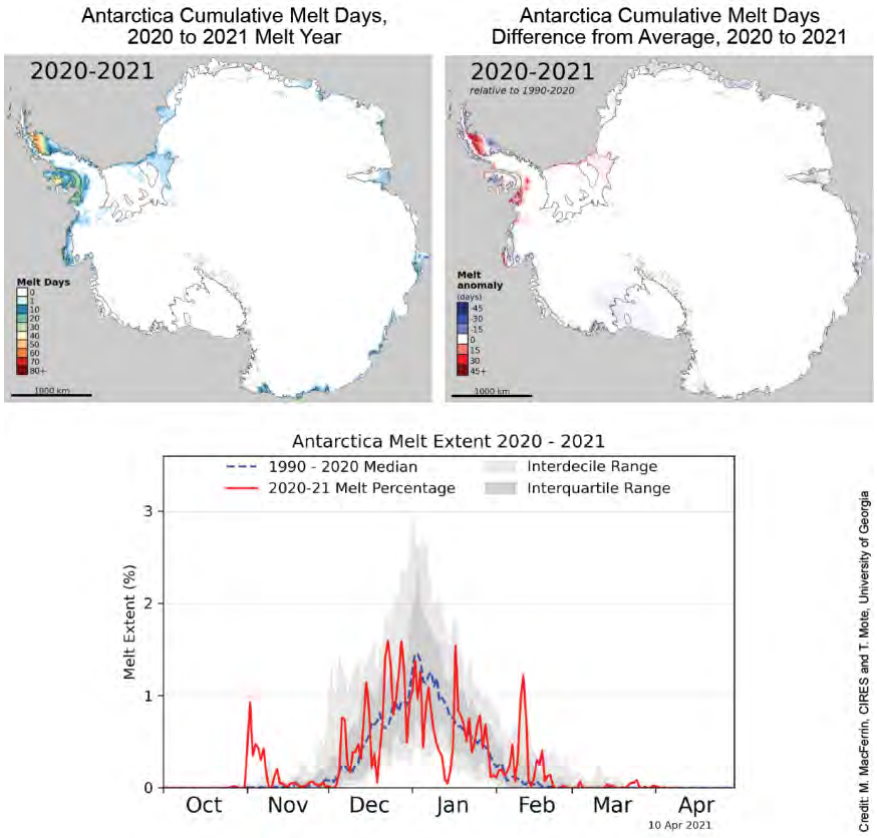


Figure 17: The 2021 melt season on the Antarctic Ice Sheet. Images courtesy of Michael MacFerrin and Thomas Mote, available from the NSIDC.

[44] http://nsidc.org/greenland-today/2021/04/the-antarctic-2020-to-2021-melt-season-in-review/

[45] Velicogna, I., Mohajerani, Y., A, G., Landerer, F., Mouginot, J., Noel, B., et al. (2020). Continuity of ice sheet mass loss in Greenland and Antarctica from the GRACE and GRACE Follow-On missions. Geophysical Research Letters, 47, e2020GL087291. https://doi.org/10.1029/2020GL087291, Rignot, E., J. Mouginot, Scheuchl, B., van den Broeke, M., van Wessem, M.J. and M. Morlighem (2019). Four decades of Antarctic Ice Sheet mass balance from 1979–2017. Proceedings of the National Academy of Sciences , 116 (4) 1095-1103; DOI: 10.1073/pnas.1812883116.

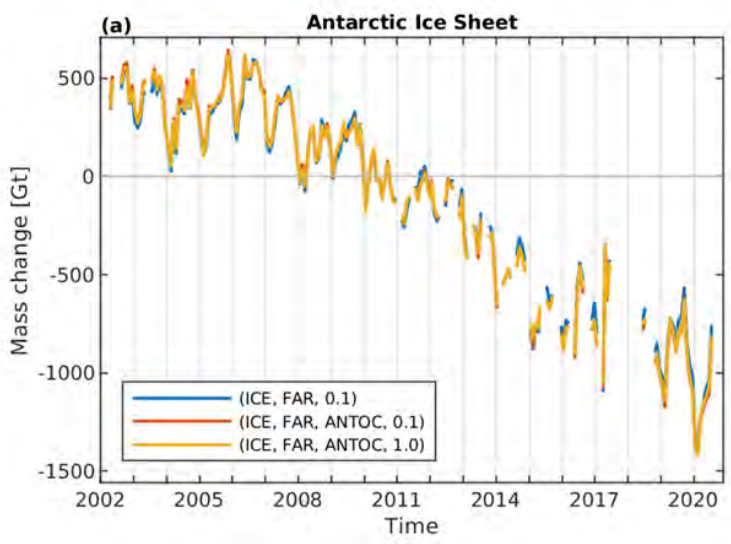


Figure 18: Antarctic Ice Sheet mass change measured by the GRACE and GRACE-FO satellite gravity missions, 2002-2021. The lines indicate different interpretations of the GRACE data (Groh and Horwath, 2021)[46].

Snow

Seasonal snow cover in the Northern Hemisphere has been experiencing a long-term decline in the late spring and summer, along with evidence of relative stability or increases in snow extent in the autumn (IPCC, 2021). Snow-cover extent (SCE) in 2021 was consistent with these long-term trends, with a May NH snow cover anomaly of -2 million km^2, the third lowest in the SCE record from 1970-2021 (Figure 19), based on analyses of the Rutgers Northern Hemisphere (NH) Snow Cover Extent (SCE) product[47]. The reduction in spring snow cover stands in contrast to the long-term trend and the most recent data for October. However, the IPCC AR6 note that the positive trends in Autumn snow cover in this data set were not replicated in other data sets[48].

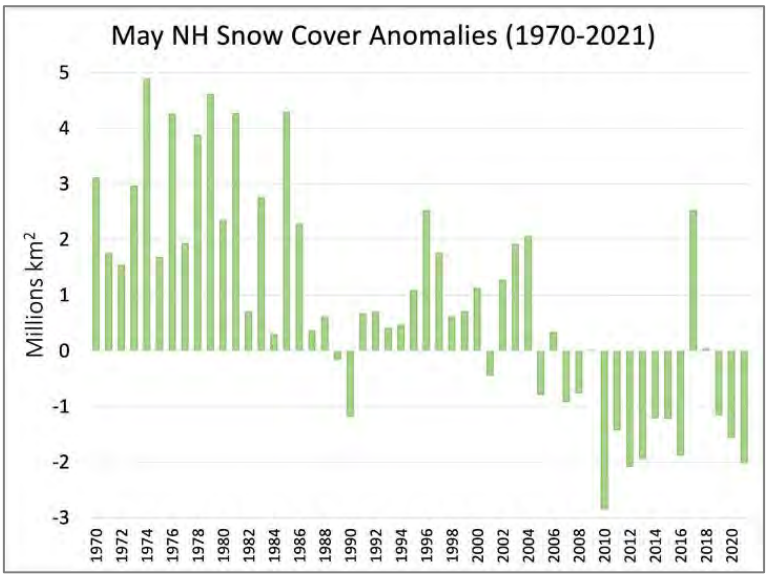


Figure 19: May snow-cover extent (SCE) anomaly in the Northern Hemisphere for the period 1970-2021, relative to the 1991-2020 average.

[46] Groh, A. and M. Horwath, 2021. Antarctic ice mass change products from GRACE/GRACE-FO using tailored sensitivity kernels. Remote Sensing 13 (9), 1736. https://doi.org/10.3390/rs13091736

[47] https://snowcover.org

[48] IPCC AR6 WG1 Chapter 9 pg 91 line 19-29.

Permafrost

Permafrost occurs beneath about one eighth of Earth's exposed land area. It is ground that remains at or below 0 °C for at least two consecutive years. Permafrost thaw can lead to landscape instability and other impacts, including the emission of greenhouse gases from previously frozen organic material. As permafrost temperature approaches 0 °C, changes in temperature in the ice-rich ground are subdued due to the phase change between ice and water. While temperature increase may level off near 0 °C for several years or decades due to the aforementioned phase change, the impacts of permafrost warming and thaw on ground stability including subsidence and mass movements, hydrology, ecosystems, and infrastructure are often clearly visible (Figure 20).



Figure 20: Recent slope instability associated with permafrost thaw, including active layer detachment slides and retrogressive thaw slumps. In the foreground, large amounts of material have pushed into the river to form a debris tongue. Foothills of the Mackenzie Mountains south of Norman Wells, north-western Canada. Image source: Government of Northwest Territories, Canada.

Since the 1990s, the Global Terrestrial Network for Permafrost (GTN-P) has compiled data sets of Permafrost Temperatures (temperature measured in boreholes) and Active Layer Thickness (the maximum thickness of the seasonally thawed layer above the permafrost). GTN-P products rely mostly on research projects to sustain activities. Long-term data series from national and regional networks operating in mountain and polar areas show a continuation of past warming trends up to 2020, the most recent data available.

Stratospheric ozone

Following the success of the Montreal Protocol, use of halons and CFCs has been reported as discontinued but their levels in the atmosphere continue to be monitored. Because of their long lifetime, these compounds will remain in the atmosphere for many decades and even if there were no new emissions, there is still more than enough chlorine and bromine present to cause complete destruction of ozone in Antarctica from August to December. As a result, the formation of the Antarctic ozone hole continues to be an annual spring event with year-to-year variation in its size and depth governed to a large degree by meteorological conditions.

The 2021 ozone hole developed relatively early and continued growing, resulting in a large and deep ozone hole. It expanded to 24 million km^2 on 24 September and remains close to this value as of mid-October 2021. The development of the hole, its extent and severity are close to that for the 2020 and 2018 seasons. The ozone hole reached its maximum area of 24.8 million km^2 on 7 October 2021 similar to the areas in 2020 and 2018 and close to the highest values observed in earlier years such as 28.2 million km^2 in 2015 and 29.6 million km^2 in 2006 according to an analysis from the National Aeronautics and Space Administration (NASA) (Figure 21a). NASA reported a minimum

ozone of 92 DU (Dobson Units) on 7 October 2021 which is the lowest value in the past 17 years (see Figure 21b). Since the end of September 2021, the concentration of stratospheric ozone was persistently reduced to near-zero values between 15 and 20 km altitude over Antarctica. Together with the season of 2020 these are some of the lowest ever ozone values measured via sondes at the Antarctic stations as reported by the National Oceanic and Atmospheric Administration (NOAA). The lowest total column value of 92 DU was reached on 7 October 2021. The unusually deep and large ozone hole this year is driven by a strong and stable polar vortex and very low temperatures in the stratosphere.

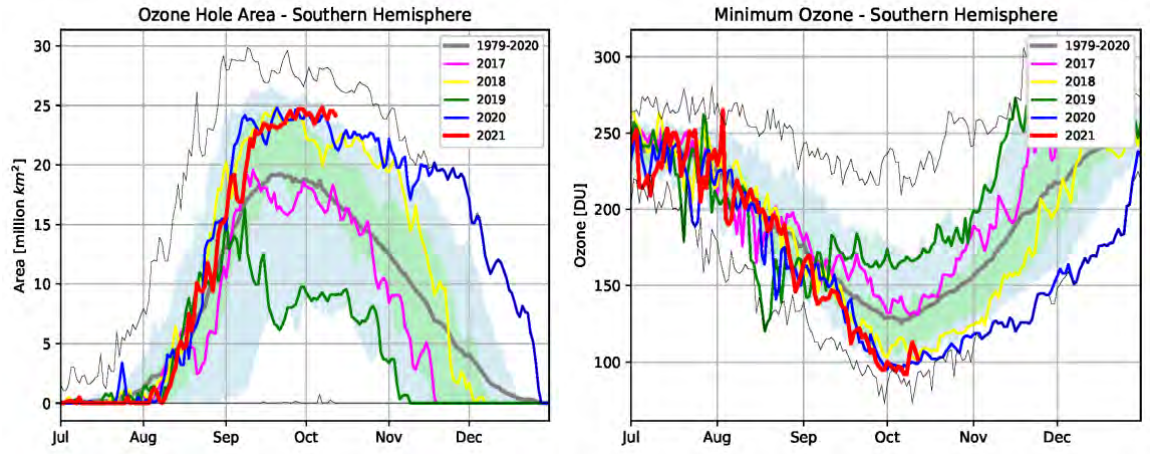


Figure 21: Area (millions of km²) and Minimum Ozone where the total ozone column is less than 220 Dobson units; 2021 is shown in red. The most recent years are shown for comparison as indicated by the legend. The smooth, thick grey line is the 1979–2020 average. The blue shaded area represents the 10th to 90th percentiles, and the green shaded area represents the 30th and 70th percentiles for the period 1979–2020. The thin black lines show the maximum and minimum values for each day in the 1979–2020 period. The plot is made at WMO on the basis of data downloaded from the NASA Ozone Watch (https://ozonewatch.gsfc.nasa.gov/). The NASA data are based on satellite observations from the OMI and TOMS instruments.

Drivers of short-term variability

There are many different natural phenomena, often referred to as climate patterns or climate modes, that affect weather at timescales ranging from days to several months. Surface temperatures change relatively slowly over the ocean, so recurring patterns in sea surface temperature can be used to understand and, in some cases, predict the more rapidly changing patterns of weather over land on seasonal time scales. Similarly, albeit at a faster rate, known pressure changes in the atmosphere can help explain certain regional weather patterns.

In 2021, the El Niño–Southern Oscillation (ENSO) and the Arctic Oscillation (AO) each contributed to major weather and climate events in different parts of the world and are described in further detail below.

ENSO El Niño Southern Oscillation

ENSO is one of the most important drivers of year-to-year variability in weather patterns worldwide. It is linked to hazards such as heavy rains, floods, and drought. El Niño, characterised by higher-than-average sea surface temperatures in the eastern tropical Pacific and a weakening of the trade winds, typically has a warming influence on global temperatures. La Niña, which is characterised by below-average sea surface temperatures in the central and eastern tropical Pacific and a strengthening of the trade winds, has the opposite effect.

La Niña conditions emerged in mid-2020 and peaked in the October–December period at moderate strength, with average sea surface temperatures 1.3 °C below the 1991–2020 normal. The La Niña

weakened through the first half of 2021, reaching an ENSO-neutral state (temperatures within 0.5 °C of normal) in May, according to both oceanic and atmospheric indicators. However, sea surface temperatures cooled after mid-year, approaching La Niña thresholds once again by October.

In addition to having a temporary cooling influence on Earth's global temperature, La Niña is associated with drier-than-normal conditions in east Africa; most of Kenya, Ethiopia, and Somalia experienced consecutive below-average rainfall seasons in late 2020 and early 2021, leading to drought in the region. In early 2021, precipitation was higher than normal over the Maritime Continent[49] and lower than normal in Patagonia at the beginning of the year, typical patterns associated with La Niña. Additionally, La Niña conditions can contribute to above-average hurricane activity in the North Atlantic, which has experienced 20 named tropical cyclones during its 2021 hurricane season to date (the 1981–2010 average for the entire season is 14), following a record-breaking season in 2020 (28 storms, also associated with La Niña).

AO Arctic Oscillation

The AO is a large-scale atmospheric pattern that influences weather throughout the Northern Hemisphere. The positive phase is characterised by lower-than-average air pressure over the Arctic and higher-than-average pressure over the northern Pacific and Atlantic Oceans. The jet stream is parallel to the lines of latitude and farther north than average, locking up cold Arctic air, and storms can be shifted northward of their usual paths. The mid-latitudes of North America, Europe, Siberia, and East Asia generally see fewer cold air outbreaks than usual during the positive phase of the AO. A negative AO has the opposite effect, associated with a more meandering jet stream and cold air spilling south into the mid-latitudes where the jet stream dips southward.

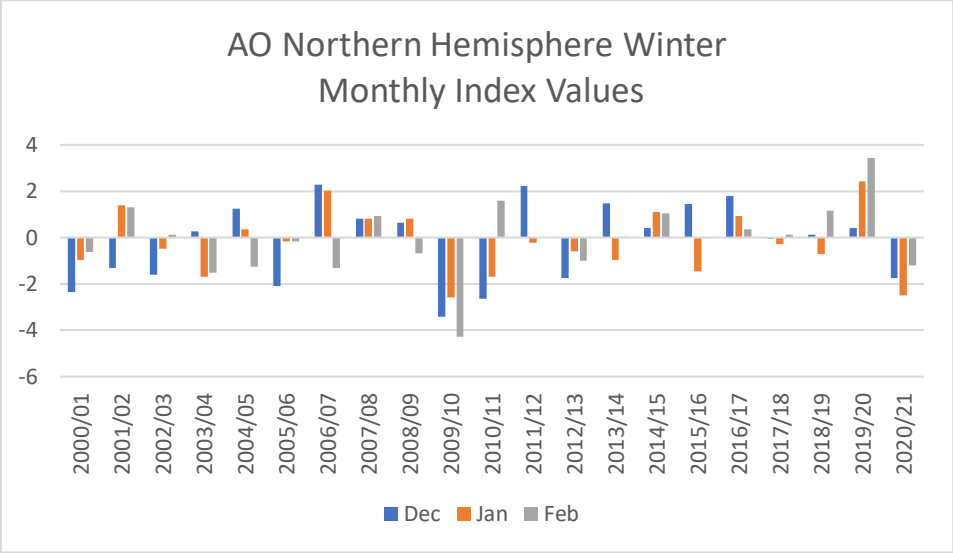


Figure 22: Arctic Oscillation monthly index values for Northern Hemisphere winter months, December in blue, January in orange and February in grey (Source: NOAA Climate Prediction Center).

The AO was negative during the Northern Hemisphere 2020-21 winter and, seasonally, was the most negative on record since winter 2009-10. The jet stream swept down over North America, contributing to its coldest February for the continent since 1994. However, the same wavy jet stream also contributed to extreme warmth in parts of northern and eastern Asia in February as it surged northward over the area, with regions in Mongolia, China, Japan, and the Republic of Korea reporting record-high temperatures for this time of year. The contrast between the positive AO

[49] The Maritime Continent refers to the islands found between mainland southeast Asia and Australia in the eastern Indian Ocean and western Pacific. It covers a similar area to the Malay Archipelago.

(winter 2019-20) and the negative AO (winter 2020-21) could explain some of the differences between temperature patterns in the first quarters of 2020 and 2021. The negative winter phase of the Arctic Oscillation has also been linked to more moderate Arctic sea ice loss the following summer[50] (see Arctic sea ice). The minimum extent for 2021, reached on 16 September, was the 12th lowest extent on record and the highest minimum since 2014.

High impact events in 2021

Although understanding broad-scale changes in the climate is important, the most acute impacts of weather and climate are often felt during extreme meteorological events such as heavy rain and snow, droughts, heatwaves, cold waves, and storms, including tropical storms and cyclones. These can lead to or exacerbate other high-impact events such as flooding, landslides, wildfires, and avalanches. This section is based largely on inputs from WMO Members. The risks and impacts associated with these events are described in Risks and impacts.

Heatwaves and wildfires

Exceptional heatwaves affected western North America on several occasions during June and July. By some measures, the most extreme was in late June in the north-western United States and western Canada. Lytton, in south-central British Columbia, reached 49.6 °C on 29 June, breaking the previous Canadian national record by 4.6 °C, with temperatures reaching the mid-40s as far west as eastern suburbs of Vancouver and in the interior of Vancouver Island. It was also more than 5 °C higher than the previous highest known temperature north of 50 °N. 569 heat-related deaths were reported in British Columbia alone between 20 June and 29 July[51]. Many long-term stations broke records by 4 to 6 °C, including Portland, Oregon (46.7 °C). There were also multiple heatwaves in the southwestern United States. Death Valley, California reached 54.4 °C on 9 July, equalling a similar 2020 value as the highest recorded in the world since at least the 1930s. It went on to be the hottest summer on record averaged over the continental United States.

There were numerous major wildfires during and after the heatwaves (including one which largely destroyed the town of Lytton the day after its record temperature). The Dixie fire in northern California, which started on 13 July, had burned about 390,000 hectares by 7 October, the largest single fire on record in California. However, the overall area burned for the season[52] in the United States was slightly below average[53].

Extreme heat affected the broader Mediterranean region on several occasions during the second half of the Northern Hemisphere summer. The most exceptional heat was in the second week of August. On 11 August, an agrometeorological station near Syracuse in Sicily reached 48.8 °C, a provisional European record, while Kairouan (Tunisia) reached a record 50.3 °C. Montoro (47.4 °C) set a national record for Spain on 14 August, while on the same day Madrid (Barajas Airport) had its hottest day on record with 42.7 °C. Earlier, on 20 July, Cizre (49.1 °C) set a Turkish national record and Tbilisi (Georgia) had its hottest day on record (40.6 °C). Major wildfires occurred across many parts of the region with Algeria, southern Turkey and Greece especially badly affected. Over 40

[50] Rigor, I. G., Wallace, J. M., & Colony, R. L. (2002). Response of sea ice to the Arctic Oscillation. Journal of Climate, 15(18), 2648–2663. https://doi.org/10.1175/1520-0442(2002)015<2648:ROSITT>2.0.CO;2

[51] https://www2.gov.bc.ca/gov/content/life-events/death/coroners-service/news-and-updates/heat-related

[52] As of 8 October.

[53] National Interagency Fire Center

deaths occurred in the Algerian fires. Other countries which experienced significant wildfires during the period included France, Italy, North Macedonia, Lebanon, Israel, Libya, Tunisia and Morocco.

June was exceptionally warm through many parts of eastern Europe. National June records were set for Estonia (34.6 °C) and Belarus (37.1 °C), whilst locations which had their hottest June day on record included St. Petersburg (35.9 °C) and Moscow (34.8 °C), both on 23 June, Yerevan (Armenia, 41.1 °C) on the 24th, and Baku (Azerbaijan, 40.5 °C) on the 26th. Tampere in Finland reported its highest temperature on record (33.2 °C) on 22 June. Libya also saw a prolonged heatwave in late June. Later in the summer, abnormal warmth also reached northwest Europe; 31.3 °C at Castlederg on 21 July was a record for Northern Ireland.

For the third successive year, there were major wildfires during the summer in Siberia, particularly in the Sakha Republic around Yakutsk. Fire activity in the Amazon region during the August-September peak season was less than in 2019 or 2020[54], but there was extensive fire activity in other parts of Brazil including the Pantanal. The Australian wildfire season in 2020-21 was also relatively inactive after a very severe season in 2019-20.

Cold spells and snow

Abnormally cold conditions affected many parts of the central United States and northern Mexico in mid-February. The most severe impacts were in Texas, which generally experienced its lowest temperatures since at least 1989, with temperatures in some areas staying below freezing continuously for 6 to 9 days, setting records in locations including Austin and Waco. On 16 February, Oklahoma City reached −25.6 °C and Dallas −18.9 °C, their lowest temperatures since 1899 and 1949 respectively. Electricity transmission was severely disrupted, with power outages affecting nearly 10 million people at the event's peak, while frozen pipes were another major cause of damage. 172 deaths were reported in the United States along with over $20 billion in economic losses, making it the most costly winter storm on record for the United States[55].

It was a cold winter in many parts of northern Asia. The Russian Federation had its coldest winter since 2009-10. Below-average temperatures affected much of Japan in late December and early January, with heavy snowfalls on a number of occasions, and a number of locations on the Sea of Japan coast of Honshu having their heaviest 72-hour snowfall on record in early January. Much of China was also cold during this period, with Beijing reaching −19.6 °C on 7 January, its lowest temperature since 1966.

A severe snowstorm hit many parts of Spain from 7 to 10 January, followed by a week of freezing air temperatures. A total of 53 cm of snow fell at the central city location of Retiro, and heavy falls were also reported in many other parts of Spain[56]. Some locations, including Toledo (−13.4 °C) and Teruel (−21.0 °C), had their lowest temperatures on record on 12 January in the wake of the storm. There were major disruptions to land and air transport. Later in the winter, in the second week of February, the Netherlands experienced its most significant snowstorm since 2010 with heavy snow also falling in Germany, Poland and the United Kingdom; in the wake of the storm, Braemar recorded −23.0 °C on 12 February, the lowest temperature in the United Kingdom since 1995. In southeast Europe, Athens had its heaviest snow since 2009 on 15 February.

An abnormal spring cold outbreak affected many parts of Europe in early April. Record low April temperatures in France included −7.4 °C at Saint-Etienne on the 8th and −6.9 °C at Beauvais on the

[54] https://queimadas.dgi.inpe.br/queimadas/portal-static/estatisticas_estados/
[55] https://www.ncdc.noaa.gov/billions/events/US/2021
[56] http://www.aemet.es/en/conocermas/borrascas/2020-2021/estudios_e_impactos/filomena

6th, while Belgrade (Serbia) had its heaviest April snowfall on record on the 7th. At high elevations, national records for April were set for Switzerland (−26.3 °C at Jungfraujoch) and Slovenia (−20.6 °C at Nova vas na Blokah). This followed a very warm end to March with France having its warmest March day on record on the 31st. Frost damage to agriculture was widespread and severe, with losses to vineyards and other crops in France alone exceeding US$4.6 billion[57]. The United Kingdom went on to have its lowest monthly mean temperature for April since 1922.

Precipitation

Compared to temperature, precipitation is characterized by higher spatial and temporal variability. Large regions with above normal (1951-2000) precipitation totals from January till September were Eastern Europe, Southeast Asia, the Maritime Continent, areas of northern South America and south-eastern North America (Figure 24). Large regions with a rainfall deficit included southwest Asia and the Middle East, parts of southern Africa, southern South America and central North America.

La Niña events are often – but not always – characterised by shifting patterns of rainfall. In some regions the pattern of precipitation anomalies were typical of those associated with La Niña conditions at the beginning of the year: wetter than average conditions over the Maritime Continent and drier than usual conditions in Patagonia. However, in Australia, where La Niña is typically associated with above-normal rainfall, precipitation anomalies were relatively weak.

The onset of the African Monsoon was delayed. Later in the season, rainfall totals were higher than normal, especially in the western monsoon region. In total, the seasonal rainfall was close to normal.

In Southern Africa, in an area centred on Zambia, rainfall amounts during the wet season until May were below the long-term mean. It was at least the second year in a row with below normal rainfall for Madagascar; rainfall totals have been below average in most years since 2011. In addition, the April-May wet season was drier than usual in the Greater Horn of Africa region.

Over North America, above average rainfall totals were observed in Alaska and the north of Canada, and in the southeast of the United States and parts of the Caribbean. Between these two wetter-than-average bands was a swath of unusually dry conditions extending across the width of the continent.

Unusually high precipitation amounts, relative to the chosen climatology period (1951-2010), were recorded in the southwest and southeast of Australia. On the other hand, abnormally low precipitation amounts were received on the North Island of New Zealand.

Unusually low precipitation amounts fell around the Mediterranean Sea, while unusually high totals were detected around the Black Sea and in parts of Eastern Europe.

[57] French national contribution

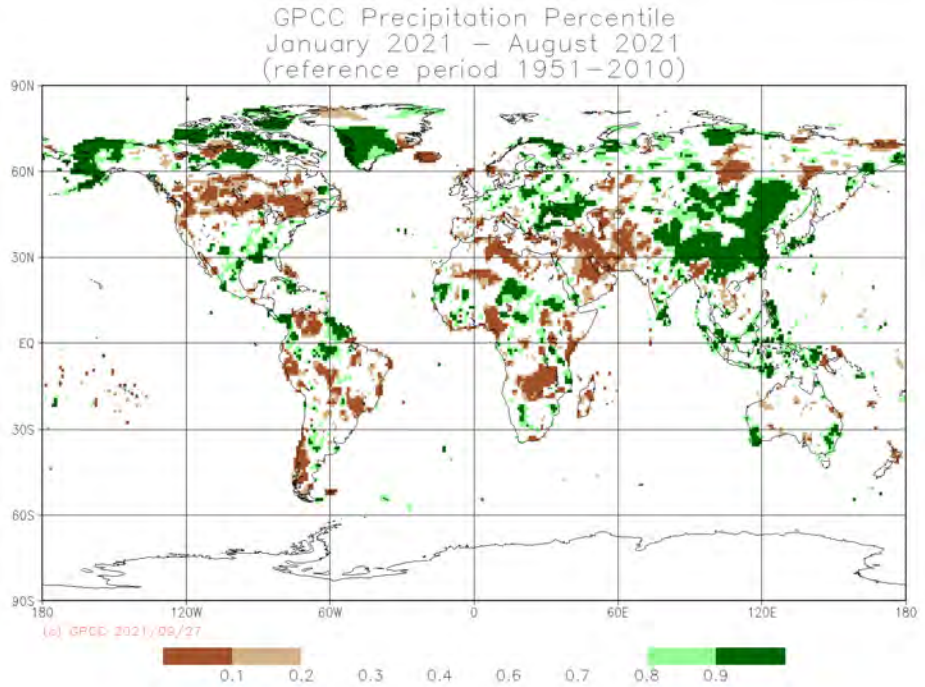


Figure 23: Total precipitation in Jan-Aug 2021, expressed as a percentile of the 1951–2010 reference period, for areas that would have been in the driest 20% (brown) and wettest 20% (green) of years during the reference period, with darker shades of brown and green indicating the driest and wettest 10%, respectively (Source: Global Precipitation Climatology Centre (GPCC), Deutscher Wetterdienst, Germany)

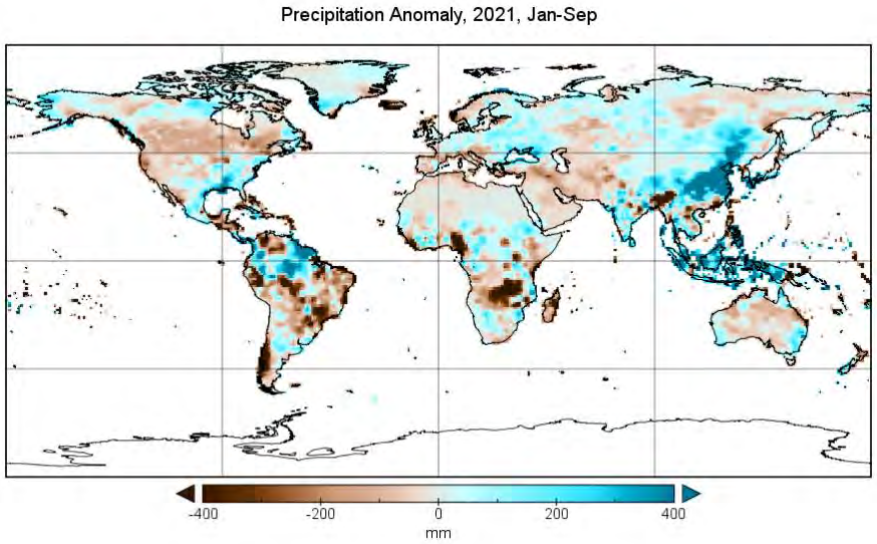


Figure 24: Total precipitation anomaly in Jan-Sep 2021 w.r.t. reference period 1951-2000. Blue indicates more precipitation than the long-term means while brown indicates less than usual rainfall totals. The darkness of the colour represents the amount of the deviation. (Source: Global Precipitation Climatology Centre (GPCC), Deutscher Wetterdienst, Germany).

Flood

Extreme rainfall, to which moisture ahead of Typhoon In-fa contributed, hit Henan Province of China from 17 to 21 July. The most severely affected area was around the city of Zhengzhou, which on 20 July received 201.9 mm of rainfall in one hour (a Chinese national record), 382 mm in 6 hours, and 720 mm for the event as a whole, more than its annual average. The city experienced extreme flash

flooding with many buildings, roads and subways inundated. 302 deaths were attributed to the flooding, and economic losses of US$17.7 billion were reported[58].

Western Europe experienced some of its most severe flooding on record in mid-July. The worst-affected area was western Germany and eastern Belgium, where 100 to 150 mm fell over a wide area on 14-15 July over ground which was already unusually wet after high recent rainfall. The highest daily rainfall was 162.4 mm at Wipperfürth-Gardenau (Germany). Numerous rivers experienced extreme flooding, with several towns inundated, and there were also several landslides. France, the Netherlands, Luxembourg, the United Kingdom and Switzerland also experienced significant flooding. 179 deaths were reported in Germany and 36 in Belgium, with economic losses in Germany exceeding US$20 billion[59].

Persistent heavy rainfall in mid-March resulted in major flooding in eastern New South Wales in Australia[60]. The week from 18 to 24 March was the wettest on record averaged over coastal New South Wales. The most severe flooding was in the Hastings, Karuah and Manning Rivers north of Sydney, but there was also significant flooding in other areas, including parts of western Sydney. There was also flooding on many inland rivers, which led to substantial recovery in water storages severely depleted by the 2017-19 drought. At least US$2.1 billion in economic losses were reported.

Two flash flood events associated with localised heavy rainfall occurred in Afghanistan during 2021, in early May around Herat in the west, and on 28-29 July centred on Nuristan in the east. There was significant loss of life in both events with 61 deaths reported in the May event and 113 in the July event[61].

Flash flooding occurred on several occasions around the Mediterranean and Black Sea coasts. The most impactful event was on the Black Sea coast of Turkey on 10 August, where several towns experienced severe damage and 77 deaths were reported. 399.9 mm of rain fell at Bozkurt in 24 hours. This event was associated with a 'Medicane' – a storm forming outside the tropics that nevertheless has characteristics of a tropical storm – in the Black Sea, with heavy rain and flooding also reported on the Russian Black Sea coast. On 4 October, exceptional rainfall fell in coastal regions of Liguria (northwest Italy), including 496.0 mm in 6 hours at Montenotte Inferiore and 740.6 mm in 12 hours at Rossiglione.

Persistent above-average rainfall in the first half of the year in parts of northern South America, particularly the northern Amazon basin, led to significant and long-lived flooding in the region. The Rio Negro at Manaus (Brazil) reached its highest level on record, peaking at 30.02 m on 20 June[62]. The most widespread flooding was reported in northern Brazil, but Guyana, Colombia and Venezuela were also affected.

The progress and withdrawal of the Indian Monsoon was delayed but overall Indian monsoon rainfall was close to average, with above-average falls in the west offset by below-average values in the northeast. During the course of the season, 529 deaths in India and 198 in Pakistan (as of 30 September) were attributed to flooding with further deaths in Bangladesh and Nepal[63]. In eastern Asia, eastern China (except for Henan) was generally less wet during the monsoon season than in

[58] RM 114.3 billion, from the Chinese national contribution
[59] German national contribution
[60] http://www.bom.gov.au/climate/current/statements/scs74.pdf?20210621
[61] EM-DAT
[62] http://www.cprm.gov.br/sace/boletins/Amazonas/20211022_11-20211025%20-%20114229.pdf
[63] National contributions for India and Pakistan, EM-DAT has 120 deaths in Nepal over two incidents and 21 in Bangladesh from one,

2020, but August was extremely wet in Japan. Western Japan had its wettest August on record[64], with some locations having more than 1400 mm of rain between 11 and 26 August.

The rainy season in the African Sahel was generally close to the average (1951-2000), and less wet than some recent years, although there was still some significant flooding reported, especially in Niger, Sudan and South Sudan as well as Mali. Elsewhere in Africa, Lake Tanganyika rose to more than 3 m above its normal level in May[65], displacing lakeshore residents in Burundi. In southern Africa, much of which had been experiencing long-term drought, rainfall during the 2020-21 rainy season was above average in regions including northern South Africa and Zimbabwe with some flooding reported but was near or below average further north.

Drought

Significant drought affected much of subtropical South America for the second successive year. Rainfall was well below average over much of central and southern Brazil[66], Paraguay, Uruguay and northern Argentina. The drought led to significant agricultural losses, exacerbated by a cold outbreak at the end of July, in which maximum temperatures were below 10°C for five consecutive days over higher parts of the south and which caused damage over many of Brazil's coffee-growing regions. Low river levels also reduced hydroelectricity production[67] and disrupted river transport. The Brazilian government declared a situation of critical scarcity of water resources in the Paraná hydrographic region, with numerous water storages at or near their lowest levels in the last 20 years[68]. The 24-month Standardised Precipitation Index (SPI) over the region reached its lowest level since the 1960s. The Paraguay River at Asuncion fell to a record low 0.75 m below the reference level on 6 October, 0.21 m below the previous record set last year. In Chile, where long-term drought has persisted for most of the last decade, 2021 was another dry year, with most locations having rainfall at least 30% below average. At Santiago, 107.7 mm had fallen as of 6 October, 67% below average.

Widespread drought in western North America, which had become established during 2020, spread and intensified in 2021. By September, extreme to exceptional drought covered most of the United States over and west of the Rocky Mountains, despite some slight easing from July onwards in parts of the inland southwest, due to an active summer monsoon. Extreme to exceptional drought also extended eastwards on both sides of the United States-Canada border, affecting northern border states as far east as Minnesota and the Prairie Provinces of Canada. The 20 months from January 2020 to August 2021 was the driest on record for the southwestern United States[69], more than 10% below the previous record. Forecast wheat and canola crop production for Canada in 2021 is 30 to 40% below 2020 levels[70], whilst in the United States, the level of Lake Mead on the Colorado River fell in July to 47 m below full supply level, the lowest level on record since the reservoir was fully commissioned.

Significant drought affected large areas of southwest Asia during 2021. Well below average precipitation fell during the 2020-21 cool season in regions including most of Iran, Afghanistan, Pakistan, southeast Turkey, and Turkmenistan. Pakistan had its third-driest February on record. Mountain snowpack was also well below average, with snow cover extent in Iran about half the

[64] https://ds.data.jma.go.jp/tcc/tcc/news/press_20210924.pdf
[65] Reliefweb: https://reliefweb.int/disaster/fl-2021-000039-bdi
[66] https://clima.inmet.gov.br/prec
[67] http://www.ons.org.br/Paginas/Noticias/20210707-escassez-hidrica-2021.aspx
[68] https://www.gov.br/ana/pt-br/assuntos/noticias-e-eventos/noticias/ana-declara-situacao-de-escassez-quantitativa-dos-recursos-hidricos-da-regiao-hidrografica-do-parana
[69] https://www.drought.gov/news/new-noaa-report-exceptional-southwest-drought-exacerbated-human-caused-warming
[70] https://www150.statcan.gc.ca/n1/daily-quotidien/210914/dq210914b-eng.htm

long-term average for most of January and February, leading to reduced streamflow in rivers depending on snowmelt, and reduced water availability for irrigation.

A severe, relatively localised, drought, which has persisted for at least two years, continues to affect southern Madagascar[71]. Rainfall for the 12 months from July 2020 to June 2021 was around 50% below normal over the region. There were significant food security issues in the area, with 1.14 million classified by the World Food Programme as needing urgent assistance as of August 2021[72].

Tropical cyclones

Tropical cyclone activity over the globe in 2021 was close to average (1981-2010). For the second successive year, the North Atlantic had a very active season, with 20 named storms as of 11 October, about double the average for that period. It was also an active season in the North Indian Ocean, but the western North Pacific and eastern North Pacific were near to or below average. The 2020-21 Southern Hemisphere season was also slightly below average in both the Pacific and Indian Oceans.

The most significant hurricane of the North Atlantic season was Ida. Ida made landfall as a category 4 system in Louisiana on 29 August with sustained 1-minute winds of 240 km/h, the equal-strongest landfall on record for the state, with major wind damage and storm surge inundation. The system then continued on a northeast track over land with significant flooding, especially in the New York City area. New York, which had already experienced flooding from Hurricane Henri two weeks earlier, had a record hourly rainfall of 80 mm, with 24-hour totals exceeding 200 mm in parts of the city. Before it developed into a tropical cyclone, Ida's precursor system also caused significant flooding in Venezuela. In total, 72 direct and 43 indirect deaths were attributed to Ida in the United States and Venezuela, with economic losses in the United States estimated at US$63.8 billion[73]. Another significant landfall during the season was Grace, which hit Veracruz (Mexico) as a category 3 hurricane, having earlier resulted in impacts, mostly from flooding, in Haiti (where it hindered post-earthquake recovery), the Dominican Republic, Jamaica, and Trinidad and Tobago.

In the Southern Hemisphere, 2021's most significant cyclone[74] was Seroja in April. Seroja formed south of Indonesia and tracked southeast towards Western Australia. It made landfall near Kalbarri on 11 April as an (Australian) category 3 cyclone, the strongest landfall so far south in Western Australia since 1956. Seroja's most severe impacts were from flooding and associated landslides from its precursor system in Timor-Leste, and the Indonesian regions of East Nusa Tenggara, Flores and Timor. Kupang (Timor) received 700.4 mm rainfall in the four days from 2 to 5 April. 272 deaths in total were attributed to Seroja, 230 in Indonesia, 41 in Timor-Leste and one in Australia[75]. Eloise in January contributed to flooding in southern Africa with damage and casualties reported in Mozambique, South Africa, Zimbabwe, Eswatini and Madagascar, while in the South Pacific, Ana and Niran caused flooding and power outages in Fiji and New Caledonia respectively.

The most severe cyclone of the North Indian Ocean season was Tauktae, which tracked north off the west coast of India, with a peak 3-minute sustained wind speed[76] of 50-53 m/s, before making landfall in Gujarat on 17 May at slightly below peak intensity, the equal strongest known landfall in Gujarat. At least 144 deaths were reported in India and 4 in Pakistan[77]. Later in the season, Cyclone Gulab crossed the eastern coast of India from the Bay of Bengal in late September; the remnant

[71] https://reliefweb.int/sites/reliefweb.int/files/resources/cb7310en.pdf
[72] https://reliefweb.int/sites/reliefweb.int/files/resources/WFP%20Madagascar%20Country%20Brief%20-%20August%202021.pdf
[73] https://www.ncdc.noaa.gov/billions/events/US/2021
[74] Tropical Cyclone Yasa (December 2020) forms part of 2020-21 seasonal statistics but was reported on in the 2020 State of the Climate.
[75] EM-DAT
[76] https://rsmcnewdelhi.imd.gov.in/uploads/report/26/26_e0cc1a_Preliminary%20Report%20on%20ESCS%20TAUKTAE-19july.pdf
[77] From national contributions

system crossed India before emerging and re-intensifying in the Arabian Sea, where it was renamed Shaheen. Shaheen made landfall on 3 October on the northern Oman coast northwest of Muscat, the first cyclone since 1890 to make landfall in this area. Al Suwaiq recorded 294 mm rain in 24 hours, about three times the region's annual average. 39 deaths were reported across India, Pakistan, Oman and Iran, mostly from flooding.

Direct impacts from North Pacific tropical cyclones were less than in recent years, although there were several significant landfalls, most notably from Typhoon Chanthu on the Batanes Islands (Philippines). Chanthu and Typhoon In-fa, in July, also both contributed to flooding and disruptions to shipping around Shanghai, while moisture ahead of In-fa was a contributor to the Henan Province floods (see Flood), and Dianmu contributed to flooding in Thailand in September after making landfall in Viet Nam.

Severe storms

There were multiple severe thunderstorm outbreaks in western and central Europe in the second half of June. An F4 tornado[78] struck several villages in southern Moravia on 24 June, with major damage and six deaths reported. This was the strongest tornado on record in the Czech Republic. Tornadoes were also reported during the month in Belgium and France. Large hail (6-8 cm in diameter) was reported in multiple countries, including the Czech Republic, Slovakia, Switzerland, and Germany. In the Czech Republic alone, losses were around US$ 700 million.

959 tornadoes were provisionally reported in the United States between January and April, slightly below the 1991-2010 average. The most significant outbreak, including the season's only EF-4 tornado[78], hit the southeast on 25 March with the most severe impacts in Alabama and western Georgia. 6 deaths and US$1.6 billion in economic losses were reported. Hailstorms in Texas and Oklahoma on 27-28 April resulted in US$2.4 billion in losses.

Attribution

Attribution of individual extreme events can often take several months to complete peer review. But increasingly it is becoming possible to carry out rapid attribution assessments that used peer-reviewed methods to reach conclusions within just a few days of a weather record being broken. Such "rapid attribution" studies have been carried out for the heatwave in northwest America in June and July[79,80] and of floods in western Europe in July[81]. Studies of the heatwave in the Pacific Northwest found that while the heatwave is still quite rare in today's climate, it would have been virtually impossible without climate change.

For the western Europe flooding, the rapid attribution study found that the detection of trends in extreme precipitation at the scale of the event in question was challenging and that saturated soils and the local hydrology were also factors in the event. However, across a wider area of western Europe, significant trends in extreme precipitation were found and these could be attributed to human-induced climate change and the study concluded that human-induced climate change had increased the likelihood of such an event.

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[78] On both the Fujita scale and the Enhanced Fujita scale, a tornado that causes devastating damage is classified as category 4 tornado (F4 and EF4 respectively). The scales differ in the wind speeds thought to be associated with "devastating damage" with lower wind speeds assumed in the Enhanced system for the same level of damage.

[79] https://www.worldweatherattribution.org/western-north-american-extreme-heat-virtually-impossible-without-human-caused-climate-change/

[80] https://blog.metoffice.gov.uk/2021/06/29/heatwave-record-for-pacific-north-west/

[81] https://www.worldweatherattribution.org/heavy-rainfall-which-led-to-severe-flooding-in-western-europe-made-more-likely-by-climate-change/

More generally, events such as these fit into a broader pattern of change. The IPCC assessed[82] that hot extremes in the regions of West North America and Northwest North American have increased, and that there is at least medium confidence in a human contribution to this increase. Similarly, the IPCC assessed that heavy precipitation has increased in the West and Central Europe region affected by flooding, but that there is currently low confidence in the attribution of this change to human influence.

Risks and impacts

The risk of climate-related impacts depends on complex interactions between climate-related hazards and the vulnerability, exposure and adaptive capacity of human and natural systems. At current levels of global greenhouse gas emissions, the world remains on course to exceed the agreed temperature thresholds of either 1.5 °C or 2 °C above pre-industrial levels, which would increase the risks of pervasive climate change impacts beyond what is already seen.

State of disasters

Disasters continue to take a heavy toll on life and assets, severely affecting and rolling back the development gains of countries. Years of investment in disaster preparedness, including early warning and rapid response capabilities, has strengthened capacities to reduce the human impact of disasters. However, economic losses remain high and continue to increase. The impact of high-frequency, low-impact events has also increased, often cumulatively exceeding the impact of single mega events.

Human impact of disasters

In the longer term, the average annual number of dead and missing persons in the event of disaster per 100 000 people has fallen from 1.98 during 2005-2014 to 1.32 during 2011-2020. Nonetheless, in absolute terms the disaster-related mortality remains high. In the last three years alone (2018-2020), a total of about 250 000 disaster-related deaths and missing persons were reported by an average of 74 countries[83].

The single largest event with highest mortality in 2021 was the earthquake in Haiti resulting in over 2500 deaths. However, the impact of climate change and variability continues to manifest in the form of hydrometeorological disasters. In 2021, floods resulted in around 1200 deaths in India, over 350 deaths in China, and over 200 deaths in Germany and Belgium. At the same time, over 600 people lost their lives due to heat waves in Northern America[84].

In the last three years (2018-2020), a total of approximately 319 million people were affected due to disasters as reported by an average of 66 countries each year[83]. In 2020 alone, 40.5 million new internal displacements were recorded, of which over 75 per cent were displaced due to disaster[85].

Driven by climate, growing vulnerability and conflict, humanitarian needs are at their highest-ever with one in every 33 people globally in need of assistance and protection[86]. Recurrent droughts continue to affect millions of people around the world, in particular in countries in Africa and Asia[84].

[82] IPCC AR6 WG1 Summary for Policymakers Figure SPM.3

[83] SFM: Sendai Framework Monitor https://sendaimonitor.undrr.org/ and https://desinventar.net
[84] EMDAT: https://public.emdat.be
[85] https://www.internal-displacement.org/global-report/grid2021/
[86] https://gho.unocha.org/

Economic cost of disasters

In the last three years (2018-2020), total economic losses of about US$ 148.32 billion have been reported by an average of 53 countries each year[83]. That this is an underestimation (due to limited reporting on loss and damage), can be ascertained from the fact that global disaster losses from natural hazards in 2020 alone is estimated to be US$210 billion by the insurance sector, which was over 25% higher than in the previous year[87]. In fact, over a four-decade period starting 1980, total losses due to such disasters have been estimated to be US$5.2 trillion[88].

In 2019, the agriculture sector accounted for 60 per cent of recorded losses, followed by the housing infrastructure sector[83]. The Food and Agriculture Organization (FAO) estimates that between 2008 and 2018, disasters cost the agricultural sectors of developing-country economies over US$108 billion in damaged or lost crop and livestock production[89]. At a global level, disaster-related losses amounted to US$280 billion. Up to 4% of the agricultural production was lost to disasters and 82% of all damage caused by drought was absorbed by the agricultural sector.

89.93 million people were reported to have lost or had livelihoods affected by disasters during 2018-2020. These figures do not yet consider the COVID-19 impact which is expected to significantly push the poverty figures - an estimated additional 97 million people dropped below the poverty line in 2020[90]. This, in combination with extreme weather events, including drought – is having devastating effects on global hunger and poverty.

Further, in 2019, Least Developed Countries accounted for about 21% of reported mortality and 5% of economic losses which is relatively higher as compared to their total population and GDP.

Food Security

Global outlook of food security in 2021

In the last ten years, conflict, extreme weather events and economic shocks have increased in frequency and intensity. The compound effects of these perils, further exacerbated by the COVID-19 pandemic, have led to a rise in hunger and, consequently, undermined decades of progress towards improving food security (Figure 25). Worsening humanitarian crises in 2021 have also led to a growing number of countries at risk of famine. Following a peak in undernourishment in 2020 (768 million people), projections indicated a decline in global hunger to around 710 million in 2021 (9%)[91]. However, as of October 2021, the numbers in many countries were already higher than in 2020. This striking increase (19%) was mostly felt among groups already suffering from food crises or worse (IPC/CH Phase 3 or above), rising from 135 million people in 2020 to 161 million by September 2021[92]. Another dire consequence of these shocks was the growing number of people facing starvation and a total collapse of livelihoods (IPC/CH Phase 5), mostly in Ethiopia, South Sudan, Yemen, and Madagascar (584 000 people). The first quarter of 2021 has also seen the highest global consumer food prices in the last six years, concentrated in Latin America and the Caribbean[91]. In West Africa, prices of coarse grains increased, driving food prices to record and near record highs in several countries, exacerbated by civil insecurity and torrential rains. In North Africa, food inflation

[87] https://www.munichre.com/en/company/media-relations/media-information-and-corporate-news/media-information/2021/2020-natural-disasters-balance.html

[88] https://www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards.html

[89] FAO. 2021. The impact of disasters and crises on agriculture and food security: 2021. Rome. https://www.fao.org/documents/card/en/c/cb3673en/

[90] https://blogs.worldbank.org/opendata/updated-estimates-impact-covid-19-global-poverty-turning-corner-pandemic-2021

[91] The State of Food Security and Nutrition in the World 2021. Rome, FAO. Transforming food systems for food security, improved nutrition, and affordable healthy diets for all. https://docs.wfp.org/api/documents/WFP-0000130141/download/?_ga=2.47516911.931354890.1634299853-763856357.1633873374

[92] GRFC. 2021. Global Report on Food Crises: Joint Analysis for Better Decisions. September 2021 Update. http://www.fightfoodcrises.net/fileadmin/user_upload/fightfoodcrises/doc/resources/FINAl_GRFC2021_Sept_Update.pdf

rates remained at modest levels in 2021, buffered by subsidies on many basic commodities that prevented price increase.

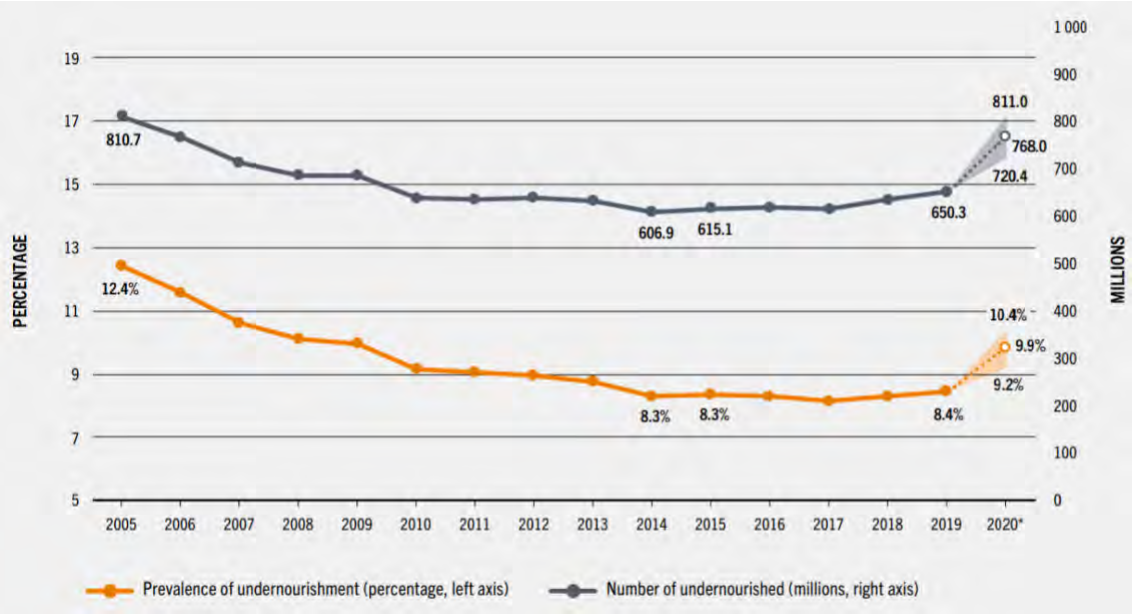


Figure 25: The number of undernourished people in the world significantly increased during the COVID-19 pandemic, from 650 million people in 2019 to 768 million people in 2020. Dotted lines and empty circles illustrate projected values in the above figure. According to the 2021 State of Food Security and Nutrition in the World, projections show a decrease in undernourishment rates between 2021 and 2030, with divergent trends across regions. While the numbers of undernourished people are likely to decrease in Asia, from 418 million in 2020 to ≈295 million in 2030, in Africa, the projected number of undernourished people is likely to increase, from 282 million in 2020 to ≈290 million in 2030. The entire series was revised to reflect new information made available since the publication of the report (GRFC, 2021).

Impacts of weather hazards on food production

Extreme weather during the 2020/21 La Niña altered rainfall seasons, disrupting livelihoods and agricultural campaigns across the world. Extreme weather events during the 2021 rainfall season have compounded shocks from the previous year(s), making it increasingly difficult to quantify impacts resulting from one single event. Consecutive droughts across large parts of Africa, Asia, and Latin America have coincided with severe storms, cyclones and hurricanes, significantly affecting livelihoods and the ability to recover from recurrent weather shocks.

Extreme dry conditions across vast areas of South America, and the recent return of La Niña conditions could further threaten crop yields within this region. However, larger than usual cultivations have to some extent offset the adverse effects of La Niña-induced crop productivity losses throughout the continent (-3.6% in 2021 compared to 2020)[93]. In the Caribbean, Haiti has been triply hit by natural disasters (earthquakes), weather shocks (irregular rains) and political instability, increasing agricultural damage and significantly worsening food insecurity.

In West Africa, floods and dry spells have caused crop damage and losses in localized areas resulting in small production downturns in 2021, but the forecasted aggregate outputs for the whole continent remain above average (+2.9% in 2021 over 2020)[93]. The 2021 first season harvest along central and southern areas of East Africa has been negatively affected by prolonged droughts, mostly in Kenya where maize outputs have been officially estimated to be 42-70% below average[93]. In northern parts of East Africa, the scale of seasonal flooding and its impact on crops has been lower compared to the severe flood impacts in 2020. In Southern Africa, the second consecutive

[93] FAO. 2021. Crop prospects and food situation. Quarterly Global report. https://www.fao.org/3/cb6901en/cb6901en.pdf

below-average rainfall season in Madagascar has led to a severe reduction in staple food production and a decline in livestock herd size. Although rainfall is projected to be near average in Madagascar in autumn 2021, seed and cutting supplies will be insufficient for the next cropping season and the lack of government and household control of weather-related hazards, pests and diseases, will result in sharp harvest declines with yield estimates 50-70% below the five-year average[94]. In Mozambique, cyclone Eloise made landfall in late January during the region's lean season when vulnerabilities were at their highest and affected communities still recovering from Cyclone Idai barely two years ago. According to the Government of Mozambique more than 441 000 people were affected by the cyclone displacing nearly 44 000 and destroying more than 45 000 hectares of cropland[95].

Drought conditions in the Near East reduced cereal production to below-average levels, exacerbating the impacts on agriculture and food security in fragile contexts, mostly in Afghanistan and the Syrian Republic. While cereal production decreased in the Near East, wheat production in the Far East reached a record high in 2021, with paddy rice outputs at high levels due to suitable weather conditions. In contrast, Central China was hit by torrential rains in mid-July 2021, leading to significant loss of life and damage to property. This sparked concerns over the potential impact on the nation's food supplies, as 1 million hectares of cropland – mostly corn, soybeans and peanuts – were affected, a third of which were wiped out.

Population Displacement

Climate-related hazards were a major driver of new displacement

Extreme weather events and conditions have had major and diverse impacts on population displacement and on the vulnerability of people already displaced throughout the year. From Afghanistan to Central America, droughts, flooding and other extreme weather events are hitting those least equipped to recover and adapt[96]. Similar to previous years, many of the largest scale displacements in 2021 occurred in populous Asian countries. Most disaster displacements in 2021 resulted from tropical storms and floods in East Asia and the Pacific, South Asia, the Americas and Sub-Saharan Africa.

Over the course of 2021, hazardous weather events and environmental degradation have further contributed to the displacement of millions more people in exposed and vulnerable situations. This includes the impact of rapid-onset events such as floods, storms and wildfires, as well as slow-onset processes such as drought and desertification, affecting people's safety and ability to meet their basic needs for survival such as food, water, resilient housing and productive land. Over the first half of the year in Afghanistan, for example, disasters brought on some 22 500 new displacements, primarily linked to floods[97]. In June, the government declared a national drought with 80% of the country classified as being in either severe or serious drought status on top of escalating conflict, food insecurity and health and socio-economic impacts of COVID-19 and with humanitarian, development and government actors foreseeing that agricultural families would very likely become displaced[98]. People forced to leave their homes had to sell their assets and engage in dangerous work to survive, while some children were sent to work in other areas or in neighbouring countries or were married off as a way to reduce financial burdens[99].

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[94] FEWSNET. 2021. *Madagascar Food Security Alert: June 10, 2021* *https://reliefweb.int/sites/reliefweb.int/files/resources/Madagascar%20Food%20Security%20Alert%20-%20June%2010%2C%202021.pdf*

[95] https://www.fao.org/mozambique/news/detail-events/en/c/1393190/

[96] UNHCR News Stories April 2021 : https://www.unhcr.org/news/stories/2021/4/60806d124/data-reveals-impacts-climate-emergency-displacement.html

[97] IDMC 2021 Mid-Year Update. https://story.internal-displacement.org/2021-midyear-review/index.html

[98] DRC https://prod.drc.ngo/about-us/for-the-media/press-releases/2021/7/drought-crisis-in-afghanistan-intensifies-risk-of-displacement/

[99] Ibid.

In line with established trends, 2021 saw the overwhelming majority of new displacements related to hazardous weather events take place within national borders. Most of these internal displacements were triggered by typhoons, floods, earthquakes and volcanic eruptions, especially in the East Asia and Pacific region. The countries with the highest numbers of displacements recorded as of October 2021 were China (more than 1.4 million evacuations recorded in July 2021), the Philippines (more than 214,000 in July and more than 386,000 in October) and Vietnam (more than 664,000 displacements recorded in September 2021)[100].

High-income countries were also affected. In the western parts of the United States and Canada exceptional heatwaves, drought, and wildfires displaced thousands from their homes. Wildfires also compounded risks related to other hazards, further increasing the risk of displacement. For instance, 15 000 people were displaced in California in January 2021, following mandatory pre-emptive evacuation orders following heavy rains[101].

Hydro-meteorological hazards fuelled patterns of protracted, prolonged and repeated displacement

Many displacement situations triggered by hydro-meteorological events have become prolonged or protracted for people unable to return to their former homes or without options for integrating locally or settling elsewhere. As of the beginning of 2021, at least 7 million people were living in internal displacement following disasters[102] related to natural hazard events in previous years (IDMC, Internal Displacement Monitoring Centre). The highest numbers of these people were in Afghanistan, India and Pakistan, followed by Ethiopia, Sudan, Bangladesh, Niger and Yemen[103].

Due to continuing or growing risk in their areas of origin (and return) or settlement, people who have been displaced by hydro-meteorological and climatic events may also be subject to repeated and frequent displacement, leaving little time for recovery between one shock and the next. In Indonesia, for example, 557 000 new disaster displacements were recorded in the first half of the year, mostly triggered by major rainy season floods. Human activities, including deforestation, urbanisation and land degradation have reduced the capacity of some regions of Indonesia to absorb heavy rainfall. With heavy rainfall during La Niña, the floods triggered an estimated 190 000 new displacements in the Kalimantan province in January and 161 000 new displacements on the island of Java in February. Further displacements are expected to arise during the new rainy season, starting from November 2021[104]. Such situations highlight the importance of disaster preparedness and risk management, but also for supporting solutions to displacement that are sustainable and supporting the resilience of people who might otherwise see their living conditions progressively eroded through repeated disasters and displacement.

Hazardous weather events and changing climatic conditions also added to the multiple risks faced by internally displaced people in conflict-affected countries and refugees

In Yemen, for instance, the annual rainy season brings heavy rainfall, high winds and flooding, particularly to coastal areas. In mid-April heavy rain and flooding hit several parts of the country affecting 7 000 people, 75% of whom were internally displaced people living in precarious conditions[105] It has also contributed to population displacement in what is already the world's fourth

[100] Data sourced from the Internal Displacement Monitoring Centre's Updates: https://www.internal-displacement.org/global-displacement-map
[101] IDMC 2021 Mid-Year Update. https://story.internal-displacement.org/2021-midyear-review/index.html
[102] IDMC 2021, GRID Report, Data as of 31 December 2020.
[103] Data sourced from the Internal Displacement Monitoring Centre's Updates, 2021: https://www.internal-displacement.org/global-displacement-map
[104] IDMC 2021 Mid-Year Update. https://story.internal-displacement.org/2021-midyear-review/index.html
[105] UNOCHA Humanitarian Update, Yemen, Issue 5, May 2021

biggest internal displacement crisis, with over 4 million internally displaced people. The annual rainy season brings heavy rainfalls, high winds and flooding, particularly to coastal areas, with thousands of families already impacted by flash floods in 2021. By blocking passage of roads, flooding also continues to impede the ability of humanitarian partners to deliver lifesaving assistance to people in need[106].

In Mozambique, multiple tropical storms and floods, on top of recurrent disease outbreaks and conflict[107], significantly increased the vulnerability of people affected[108], including thousands of families still displaced since Cyclones Idai and Kenneth in 2019. In January, strong winds and floods from Tropical Storm Chalane and then Cyclone Eloise damaged or destroyed the shelters of over 8 700 of these internally displaced families as well as schools and hospitals[109]. These events also resulted in new displacement, with Cyclone Eloise displacing more than 43 300 people[110]. Greater attention is needed to reduce climate vulnerability and risks in fragile and conflict-affected contexts and strengthen community-based preparedness[111].

In East Africa, floods and droughts resulted in large-scale displacement, especially in Somalia and Ethiopia, many of whom were people already living in overcrowded and insecure camps for internally displaced people to which many newly flood-displaced people also moved. Farmers whose crops were devastated by desert locusts were also forced to move in search of survival assistance[112].

Nigeria also experienced drought and floods, which affected agricultural activities, resulting in loss of shelter and increased vulnerability of people already displaced by conflict in the northeast. The situation further deteriorated in the first half of 2021, with around 294 000 new displacements reported between January and June 2021[113].

In Bangladesh, monsoon rains led to massive flooding and the displacement of millions of people following Cyclone Yaas in June 2021. In the Rohingya refugee sites in Cox's Bazar, over 6 000 shelters were damaged and more than 25 000 refugees were forced to seek shelter in communal facilities or with other families[114]. Without preparedness measures undertaken in the camp areas, including the strengthening of shelters, the building of retaining structures on hillsides and improved drainage, roads and bridges, these impacts would have been far worse.

Climate impacts on ecosystems

Ecosystems – including terrestrial, freshwater, coastal and marine ecosystems – and the services they provide, are affected by the changing climate and some are more vulnerable than others[115]. In addition, ecosystems are degrading at an unprecedented rate. The degradation of ecosystems is

[106] Relief Web, Yemen August 2021, https://reliefweb.int/report/yemen/climate-crisis-exacerbates-humanitarian-situation-yemen-enar

[107] UNHCR 2021: https://www.unhcr.org/news/briefing/2021/4/606c17bf4/unhcr-scales-response-thousands-flee-attacks-northern-mozambique.html

[108] UNHCR News Mozambique April 2021 https://www.unhcr.org/news/briefing/2021/4/606c17bf4/unhcr-scales-response-thousands-flee-attacks-northern-mozambique.html

[109] IOM/DTM Mozambique Flash Report 16- Cyclone Eloise (January 2021) https://displacement.iom.int/reports/mozambique-%E2%80%93-flash-report-16-tropical-cyclone-eloise-january-2021?close=true

[110] https://reliefweb.int/report/afghanistan/internal-displacement-mid-year-10-situations-review

[111] Ibid

[112] UNHCR News Somalia August 2021, https://www.unhcr.org/news/stories/2021/8/611a2bca4/displaced-somalis-refugees-struggle-recover-climate-change-brings-new-threats.html

[113] Ibid

[114] UNHCR, News Bangladesh July 2021 https://www.unhcr.org/news/stories/2021/7/6103c43c4/floods-bring-new-misery-rohingya-refugees-bangladesh-camps.html

[115] United Nations Environment Programme (2021). Adaptation Gap Report 2020. Nairobi.

limiting their ability to support human well-being and harming their adaptive capacity to build resilience[116].

For example, mountain ecosystems – the water towers of the world – are vulnerable and can be profoundly affected by climate change due to their low capacity to adapt. This may affect the 1.9 million people living in mountain areas[117]. Climate change may exacerbate water stress, especially in areas of decreased precipitation and where groundwater is already being depleted, affecting agricultural production, arable land, and the more than 2 billion people who are already experiencing water stress[116].

Climate change is also affecting temperature-sensitive plants and other species. There is evidence that temperature-sensitive plants are leafing out and flowering earlier in spring and dropping their leaves later in autumn. Also, there has been a clear shift in the timing of marine and freshwater fish spawning events and animal migrations worldwide. Substantial changes in species' abundance and distribution may in turn affect the interactions between species[118]. Climate change also exacerbates other threats to biodiversity. The number of species projected to go extinct increases dramatically as global temperatures rise – and is 30% higher at 2 °C warming than at 1.5 °C warming[116].

Meanwhile, large-scale changes have been observed in marine ecosystems, including declining ocean productivity, migration of species to higher latitudes, and damage to coral reefs and mangroves. Warming towards 1.5 °C will increase water temperatures and change the ocean's chemistry (e.g., acidification), resulting in new ecosystems. Species that are less able to relocate are projected to experience high rates of mortality and loss[119]. Climate change is also triggering the disintegration of the Greenland and Antarctic ice sheets and increasing the chances of the Arctic Ocean being ice-free in the summer, further disrupting ocean circulation and Arctic ecosystems[116].

Rising temperatures heighten the risk of irreversible loss of marine and coastal ecosystems, including seagrass meadows and kelp forest. Coral reefs are especially vulnerable to climate change. They are projected to lose between 70 and 90% of their former coverage area at 1.5 °C of warming and over 99% at 2 °C. Between 20 and 90% of current coastal wetlands are at risk of being lost by the end of this century, depending on how fast sea levels rise. This will further compromise food provision, tourism, and coastal protection, among other ecosystem services[116].

[116] United Nations Environment Programme (2021). Making Peace with Nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies. Nairobi.
[117] Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T. et al. (2020). Importance and vulnerability of the world's water towers. Nature 577, 364-369. https://doi.org/10.1038/s41586-019-1822-y.
[118] Scheffers, B.R., De Meester, L., Bridge, T.C., Hoffmann, A.A., Pandolfi, J.M., Corlett, R.T. et al. (2016). The broad footprint of climate change from genes to biomes to people. Science 354(6313), aaf7671. https://doi.org/10.1126/science.aaf7671.
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Contributors

WMO Members

Algeria, Andorra, Argentina, Armenia, Australia, Austria, Bahrain, Belarus, Bosnia and Herzegovina, Bulgaria, Burkina Faso, Cameroon, Canada, Chile, China, Colombia, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Guinea, Guinea Bissau, Hungary, India, Iran, Ireland, Israel, Italy, Japan, Jordan, Kazakhstan, Kenya, Latvia, Libya, Lithuania, Luxembourg, Macao China, Madagascar, Mali, Mauritius, Moldova, Morocco, New Zealand, Niger, Nigeria, North Macedonia, Norway, Pakistan, Peru, Poland, Portugal, Romania, Russian Federation, Saudi Arabia, Senegal, Serbia, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Syria, Tanzania, Thailand, The Netherlands, Togo, Trinidad and Tobago, Tunisia, Turkey, Ukraine, United Kingdom, United States, Uruguay, Uzbekistan.

Institutional contributors

ARC Centre of Excellence for Climate Extremes, University of Tasmania; British Antarctic Survey (BAS); Bureau of Meteorology (BoM); Carbon Portal, Lund University; Centre National d'Études Spatiales, CNES, France; Mercator Ocean international, France; Observatoire Midi-Pyrénées, France; IFREMER, France; University of Brest, France; Centre National de la Recherche Scientifique, (CNRS), France; Institut de Recherche pour le Développement (IRD), France; Laboratoire d'Océanographie Physique et Spatiale (LOPS), France; Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), France; Institut Universitaire Européen de la Mer (IUEM), France; CELAD, France; Sorbonne Université, France; Laboratoire d'Océanographie de Villefranche, France; Center for Ocean Mega-Science, Chinese Academy of Sciences; Copernicus Climate Change Service (C3S); CSIRO Oceans and Atmosphere; Danmarks Meteorologiske Institut (DMI); Global Precipitation Climatology Centre, Deutscher Wetterdienst (GPCC, DWD); Environment and Climate Change Canada (ECCC); ETH Zürich; European Centre for Medium Range Weather Forecasts (ECMWF); Food and Agriculture Organisation (FAO); George Washington University; Hong Kong Observatory; Ifremer; Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP, CAS); Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC UNESCO); Japan Marine-Earth Science and Technology (JAMSTEC); Joint Institute for Marine and Atmospheric Research, University of Hawai'i (JIMAR); Laboratory of Space Geophysical and Oceanographic Studies (LEGOS); Mercator Ocean International; Met Office Hadley Centre; Meteorological Research Institute, Department of Atmosphere, Ocean and Earth System Modeling Research; National Oceanographic and Atmosphere Administration, National Centers for Environmental Information (NOAA NCEI); NOAA, Pacific Marine Environmental Laboratory (NOAA PMEL); National Oceanography Centre (NOC); Natural Resources Canada; Norwegian Meteorological Institute; Rutgers University; Scripps Institution of Oceanography; Tokyo Climate Center, Japan Meteorological Agency (TCC, JMA); United Nations Environment Programme (UNEP); United Nations High Commissioner for Refugees (UNHCR); United Nations Office for Disaster Risk Reduction (UNDRR); Universidade Federal do Rio de Janeiro; University of Exeter; Woods Hole Oceanographic Institution; World Climate Research Programme (WCRP); World Data Centre for Greenhouse Gases (WDCGG); World Food Programme (WFP)

Individual contributors

Signe Aaboe (Norwegian Meteorological Institute), Jorge Alvar-Beltrán (FAO), Omar Baddour (WMO), Jessica Blunden (NOAA NCEI), Tim Boyer (NOAA NCEI), Anny Cazenave (LEGOS CNES and OMP), Lijing Cheng (IAP; Center for Ocean Mega-Science, Chinese Academy of Sciences), Louis Clement (National Oceanography Centre), Damien Desbruyères (Ifremer, CNRS, IRD, Laboratoire d'Océanographie Physique et Spatiale), Catia Domingues (NOC; ARC Centre of Excellence for Climate

Extremes, University of Tasmania), Robert Dunn (Met Office Hadley Centre), Thomas Estilow (Rutgers University), Florence Geoffroy (UNHCR), Nathan Gillett (ECCC), John Gilson (University of California), Loretta Hieber Girardet (UNDRR), Atsushi Goto (TCC, JMA), Yvan Gouzenes (LEGOS and OMP), Stephan Gruber, (Carleton University), Ana Heureux (FAO), Shigeki Hosoda (JAMSTEC), Matthias Huss (ETH Zürich), Kirsten Isensee (IOC UNESCO), Masayoshi Ishii (Meteorological Research Institute, Department of Atmosphere, Ocean and Earth System Modeling Research), Gregory C. Johnson (NOAA, PMEL), Maarten Kappelle (UNEP), John Kennedy (Met Office Hadley Centre), Rachel Killick (Met Office Hadley Centre), Brian A. King (NOC), Nicolas Kolodziejczyk (University of Brest, CNRS, IRD, Ifremer, Laboratoire d'Océanographie Physique et Spatiale, IUEM), Animesh Kumar (UNDRR), Gernot Laganda (WFP), Thomas Lavergne (Norwegian Meteorological Institute), Renata Libonati (Universidade Federal do Rio de Janeiro), John Lyman (NOAA, Pacific Marine Environmental Laboratory; JIMAR, University of Hawaii), Shawn Marshall (Environment and Climate Change Canada and University of Calgary), Jesse Mason (WFP), Brian Menounos (University of Northern British Columbia), Maeva Monier (CELAD/Mercator Ocean International), Lev Neretin (FAO), Didier Paolo Monselesan (Scripps Institution of Oceanography, University of California San Diego), Colin Morice (Met Office Hadley Centre), Stoyka Netcheva (WMO), Rodica Nitu (WMO), Jeannette Noetzli, (Institute for Snow and Avalanche Research), Ben Pelto (University of Northern British Columbia), David Robinson (Rutgers University), Dean Roemmich (CSIRO Oceans and Atmosphere), Kanako Sato (JAMSTEC: Japan Marine-Earth Science and Technology), Yousuke Sawa (Japan Meteorological Agency, WDCGG), Robert W. Schlegel (Sorbonne Université, CNRS, Laboratoire d'Océanographie de Villefranche), Katherina Schoo (IOC UNESCO), Karina von Schuckmann (Mercator Ocean international), Rahul Sengupta (UNDRR), Fumi Sezaki (TCC, JMA), Sharon Smith, (Natural Resources Canada), Michael Sparrow (WCRP), Martin Stendel (DMI), Peter Stott (Met Office Hadley Centre, University of Exeter), Dmitry Streletskiy, (George Washington University), Toshio Suga (JAMSTEC: Japan Marine-Earth Science and Technology; Tohoku University), Oksana Tarasova (WMO), Blair Trewin (Bureau of Meteorology), John Turner (BAS), Freja Vamborg (ECMWF), Alex Vermeulen (Carbon Portal, Lund University), Ying Wang (UNEP), Susan E. Wijffels (Scripps Institution of Oceanography; Woods Hole Oceanographic Institution), Michelle Yonetani (UNHCR), Markus Ziese (DWD).

Data sets and methods

Greenhouse gas data

Estimated concentration from 1750 are used to represent pre-industrial conditions. Calculations assume a pre-industrial mole fraction of 278 ppm for CO_2, 722 ppb for CH_4 and 270 ppb for N_2O.

WMO Greenhouse Gas Bulletin, No.17, October 2021,
https://library.wmo.int/index.php?lvl=notice_display&id=21975

World Data Centre for Greenhouse Gases operated by Japan Meteorological Agency
https://gaw.kishou.go.jp/

World Ozone and Ultraviolet Radiation Data Centre operated by Environment and Climate Change Canada

https://woudc.org/home.php

Global Temperature data

Six data sets are used in the calculation of global temperature. Global mean temperature anomalies are calculated relative to an 1850 to 1900 baseline using the following steps

1. For each data set, anomalies are calculated relative to the 1981-2010 average
2. 0.69 °C was added to each series, based on the estimated difference between 1850-1900 and 1981-2010 calculated using the method from IPCC AR6 WG1 (see caption for Figure 1.12).
3. The mean and standard deviation of the six estimates were calculated.
4. The uncertainty in the IPCC estimate was combined with the standard deviation assuming the two are independent and assuming the IPCC uncertainty range (0.54 to 0.78 °C) is representative of a 90% confidence range (1.645 standard deviations).

The following six data sets used were:

HadCRUT.5.0.1.0 —Morice, C.P. et al., 2021. An Updated Assessment of Near-Surface Temperature Change From 1850: The HadCRUT5 Data Set. Journal of Geophysical Research: Atmospheres, 126(3): e2019JD032361. doi: https://doi.org/10.1029/2019JD032361. HadCRUT.5.0.1.0 data were obtained from http://www.metoffice.gov.uk/hadobs/hadcrut5 on 24 October 2021 and are © British Crown Copyright, Met Office 2021, provided under an Open Government License, http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

NOAAGlobalTemp v5 — Zhang, H.-M., et al., NOAA Global Surface Temperature Dataset (NOAAGlobalTemp), Version 5.0. NOAA National Centers for Environmental Information. doi:10.7289/V5FN144H, https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00934. Huang, B. et al., 2020: Uncertainty Estimates for Sea Surface Temperature and Land Surface Air Temperature in NOAAGlobalTemp Version 5. Journal of Climate 33(4): 1351–1379, https://journals.ametsoc.org/view/journals/clim/33/4/jcli-d-19-0395.1.xml.

GISTEMP v4 — GISTEMP Team, 2019: GISS Surface Temperature Analysis (GISTEMP), version 4. NASA Goddard Institute for Space Studies, https://data.giss.nasa.gov/gistemp/. Lenssen, N.J.L. et al., 2019: Improvements in the GISTEMP Uncertainty Model. Journal of Geophysical Research: Atmospheres 124(12): 6307–6326, doi: https://doi.org/10.1029/2018JD029522.

Berkeley Earth – Rohde, R. A. and Hausfather, Z.: The Berkeley Earth Land/Ocean Temperature Record, Earth Syst. Sci. Data, 12, 3469–3479, https://doi.org/10.5194/essd-12-3469-2020, 2020.

ERA5 — Hersbach, H. et al., 2020 : The ERA5 Global Reanalysis. Quarterly Journal of the Royal Meteorological Society 146(730): 1999–2049, doi: https://doi.org/10.1002/qj.3803.

JRA-55 — Kobayashi, S. et al., 2015: The JRA-55 Reanalysis: General Specifications and Basic Characteristics. Journal of the Meteorological Society of Japan. Ser. II 93(1): 5–48, doi:10.2151/jmsj.2015-001, https://www.jstage.jst.go.jp/article/jmsj/93/1/93_2015-001/_article.

Ocean heat content data

Hosoda, S. et al., 2008: A Monthly Mean Dataset of Global Oceanic Temperature and Salinity Derived from Argo Float Observations. JAMSTEC Report of Research and Development, 8: 47–59, doi: https://www.jstage.jst.go.jp/article/jamstecr/8/0/8_0_47/_article.

JAMSTEC,

CARS2009 (http://www.marine.csiro.au/~dunn/cars2009/),

Roemmich, D. and J. Gilson. 2009: The 2004–2008 Mean and Annual Cycle of Temperature, Salinity, and Steric Height in the Global Ocean from the Argo Program. Progress in Oceanography, 82(2): 81–100, https://www.sciencedirect.com/science/article/abs/pii/S0079661109000160?via%3Dihub.

Copernicus Marine Ocean Monitoring Indicators (http://marine.copernicus.eu/science-learning/ocean-monitoring-indicators; CORA);

Good, S.A. et al., 2013: EN4: Quality Controlled Ocean Temperature and Salinity Profiles and Monthly Objective Analyses with Uncertainty Estimates. Journal of Geophysical Research: Oceans 118(12): 6704–6716, doi: https://agupubs.onlinelibrary.wiley.com/doi/ full/10.1002/2013JC009067.

Desbruyères, D.G. et al., 2016: Deep and Abyssal Ocean Warming from 35 Years of Repeat Hydrography. Geophysical Research Letters 43(19): 10,356-10,365, doi: https://doi.org/10.1002/2016GL070413 .

Sea level data

GMSL from CNES/Aviso+ https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/data-acces.html#c12195

Marine heatwave and marine cold spell data

MHWs are categorized as moderate when the sea-surface temperature (SST) is above the 90th percentile of the climatological distribution for five days or longer; the subsequent categories are defined with respect to the difference between the SST and the climatological distribution average: strong, severe, or extreme, if that difference is, respectively, more than two, three or four times the difference between the 90th percentile and the climatological distribution average (Hobday et al., 2018). MCS categories are analogous but counting days below the 10th percentile.

The baseline used for MHWs and MCSs is 1982–2011, which is shifted by one year from the standard normal period of 1981–2010 because the first full year of the satellite SST series on which it is based is 1982.

Hobday, A.J. et al., 2018: Categorizing and Naming Marine Heatwaves. Oceanography, 31(2): 1–13. doi: https://eprints.utas.edu.au/27875/.

NOAA OISST v2: Optimum Interpolation Sea Surface Temperature (OISST):

Banzon, V. et al., 2016: A Long-Term Record of Blended Satellite and in Situ Sea-Surface Temperature for Climate Monitoring, Modeling and Environmental Studies. Earth System

Science Data, 8(1): 165–176. doi: https://essd.copernicus.org/articles/8/165/2016/.

Greenland ice sheet data

Changes in surface mass balance and total mass balance are based on the average of three regional climate and mass balance models. See Mankoff, K. D., X. Fettweis, P.L. Langen, M. Stendel, K.K. Kjeldsen, N.B. Karlsson, B. Noël, M.R. van den Broeke, W. Colgan, S.B. Simonsen, J.E. Box, A. Solgaard, A.P. Ahlstrøm, S.B. Andersen and R.S. Fausto, 2021: Greenland ice sheet mass balance from 1840 through next week. Earth Syst. Sci. Data, https://doi.org/10.5194/essd-2021-131, accepted.

The melt season is defined as the first of at least three days in a row with melting over at least 5% of the area of the ice sheet.

Ablation is defined as the first of at least three days in a row with a negative surface mass balance of at least -1 Gt.

Snow data

Snow data and monthly anomaly timeseries charts are available at:

https://climate.rutgers.edu/snowcover/files/wmo/rutgers-nh-sce-anomalies-2020-21-data.xlsx

Sea ice data

Data set background: The sea ice section uses data from the EUMETSAT OSI SAF Sea Ice Index v2.1 (OSI-SAF, based on Lavergne et al., 2019) and the NSIDC v3 Sea Ice Index (Fetterer et al., 2017). Sea ice concentrations are estimated from microwave radiances measured from satellites. Extent is calculated as the area of ocean grid cells where the sea-ice concentration exceeds 15%. Although there are relatively large differences in the absolute extent between data sets, they agree well on the year-to-year changes and the trends. In this report, NSIDC are reported for absolute extents (e.g. "18.95 million km2") for consistency with earlier reports, while rankings are reported for both data sets.

Fetterer, F., K. Knowles, W. N. Meier, M. Savoie, and A. K. Windnagel. 2017, updated daily. Sea Ice Index, Version 3. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: https://doi.org/10.7265/N5K072F8. Accessed Oct. 2021.

EUMETSAT Ocean and Sea Ice Satellite Application Facility, Sea ice index 1979-onwards (v2.1, 2020), OSI-420, Data extracted from OSI SAF FTP server: 1979-2020, Northern and Southern Hemisphere, accessed Oct. 2021.

Lavergne, T., Sørensen, A. M., Kern, S., Tonboe, R., Notz, D., Aaboe, S., Bell, L., Dybkjær, G., Eastwood, S., Gabarro, C., Heygster, G., Killie, A., Brandt Kreiner, M., Lavelle, J., Saldo, R., Sandven, S., and Pedersen, L. T.: Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records, The Cryosphere, 13, 49–78, https://doi.org/10.5194/tc-13-49-2019, 2019.

Permafrost data

Noetzli, J., Christiansen, H.H., Hrbáček, F., Isaksen, K., Smith, S. L., Zhao, L., and Streletskiy, D.A. (2021) [Global Climate] Permafrost Thermal State [in State of the Climate in 2020]. Bulletin of the American Meteorological Society, 102 (8): S42-S44. doi:10.1175/BAMS-D-21-0098.1

Smith, S.L., Romanovsky, V.E., Isaksen, K., Nyland, K.E., Kholodov, A.L., Shiklomanov, N.I., Streletskiy, D.A., Farquharson, L.M., Drozdov, D.S., Malkova, G.V., and Christiansen, H.H. (2021) [Arctic] Permafrost [in State of the Climate in 2020]. Bulletin of the American Meteorological Society, 102 (8): S293-S297. doi:10.1175/BAMS-D-21-0086.1

Precipitation data

These GPCC data sets were used in the analysis:

- First Guess Monthly, DOI: 10.5676/DWD_GPCC/FG_M_100
- Monitoring Product (Version 2020), DOI: 10.5676/DWD_GPCC/MP_M_V2020_100
- Full Data Monthly (Version 2020), DOI: 10.5676/DWD_GPCC/FD_M_V2020_100
- First Guess Daily, DOI: 10.5676/DWD_GPCC/FG_D_100
- Full Data Daily (Version 2020), DOI: 10.5676/DWD_GPCC/FD_D_V2020_100

Indian Monsoon: https://mausam.imd.gov.in/imd_latest/contents/monsoon.php

DOCUMENT 8

2021 Report

The Production Gap

Governments' planned fossil fuel production remains dangerously out of sync with Paris Agreement limits



SEI Stockholm Environment Institute

IISD

ODI

E3G

UN environment programme

About This Report

The Production Gap Report — first launched in 2019 — tracks the discrepancy between governments' planned fossil fuel production and global production levels consistent with limiting warming to 1.5°C or 2°C. The report represents a collaboration of several research and academic institutions, including input from more than 40 experts. UNEP staff provided guidance and insights from their experience leading other gap reports.

This year's report presents the first comprehensive update of the production gap analysis since our 2019 assessment. The report also tracks how governments worldwide are supporting fossil fuel production through their policies, investments, and other measures, as well as how some are beginning to discuss and enact policies towards a managed and equitable transition away from fossil fuel production. This year's report features individual country profiles for 15 major fossil fuel-producing countries, and a special chapter on the role of transparency in helping to address the production gap.

Assessment of the production gap is based on recent and publicly accessible plans and projections for fossil fuel production published by governments and affiliated institutions. For other elements of the report, such as the magnitude of producer subsidies or the status of policies to limit production, the report draws from a mix of publicly available government, intergovernmental, and research sources as cited and listed in the references.

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http://productiongap.org/2021report

Photo Credits

Wikipedia image. P. 23: Jharia coal mine. Photo by TripodStories-AB, Wikipedia:
https://en.wikipedia.org/wiki/Jharia_coalfeld. All other photos: Getty Images.

Errata: Earlier versions of the report contained an error in the "IEA NZE" pathway plotted in Figure 2.4, an error in Figure 2.5 where methane emissions from the energy sector was plotted instead of total methane emissions as intended, and an error on page 44 where "1,149 million tonnes" was incorrectly referenced as "1,149 tonnes".

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Steering Committee

Joanna Depledge (Cambridge Centre for Environment, Energy and Natural Resource Governance), Andrea Guerrero García (UN Secretary General's Climate Action Team), Niklas Hagelberg (United Nations Environment Programme), Youba Sokona (South Centre), Fernando Tudela (Interdisciplinary Center for Biodiversity and Environment A.C.).

Authors

Asterisk (*) connotes lead authors.

Chapter 1

Peter Erickson* (Stockholm Environment Institute).

Chapter 2

Ploy Achakulwisut* (Stockholm Environment Institute), Peter Erickson* (Stockholm Environment Institute), Céline Guivarch (International Research Center on Environment and Development), Ritu Mathur (The Energy & Resources Institute), Steve Pye (University College London), Roberto Schaeffer (Universidade Federal do Rio de Janeiro).

Chapter 3

Chandra Bushan (iFOREST), Lucile Dufour* (International Institute for Sustainable Development), Lisa Fischer (E3G), Ipek Gençsü (ODI), Patrick Heller (Natural Resource Governance Institute), Robin Hocquet (Stockholm Environment Institute) Natalie Jones (University of Cambridge), David Manley (Natural Resource Governance Institute), Miquel Muñoz Cabré (Stockholm Environment Institute), Greg Muttitt (International Institute for Sustainable Development), Angela Picciariello (ODI), Luma Ramos (Boston University Global Development Policy center), Leo Roberts (E3G), Bronwen Tucker (Oil Change International).

Chapter 4

Ploy Achakulwisut (Stockholm Environment Institute), Fernanda Barbosa (Universidade Federal do Rio de Janeiro), Jesse Burton (E3G; University of Cape Town), Vanessa Corkal (International Institute for Sustainable Development), Diógenes Cruz-Figueroa, Bruno Cunha (Universidade Federal do Rio de Janeiro), Nikita Dobroslavsky (SKOLKOVO), Laura El-Katiri, Peter Erickson



(Stockholm Environment Institute), Lisa Fischer (E3G), Vibhuti Garg (International Institute for Sustainable Development), Robin Hocquet (Stockholm Environment Institute), Frank Jotzo (The Australian National University), Bård Lahn (CICERO), Michael Lazarus (Stockholm Environment Institute), Hongyou Lu (Lawrence Berkeley National Laboratory), Tatiana Mitrova (SKOLKOVO), Miquel Muñoz Cabré (Stockholm Environment Institute), Greg Muttitt (International Institute for Sustainable Development), Leo Roberts (E3G), Roberto Schaeffer (Universidade Federal do Rio de Janeiro), Anissa Suharsono (International Institute for Sustainable Development), Alexandre Szklo (Universidade Federal do Rio de Janeiro), Balasubramanian Viswanathan (International Institute for Sustainable Development), Guillermo Zúñiga (EarthJustice).

Chapter 5

Elisa Arond (Stockholm Environment Institute), Harro van Asselt* (University of Eastern Finland/Utrecht University), Siân Bradley (Chatham House), Chandra Bushan (iFOREST), Ipek Gençsü (ODI), Fergus Green (University College London), Aarti Gupta (Wageningen University and Research), Patrick Heller (Natural Resource Governance Institute), Robin Hocquet (Stockholm Environment Institute), Natalie Jones (University of Cambridge), Angela Picciariello (ODI), David Manley (Natural Resource Governance Institute), Georgia Piggot* (University of Auckland), Robert Schuwerk (Carbon Tracker Initiative), Romain Weikmans (Université Libre de Bruxelles).

Chapter 6

Ploy Achakulwisut (Stockholm Environment Institute), Chandra Bushan (iFOREST), Robin Hocquet (Stockholm Environment Institute), Michael Lazarus* (Stockholm Environment Institute), Miquel Muñoz Cabré (Stockholm Environment Institute), José Vega Araújo (Stockholm Environment Institute), Cleo Verkuijl (Stockholm Environment Institute).

Reviewers

The following people reviewed one or more sections of this report: Tabaré Arroyo Currás (TAC Energy Concepts), Kathleen Brophy (Sunrise Project), Rebecca Byrnes (Fossil Fuel Non-Proliferation Treaty), Roderick Campbell (The Australia Institute), Ana Carolina González Espinosa (Ford Foundation), Angela Carter (University of Waterloo), Sarah Colenbrander (ODI), Knut Einar Rosendahl (Norwegian University of Life Sciences), Lisa Fischer (E3G), Ipek Gençsü (ODI), Ricardo Gorini (International Renewable Energy Agency), Andrew Grant (Carbon Tracker Initiative), Moustapha Gueye (International Labour Organization), Hongyu Guo (G:Hub), Karl Hallding (Stockholm Environment Institute), Guoyi Han (Stockholm Environment Institute), Kathryn Harrison (University of British Columbia), Hauke Hermann (Öko-Institut), Bharath Jairaj (World Resources Institute), Jim Krane (Rice University), Julia Levin (Environmental Defence), Gaylor Montmasson-Clair (Trade & Industrial Policy Strategies), Thomas Muinzer (University of Aberdeen), Greg Muttitt (International Institute for Sustainable Development), Ramon Olivas Gastelum (DAI - Mexico Energy Programme), Julien Perez (Oil and Gas Climate Initiative), Angela Picciariello (ODI), Joana Portugal Pereira (Universidade Federal do Rio de Janeiro; Imperial College London), Collin Rees (Oil Change International), Leo Roberts (E3G), Michael Ross (University of California UCLA), Lambert Schneider (Öko-Institut), Benjamin Sovacool (University of Sussex), Tom Swann (The Sunrise Project), May Thazin Aung (Stockholm Environment Institute), Maxim Titov (European University at St.Petersburg), Kelly Trout (Oil Change International), Jorge Villareal (Iniciativa Climática de México), Peter Wooders (International Institute for Sustainable Development), Lihuan Zhou (World Resources Institute).

Project Coordination

Ploy Achakulwisut, Michael Lazarus, and Miquel Muñoz Cabré (Stockholm Environment Institute) served as coordinating lead authors for the report.

Editing and Communications

Emily Yehle, Cleo Verkuijl, Annika Flensberg and Lynsi Burton (Stockholm Environment Institute) led the report's editing and communications.

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Glossary

Countries' plans and projections (CPP)
A global pathway of fossil fuel production estimated in this report, based on our review and assessment of recent national energy plans, strategy documents, and outlooks published by governments and affiliated institutions.

Extraction-based emissions accounting
An accounting framework that attributes greenhouse gas emissions from the burning of fossil fuels to the location of fuel extraction.

Fossil fuel production
A collective term used in this report to represent processes along the fossil fuel supply chain, which includes locating, extracting, processing, and delivering coal, oil, and gas to consumers.

Greenhouse gases (GHGs)
Atmospheric gases that absorb and emit infrared radiation, trap heat, contribute to the greenhouse effect, and cause global warming. The principal GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

Just transition
In the context of climate policy, this refers to a shift to a low-carbon economy that ensures disruptions are minimized for workers, communities, consumers, and other stakeholders who may be disproportionately affected (ITUC 2017; UNFCCC 2016).

Long-term low greenhouse gas emission development strategies (LT-LEDS)
Under the Paris Agreement and its accompanying decision, all countries are invited to communicate LT-LEDS by 2020, taking into account their common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.

Nationally determined contributions (NDCs)
Submissions by Parties to the Paris Agreement that contain their stated ambitions to take climate change action towards achievement of the Agreement's long-term goal of limiting global temperature increase to well below 2°C, while pursuing efforts to limit the increase to 1.5°C. Parties are requested to communicate new or updated NDCs by 2020 and every five years thereafter.

Production gap
The discrepancy between countries' planned fossil fuel production and global production levels consistent with limiting warming to 1.5°C or 2°C.

Stranded assets
Assets that suffer from unanticipated or premature write-offs or downward revaluations, or that are converted to liabilities, as the result of a low-carbon transition or other environment-related risks (Ansar et al. 2013).

Subsidy
A financial benefit accorded to a specific interest (e.g. an individual, organization, company, or sector) by a government or public body including direct transfer of government funds; tax expenditure, other revenue foregone, and underpricing of goods and services; induced transfers (price support); and transfer of risk to government.



Abbreviations

AFOLU	Agriculture, forestry, and other land use
Bcf	Billion cubic feet
BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CPP	Countries' plans and projections
°C	Degree Celsius
DFI	Development finance institution
ECA	Export credit agency
EITI	Extractive Industries Transparency Initiative
EJ	Exajoule
EU	European Union
FPIC	Free, prior, and informed consent
G7	Group of Seven
G20	Group of Twenty
GDP	Gross domestic product
GHG	Greenhouse gas
Gt	Gigatonne (billion tonnes or metric tons)
IEA	International Energy Agency
ILO	International Labour Organization
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied natural gas
LT-LEDS	Long-term, low-emission development strategies
Mb/d	Million barrels per day
MDB	Multilateral development bank
Mt	Million tonnes (metric tons)
NDC	Nationally determined contribution
NOC	National oil and gas company
NZE	IEA's Net Zero by 2050 pathway for the energy sector
OECD	Organization for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PFI	Public finance institution
PGR	Production Gap Report
SDG	Sustainable Development Goal
SOE	State-owned enterprise
TCFD	Taskforce for Climate-Related Financial Disclosures
UAE	United Arab Emirates
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	UN Framework Convention on Climate Change
UK	United Kingdom
US	United States
WTO	World Trade Organization

Foreword



The latest Intergovernmental Panel on Climate Change Report serves as a crucial reminder that climate change is already affecting our lives today: the damages are widespread, rapid, and intensifying. The report also serves as a clarion call that while there is still time to limit long-term warming to 1.5°C, that window of opportunity is rapidly closing.

The Production Gap Report – now in its third edition – shines a spotlight on the path that governments must take to align their fossil fuel supply with the goals of the Paris Agreement. Thus far, this action has largely been restricted to promoting carbon capture and storage and minimizing emissions from extraction processes. However, as this year's report shows, these measures alone are insufficient; they cannot substitute for a global, long-term wind down of coal, oil, and gas.

A global transition away from fossil fuels is paramount to avoiding dangerous climate change, saving millions of lives from air pollution, ending harm to local communities in extraction frontiers, and protecting our biodiversity and ecosystems.

At COP26 and beyond, the world's governments must take immediate steps to address the production gap, while ensuring that this transition occurs in a just and equitable manner.



Inger Andersen
Executive Director
United Nations Environment Programme



A growing number of countries are announcing targets to achieve net-zero emissions by mid-century. While this is a positive development, bending the emissions curve downwards requires these pledges to be accompanied by concrete, near- and long-term actions. This includes immediate, steep, and sustained reductions in fossil fuel production and burning.

However, the world's energy supply remains dominated by coal, oil, and gas. And as this report reveals, the global production gap has remained largely unchanged since the first assessment in 2019. Governments are still planning to produce more than twice the amount of fossil fuels in 2030 than would be consistent with limiting global warming to 1.5°C. This discrepancy points to the urgent need for net-zero pledges to be translated into action to wind down fossil fuel production.

Governments have a key role to play here. State-owned companies control more than half of global fossil fuel production, and government policies and spending shape energy markets in significant ways. It is imperative that fossil fuel-producing nations recognize their role and responsibility in closing the production gap and steering us towards a safe climate future.



Måns Nilsson
Executive Director
Stockholm Environment Institute



Contents

Acknowledgements . . . iii
Glossary . . . v
Abbreviations . . . vi
Foreword . . . vii

Executive Summary . . . 2

1. Introduction . . . 8

2. The Production Gap . . . 12
2.1 The fossil fuel production gap . . . 13
2.2 A breakdown of the "countries' plans and projections" pathway . . . 16
2.3 Implications of mitigation pathways on the production gap . . . 19
2.4 Conclusions . . . 23

3. Government support and policies for fossil fuel production . . . 24
3.1 Plans, targets, and projections . . . 25
3.2 National support mechanisms . . . 27
3.3 Multilateral and bilateral finance . . . 29

4. Fossil fuel production and policies in key countries . . . 34
China . . . 38
United States . . . 39
Russia . . . 40
Saudi Arabia . . . 41
Indonesia . . . 42
Australia . . . 43
India . . . 44
Canada . . . 45
United Arab Emirates . . . 46
South Africa . . . 47
Brazil . . . 48
Norway . . . 49
Mexico . . . 50
United Kingdom . . . 51
Germany . . . 52

5. The critical role of transparency in addressing the production gap . . . 54
5.1 Existing transparency initiatives and information gaps . . . 55
5.2 Strengthening transparency . . . 57
5.3 Conclusions . . . 62

6. Closing the fossil fuel production gap . . . 64

References . . . 69

Appendix A . . . 90

Executive Summary

Key Findings

Governments plan to produce more than twice the amount of fossil fuels in 2030 than would be consistent with limiting warming to 1.5°C. The production gap has remained largely unchanged since our first analysis in 2019.

Global fossil fuel production must start declining immediately and steeply to be consistent with limiting long-term warming to 1.5°C.

Most major oil and gas producers are planning on increasing production out to 2030 or beyond, and several major coal producers are planning on continuing or increasing production.

G20 countries have directed more new funding to fossil fuels than clean energy since the beginning of the COVID-19 pandemic.

International public finance for the production of fossil fuels from G20 countries and multilateral development banks (MDBs) has significantly decreased in recent years.

Governments have a primary role to play in closing the production gap and in ensuring that the transition away from fossil fuels is just and equitable.

Executive Summary

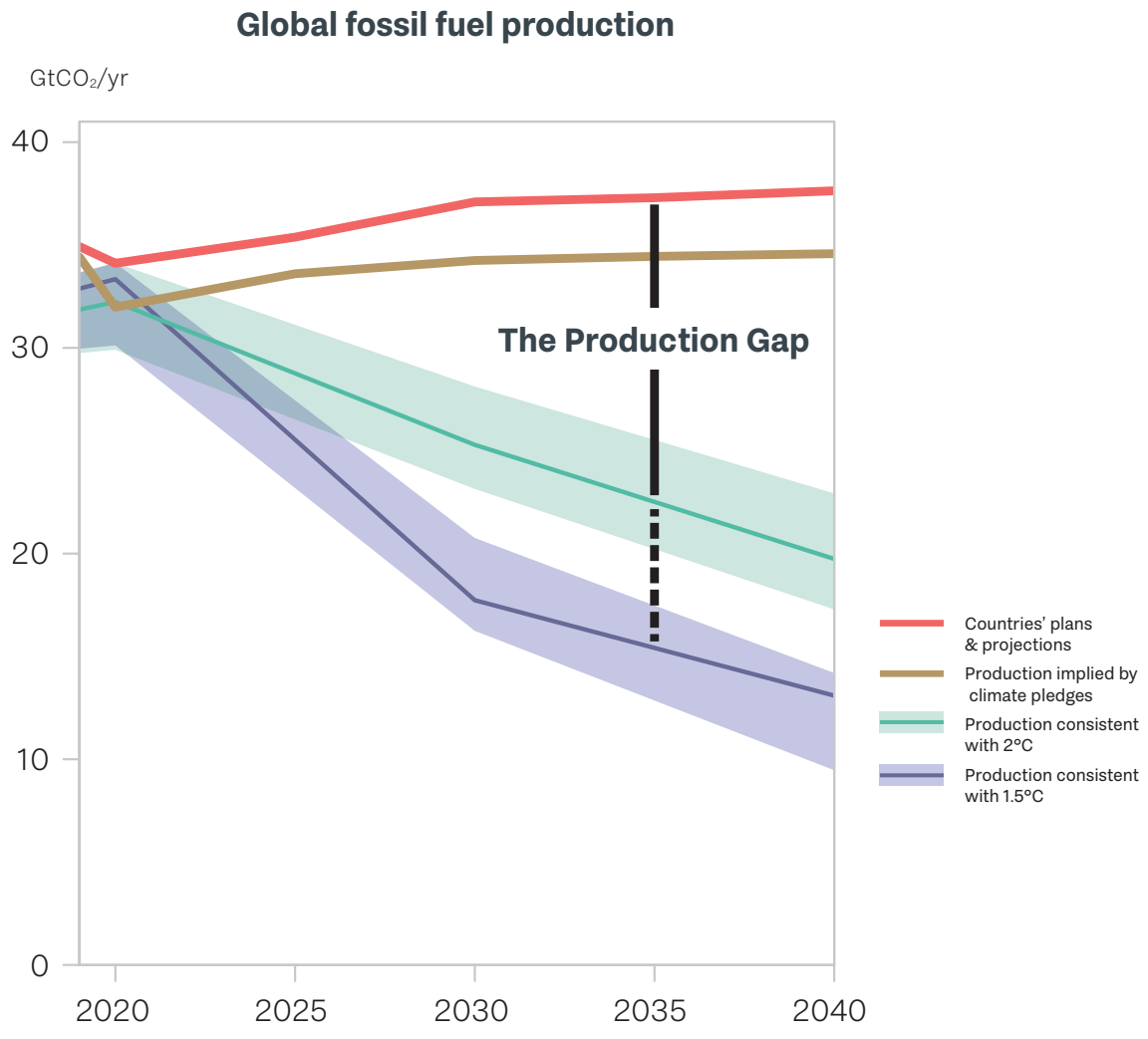
This report first introduced and quantified the "production gap" in 2019, finding that the world's governments planned to produce far more fossil fuels than consistent with their Paris Agreement commitment to limit global warming. Two years on, with the climate crisis clearer and more urgent than ever, governments continue to bet on extracting far more coal, oil, and gas than is consistent with agreed climate limits.

Specifically, this report's production gap analysis — the first full update since 2019 — finds that the world's governments still plan to produce more than double the amount of fossil fuels in 2030 than would be consistent with limiting global warming to 1.5°C, and 45% more than consistent with limiting warming to 2°C. Collectively, although many governments have pledged to lower their emissions and even set net-zero targets, they have not yet made plans to wind down production of the fossil fuels that, once burned, generate most of those emissions.

The latest Intergovernmental Panel on Climate Change report issued an important call to action: we are running out of time to limit long-term global warming to 1.5°C or

Figure ES.1

The fossil fuel production gap — the difference between global fossil fuel production projected by governments' plans (red line) and those consistent with 1.5°C- and 2°C-warming pathways (blue and green lines), as expressed in carbon dioxide (CO_2) emissions released when the extracted fuels are burned — remains large.



even 2°C. This report shows that doing so requires steep and sustained reductions in fossil fuel production and use. The world's governments must take urgent action to close the production gap.

The report's main findings are as follows:

As countries set net-zero emission targets, and increase their climate ambitions under the Paris Agreement, they have not explicitly recognized or planned for the rapid reduction in fossil fuel production that these targets will require. Rather, the world's governments plan to produce more than twice the amount of fossil fuels in 2030 than would be consistent with limiting warming to 1.5°C. The production gap has remained largely unchanged since our first analysis in 2019.

Since the release of the first Production Gap Report in 2019, many governments have announced new, more ambitious greenhouse gas (GHG) emission reduction targets, including net-zero pledges. While this is a positive development, only a few fossil-fuel-producing countries have begun to grapple with how zeroing out global GHG emissions will affect their future coal, oil, and gas production.

As shown in Figure ES.1, according to our assessment of recent national energy plans and projections, governments are in aggregate planning to produce 110% more fossil fuels in 2030 than would be consistent with limiting global warming to 1.5°C, and 45% more than would be consistent with limiting warming to 2°C, on a global level. By 2040, this excess grows to 190% and 89%, respectively.

Collectively, governments are planning and projecting production levels higher than those implied by their emission reduction goals, as announced in their nationally determined contributions (NDCs) under the UN climate process and other climate policies as of mid-2020, as also shown in Figure ES.1.

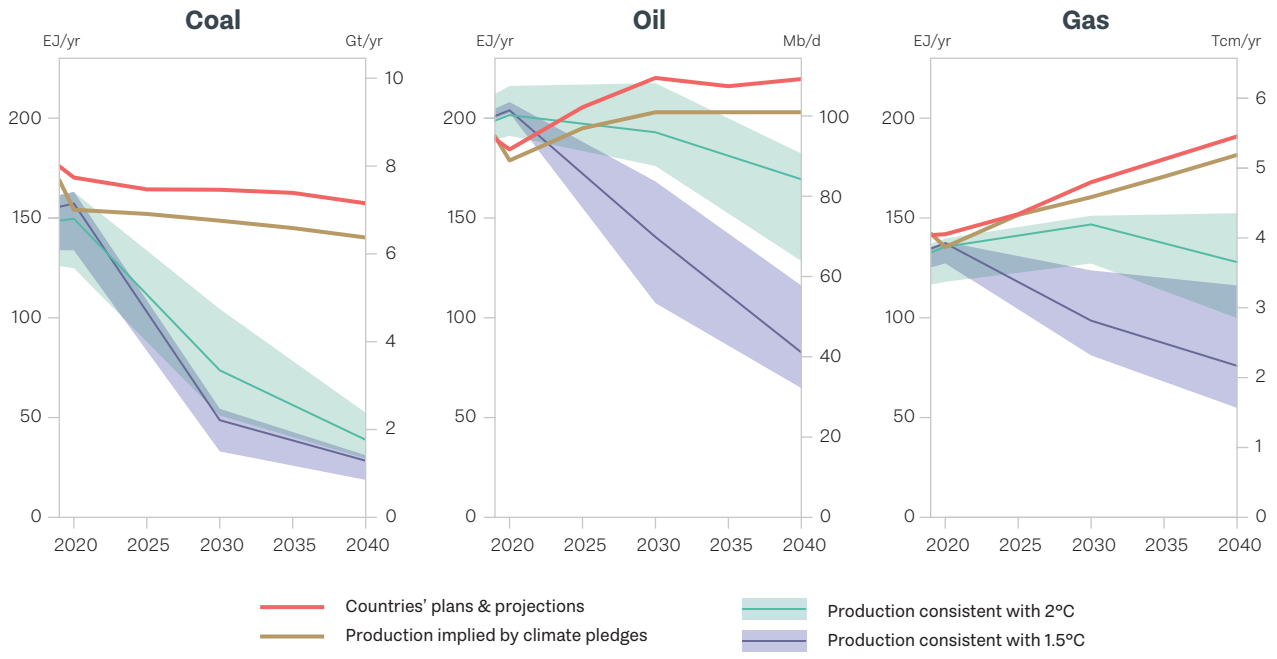
Global fossil fuel production must start declining immediately and steeply to be consistent with limiting long-term warming to 1.5°C.

However, as shown in Figure ES.2, governments are collectively projecting an increase in global oil and gas production, and only a modest decrease in coal production, over the next two decades. This leads to future production levels far above those consistent with limiting warming to 1.5°C or 2°C.

The production gap is widest for coal in 2030: governments' production plans and projections would lead to around 240% more coal, 57% more oil, and 71% more gas than would be consistent with limiting global warming to 1.5°C.

Figure ES.2

Governments are collectively projecting an increase in global oil and gas production, and only a modest decrease in coal production, over the next two decades. This leads to future production levels far above those consistent with limiting warming to 1.5°C or 2°C.



Compared to global production levels under the 2°C-consistent pathways, governments' production plans and projections would lead to 120% more coal, 14% more oil, and 15% more gas in 2030. The production gaps for all fuels grow much wider by 2040 under both temperature limits.

This disconnect could be even worse than our analysis implies. As explored in Chapter 2, our estimate of the size of the production gap depends on model assumptions and conceptions of how the low-carbon transition unfolds, such as how much carbon dioxide can be captured and stored or sequestered, and the tradeoffs among different emission-reduction strategies. If carbon dioxide removal technologies fail to develop at large scale, or if methane emissions are not rapidly reduced, the production gap would be wider than estimated here. Furthermore, Chapter 2 shows that minimizing methane emissions from fossil fuel extraction and distribution alone is not a substitute for a rapid wind-down in fossil fuel production itself.

G20 countries have directed nearly USD 300 billion in new funds towards fossil fuel activities since the beginning of the COVID-19 pandemic — more than they have toward clean energy. In contrast, they have significantly decreased new international public finance for fossil fuel production in recent years; multilateral development banks (MDBs) and G20 development finance institutions (DFIs) holding a total of over USD 2 trillion in assets have adopted policies that exclude fossil fuel production activities from future finance.

The trajectory of fossil fuels will be shaped by the unprecedented levels of investment that many governments are now injecting into their economies, as part of their COVID-19 recovery efforts. Since January 2020, G20 countries have directed USD 297 billion of new public financial commitments towards fossil-fuel-consuming and -producing activities. Though governments have begun to shift more of their COVID-19 recovery spending to clean energy, they still spend more on support for fossil fuels.

While international public finance institutions continue to support fossil fuel extraction, distribution, and processing, there are promising trends: new public finance for the production of fossil fuels from MDBs and G20 countries has significantly decreased since 2017, and, increasingly, MDBs and G20 DFIs have policies that exclude future investment in these activities.

This report details the government strategies, support, and plans for fossil fuel production in 15 major producer countries. Most major oil and gas producers are planning on increasing production out to 2030 or beyond, while several major coal producers are planning on continuing or increasing production.

This report provides country profiles for Australia, Brazil, Canada, China, Germany, India, Indonesia, Mexico, Norway, Russia, Saudi Arabia, South Africa, the United Arab Emirates, the United Kingdom, and the United States. The profiles summarize each country's stated national climate ambitions; available information on government views, projections, and support for fossil fuel production; and emerging policies and discussions towards a managed and equitable wind-down of production.

These countries have announced GHG emission reduction targets through their NDCs and, in some cases, have set net-zero goals. However, few have assessed, at least publicly, whether their projected fossil fuel production is consistent with the goals of the Paris Agreement. This focus on emissions alone ignores their roles and responsibilities in producing the predominant source of these emissions.

Moreover, the country profiles show that most of these governments continue to provide significant policy support for fossil fuel production, through tax breaks, finance, direct infrastructure investments, exemptions from environmental requirements, and other measures. As Figure ES.3 shows, most major oil- and gas-producing countries are planning on expanding production. For coal, some countries plan to reduce production while others still plan to continue or increase it. While some countries are beginning to discuss and enact policies towards a just and equitable transition away from fossil fuel production, these efforts have not yet affected the plans and strategies of major producing countries.

Verifiable and comparable information on fossil fuel production and support — from both governments and companies — is essential to addressing the production gap. Governments should strengthen transparency by disclosing their production plans in their climate commitments under the Paris Agreement.

While existing transparency initiatives have shed some light on fossil fuel production, the available information is incomplete, inconsistent, and scattered. Addressing

Figure ES.3

Most countries profiled in this report are planning on increasing oil and gas production, and several are planning on continued or increasing coal production.

Country	Planned/projected change in national fossil fuel production for 2030 relative to 2019 (EJ)		
	Coal	Oil	Gas
Australia	■	▲ 0.2 EJ	▲ 0.6 EJ
Brazil	●	▲ 5.3 EJ	▲ 1.3 EJ
Canada	▼ 0.5 EJ	▲ 1.4 EJ	▲ 0.3 EJ
China	▼ 9.2 EJ	▲ 0.6 EJ	▲ 3.8 EJ
Germany	▼ 0.6 EJ	●	●
India+	▲ 6.1 EJ	▲ 0.5 EJ	▲ 0.8 EJ
Indonesia	■	▼ 0.7 EJ	▼ 0.2 EJ
Mexico	●	▲ 2.4 EJ	▲ 0.5 EJ
Norway	●	▲ 0.3 EJ	▼ 0.6 EJ
Russia	▲ 3.6 EJ	■	▲ 4.3 EJ
Saudi Arabia	●	▲ 7.1 EJ	▲ 4.7 EJ
South Africa	No available projections	●	●
United Arab Emirates	●	▲ 1.9 EJ	No available projections
United Kingdom	●	▼ 1.2 EJ	▼ 0.7 EJ
United States	▼ 4.3 EJ	▲ 5.2 EJ	▲ 3.8 EJ

+ For India, changes shown are for 2024 relative to 2019.

▲ Denotes an increase of greater than 5% by 2030, relative to 2019 production in energy terms.

▼ Denotes a decrease of greater than 5% by 2030, relative to 2019 production in energy terms.

■ Denotes change in production by 2030 stays within 5% of 2019 production in energy terms.

● Annual production in 2019 is less than 0.5 EJ.

the production gap requires governments to be far more transparent in their plans and projections for oil, gas, and coal production.

Governments have already committed to reporting climate-related information as part of the Paris Agreement. This reporting currently focuses on emissions goals, but governments could also include production plans and projections — and how these plans align with climate goals — in their NDCs, their long-term, low-emissions development strategies (LT-LEDS), and their progress reports on implementing and achieving their NDCs.

Governments can also mandate that investor- and state-owned fossil fuel companies disclose their spending, project plans, emissions, and climate-related financial risks in a way that is consistent across countries.

Governments have a primary role to play in closing the production gap.

In addition to strengthening measures to reduce the demand for fossil fuels, governments should also take actions to ensure a managed and equitable decline in production, such as the following:

- Acknowledge in their energy and climate plans that there is a need to wind down global fossil fuel production in line with the Paris Agreement's temperature limits. This creates impetus and accountability for policy action.
- Chart the course towards a rapid, just, and equitable wind-down of fossil fuel production as part of overall decarbonization plans. Comprehensive efforts to wean countries off the use of coal, oil, and gas should be coupled with strategies to ramp down production to ensure a less disruptive transition.
- Place restrictions on fossil fuel exploration and extraction to avoid locking in levels of fossil fuel supply that are inconsistent with climate goals.
- Phase out government support for fossil fuel production. Governments can end subsidies and other support for production, exclude fossil fuels from public finance, and direct greater support towards low-carbon development.
- Leverage international cooperation to ensure a more effective and equitable global wind-down of production. A just, equitable, and effective transition will require greater international support for countries highly dependent on fossil fuel production and with limited financial and institutional capacity. Countries with greater capacity can lead the way.



1

Introduction

1. Introduction

For many people, the extraction, processing, and burning of coal, oil, and gas is invisible; it happens out of sight and out of mind. We turn on lights, heat water, light a stove, buy goods — and rarely see the physical fuel itself, let alone the emissions caused by burning it. Further from view is where the fuel came from: the well or mine.

Governments, however, very much have fossil fuels in their sights. The production and export of fossil fuels can support or hinder local economies, aid or impede alliances between countries, and make or break the political careers of government policymakers.

This report, now in its third edition, highlights the tension between the importance that governments have traditionally attached to fossil fuels and a harmful effect of fossil fuel production and trade: global warming. We find that government plans for fossil fuel production are still far more in line with worsening climate disasters than they are with internationally agreed temperature limits.

This disconnect is the "production gap" — the difference between government plans for fossil fuel production and the levels consistent with globally agreed climate limits. And while the breadth of the gap is sobering, governments have the power to address it.

Fossil fuels are something governments have substantial control over. More than half of the world's fossil fuel production is directly owned by governments, including by state-owned companies. Even when governments do not directly own fossil fuels, their policies and permits still control, to a large degree, how much fossil fuel gets extracted.

This ability to steer fossil fuel supply can be an important component of meeting global temperature and emissions goals, including "net-zero" emissions targets. When fewer fossil fuels are produced, fewer are burned, and fewer greenhouse gas emissions are released. Therefore, by working together to constrain fossil fuel production, countries can help bend the emissions curve downwards on a path towards net zero.

Working together on emissions from fossil fuels is something nations already do, through major critical venues like the United Nations Framework Convention on Climate Change (UNFCCC), which yielded the Paris Agreement in 2015. Though nations have also cooperated on steering fossil fuel production — such as through the Organization of the Petroleum Exporting Countries (OPEC) — they have not yet done so with the intent of limiting climate change.



A few countries, however, are starting to announce their intentions to ban or move away from producing fossil fuels. This collection of nations is — so far — composed of countries with relatively limited fossil fuel resources (such as Costa Rica and Denmark), but it could expand, while other groups and coalitions of fossil-fuel-producing nations could form or adapt their missions to focus on climate.

After all, major fossil-fuel-producing countries have reason to limit the supply of fossil fuels: tighter supply leads to higher prices and revenues for existing fossil fuel resource holders, which can boost local economies. Higher prices also can help reduce emissions.

Governments may be wary of being perceived as getting too directly involved in fossil fuel markets in a way that might increase prices for energy consumers. That is understandable, and fossil fuel prices that are too high can negatively affect the economy. However, the bigger, longer-term risk is instead prices that are too low. By enacting measures to limit greenhouse gas emissions in line with the Paris Agreement, and hence cutting fossil fuel demand, countries will already be pushing producer prices lower.

As an example of the problem of low fossil fuel prices, the International Energy Agency (IEA) recently found in its *Net Zero by 2050* report that oil prices could head steadily downward toward USD 37 per barrel by the end of this decade, as nations move to low-carbon forms of



transport such as electric vehicles. To ward off volatility and keep prices from sinking even lower, the IEA foresees that even fossil-fuel-rich states may need to purposefully limit supply, so as not to threaten the financial value of their existing deposits.

In other words, working together to limit supply, in tandem with demand, could bring more certainty to the markets, adding extra force to the low-carbon transition.

Furthermore, constraining supply can help ensure that, as fossil fuel demand declines, prices do not get so low as to spur new consumption, undermining the path to net-zero emissions. Put simply, limits on supply can ensure that when increasingly stringent climate policy prevents a barrel of oil or ton of coal from being burned in one location, it is not instead burned somewhere else.

The way forward for aligning fossil fuel production with climate limits is not easy. Government efforts to limit fossil fuel production will need strong support to succeed politically. That is a challenge, in part due to the long history of fossil fuel extraction — and associated social and political institutions that maintain fossil fuel dominance — in many coal-, oil-, and gas-producing communities.

One source of support may be local residents. They feel the health effects of extracting fossil fuels, whether through water pollution, coal dust, or other dangerous chemicals in the air. Local residents also value biodiversity, recreation, and tourism; fossil fuel development conflicts with these priorities. And, in many areas of the world, engaged citizens are the ones who have most clearly pointed out the disconnect between fossil fuel development and climate change mitigation.

Another source of support may be the courts. National courts in some countries have issued rulings that underscore the conflict between expanding fossil fuel production and climate limits. For example, the District Court of The Hague in the Netherlands ruled that Royal Dutch Shell's production levels contribute to global warming, and that, by reducing production of fossil fuels, Shell would help reduce global carbon emissions.

Still, few national policymakers are on board with limiting fossil fuel supply in the name of climate protection. The most recent cooperative climate effort from major fossil-fuel-producing national governments — the Net-Zero Producers Forum — has thus far focused on extracting fossil fuels in less-polluting ways, not on winding down production levels in line with climate goals.

Those efforts are important, as reducing methane and other emissions at fossil fuel extraction sites is a critical step in meeting the goals of the Paris Agreement. But as we show in this report, making fossil fuel extraction less polluting is also highly insufficient. The overall levels of fossil fuel production urgently need to decrease.

Governments, with fossil fuels under their policy control, are key to closing the production gap. They can establish the norms and rules that will ensure that companies extract less fossil fuels, and only they have the broad, economy-wide interests, power, and responsibilities to protect social and economic stability during the transition. While private-sector actors — including energy companies and financial institutions — should also move away from extracting and investing in fossil fuels, their action is no substitute for the economy-wide, public-interest role and responsibility of government.

This report thus focuses on governments, and their role in widening, or closing, the production gap. It quantifies the size of the production gap (Chapter 2), summarizes how governments support fossil fuel production (Chapter 3), details how governments in 15 key countries deal with fossil fuel production (Chapter 4), and highlights opportunities for strengthening the transparency necessary to help close the production gap (Chapter 5). Finally, a concluding chapter (Chapter 6) discusses how governments can manage the decline of fossil fuel production in line with climate goals in a just and equitable way.



2

The Production Gap

Key Messages

The world's governments are planning to produce 110% more fossil fuels in 2030 than would be consistent with limiting global warming to 1.5°C, and 45% more than would be consistent with limiting warming to 2°C. The production gap grows much wider by 2040.

The size of the production gap has remained largely unchanged compared to our prior assessments.

The production gap is widest for coal: governments' production plans and projections would lead to around 240% more coal, 57% more oil, and 71% more gas in 2030 than global levels consistent with limiting warming to 1.5°C.

Governments are in aggregate planning on increasing gas production out to at least 2040. This continued, long-term expansion in gas production is inconsistent with the Paris Agreement's temperature limits.

Global coal, oil, and gas production must start declining immediately and steeply to be consistent with limiting long-term warming to 1.5°C.

If carbon dioxide removal technologies fail to develop at large scale, fossil fuel production would need to decline even more rapidly.

2. The Production Gap

Since the release of the first Production Gap Report in 2019, many governments have updated their nationally determined contributions (NDCs) under the Paris Agreement and announced new, more ambitious greenhouse gas (GHG) emission reduction targets, including net-zero pledges. While this is a positive development, only a few fossil-fuel-producing countries have begun to grapple with how zeroing out global GHG emissions will affect their future coal, oil, and gas production.

This chapter quantifies the global fossil fuel production gap: the discrepancy between the global levels of fossil fuel production implied by governments' plans and projections and the levels consistent with the Paris Agreement's goals (namely, limiting warming to well below 2°C and "pursuing efforts to limit the temperature increase to 1.5°C"). It provides the first comprehensive update to the production gap estimate since the inaugural edition of this report in 2019.[1] We first quantify the production gap in Section 2.1, before discussing the major trends and drivers of the gap — and its changes compared to our 2019 assessment — in Section 2.2. We then explore the uncertainties of the production gap, due to assumptions underlying different mitigation pathways, in Section 2.3.



2.1 The fossil fuel production gap

The calculation of the production gap relies on two major elements. The first is the pathway of global future fossil fuel production implied by the plans and projections of national governments. The second is the pathway of global fossil fuel production that would be consistent with limiting warming to 1.5°C or to 2°C.

The first element relies on our compilation of government projections for fossil fuel production, as outlined in recent and publicly available national energy outlooks and targets as of August 2021.[2] This year, that includes outlooks from the eight major countries included in our 2019 report, as well as outlooks from seven additional countries. Altogether, these 15 countries accounted for around 75% of global fossil fuel extraction, on an energy basis, in 2020. Their combined production levels are then scaled up to a global estimate, based on these countries' projected future shares of global production (see details in Section 2.2 and online Appendix B). The result is our global "countries' plans and projections" pathway. Our updated assessment of the gap therefore reflects — to the extent possible based on data availability — how governments expect their fossil fuel production will be influenced by more ambitious climate mitigation targets and policies, the COVID-19 pandemic, and other factors.

The second element to the production gap is the pathway of global fossil fuel production that would be consistent with limiting warming to 1.5°C or to 2°C, based on the mitigation scenarios compiled by the Intergovernmental Panel on Climate Change (IPCC) for their *Special Report on Global Warming of 1.5°C,* which the IPCC refers to as "SR1.5" (IPCC, 2018b; Rogelj et al., 2018). These scenarios show how much "primary energy" is supplied by coal, oil, and gas under emissions pathways with varying global warming outcomes, from which we calculate the median values and interquartile ranges. We calculated the "2°C-consistent" pathway as the median of scenarios that have at least a 66% probability of limiting warming to below 2°C over the *entire* 21st century (meaning, no temperature overshoot), relative to the pre-industrial global average atmospheric temperature. We calculated the "1.5°C-consistent" pathway as the median of scenarios with at least a 50% likelihood of limiting warming to below 1.5°C by *end-of-century* (meaning, with a low amount of

[1] Last year's Special Report 2020 put the production gap in the context of the COVID-19 pandemic, but did not fully re-assess the production gap.

[2] Throughout the report, we collectively refer to the sources from which future fossil fuel production is estimated as "plans and projections", given that there are varying levels of details, certainty, and intent associated with each document published by governments and affiliated institutions. Governments take a variety of factors into consideration in assembling these plans and projections, including the state of each country's fossil fuel reserves, the evolution of technologies and costs of extraction, the presence of subsidies and regulations, and foreseeable dynamics of domestic and international demand. Some of these factors are described further in Chapters 3 and 4.

temporary overshoot allowed before 2100).[3] We further constrained these two sets of scenarios by how much carbon they sequester from bioenergy with carbon capture and storage (BECCS) and by afforestation; specifically, we only included scenarios in which BECCS sequesters an average of less than 5 billion tonnes of carbon dioxide per year ($GtCO_2$/yr) and in which afforestation sequesters an average of less than 3.6 $GtCO_2$/yr, both as assessed between 2040 and 2060. This approach follows the Climate Action Tracker's interpretation of sustainable limits for these carbon dioxide removal (CDR) practices, given their "multiple feasibility and sustainability constraints," as noted by the IPCC (IPCC, 2018a, p. 19; New Climate Institute et al., 2018). Further details are provided in online Appendix B.

These low-carbon pathways are identical to those we used in prior assessments of the production gap, since new scenario sets from the IPCC were not yet available when we conducted this year's gap analysis. The release of the IPCC's *Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report* in 2022 will enable us to update these low-carbon pathways in the future.[4]

The global levels of fossil fuel production under each of these pathways are shown in Figure 2.1. The production gap is the difference between the production level under the low-carbon pathways (2°C or 1.5°C) and the level under the countries' plans and projections pathway in any given year. In this figure, the production gap is denominated in units of billion tonnes of carbon dioxide ($GtCO_2$), representing the amount of CO_2 emissions expected to be released from the combustion of extracted coal, oil, and gas.[5]

As shown, countries are planning on producing around 110% more fossil fuels (or more than double the amount) in 2030 than would be consistent with the median 1.5°C-warming pathway, and 45% more fossil fuels in 2030 than would be consistent with the median 2°C-warming pathway. This amounts to 19 $GtCO_2$ more than the median 1.5°C pathway (with an interquartile range of 16–21 $GtCO_2$ relative to all 1.5°C pathways analysed), and 12 $GtCO_2$ more than the median 2°C pathway (with a range of 9–14 $GtCO_2$), in 2030.

The gap then grows wider beyond 2030, as countries' plans and projections continue upward, further departing from the low-carbon pathways. By 2040, countries' plans and projections show 190% more fossil fuels than would be consistent with the median 1.5°C pathway, and 89% more than the median 2°C pathway.

Figure 2.1 also shows a fourth pathway (gold line): global fossil fuel production levels implied by countries' climate pledges, as modelled by the International Energy Agency (IEA) in their Stated Policies Scenario (STEPS) in the World Energy Outlook 2020 (IEA, 2020). This pathway reflects the estimated levels of fossil fuel production that would result from countries' nationally determined contributions (NDCs under the UN climate process), as well as other announced policy intentions as of mid-2020 (IEA, 2020, p. 415). We find that governments' fossil fuel production plans and projections in aggregate (red line) exceed, by close to 10%, the levels of global fossil fuel production implied by their own stated climate pledges (gold line).[6]

The production gap can also be quantified in terms of its component fuels. Figure 2.2 shows the individual production gaps for coal, oil, and gas. Here, the amounts of fossil fuel production under the four different pathways are calculated and shown in energy-based units (exajoules). This enables a direct comparison between the levels of production under the countries' plans and projections pathway, and those under the 1.5°C- and 2°C-consistent pathways (which are in their original energy-based units, as reported by the integrated assessment model scenarios compiled by the IPCC SR1.5) (IPCC, 2018b).

Under both the median 1.5°C- and 2°C-warming pathways, global coal and oil production peak in 2020 and decline thereafter. The same is true for gas under the 1.5°C-warming pathway; under the 2°C-warming pathway, it rises modestly until 2030 before declining thereafter.

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[3] The Paris Agreement does not provide a precise definition for what is meant by its reference to "well below" 2°C. The "2°C-consistent" pathways in this report include those that limit peak warming to below 2°C throughout the entire 21st century with a 66% likelihood or greater (these scenarios are categorized as "lower-2°C" in the IPCC SR1.5 database), as well as pathways that limit median warming to below 1.5°C in 2100 with a 67% probability of temporarily overshooting that level earlier (these scenarios are categorized as "1.5°C-high overshoot"). This report's "1.5°C-consistent" pathways include those with a lower probability of overshoot (i.e., 50%-67%, which are categorized as "1.5°C-low overshoot" in the SR1.5 database).

[4] *The Contribution of Working Group I to the Sixth Assessment Report* — published in August 2021 — focuses on the physical science of climate change (IPCC, 2021). The Working Group III report will assess new mitigation scenarios in detail and will be accompanied by the scenario database that will allow us to update our analysis of coal, oil, and gas production under low-carbon pathways.

[5] This accounting method does not consider other GHGs besides CO_2, such as methane emissions from production processes. The 1.5°C- and 2°C-consistent levels of fossil fuel production are derived from the outputs of "primary energy" supply of coal, oil, and gas in the mitigation scenarios compiled for the IPCC SR1.5. Primary energy supply by fossil fuels represents the amount of energy that can be harvested directly from the fuels prior to any conversion. The primary energy variables generally include non-energy uses of coal, oil, and gas (such as for chemical or plastics feedstocks), though this reporting may vary between models. The IPCC database does not report what fraction of coal, oil, or gas primary energy is for non-energy uses in past or future years. In this analysis, we assume that the percentage of each fuel that is non-energy remains constant at recent levels for the purpose of tallying extraction-based CO_2 emissions from fossil fuel production under all four pathways (Davis et al., 2011). For more details, see online Appendix B.

[6] The IEA estimates that GHG emissions under their Stated Policies Scenario (STEPS) would lead to a long-term temperature rise of around 2.7°C by 2100 (with a 50% probability) (IEA, 2020). The levels of fossil fuel production in our countries' plans and projections pathway are higher than those in the STEPS and therefore would likely imply greater warming (unquantified here).

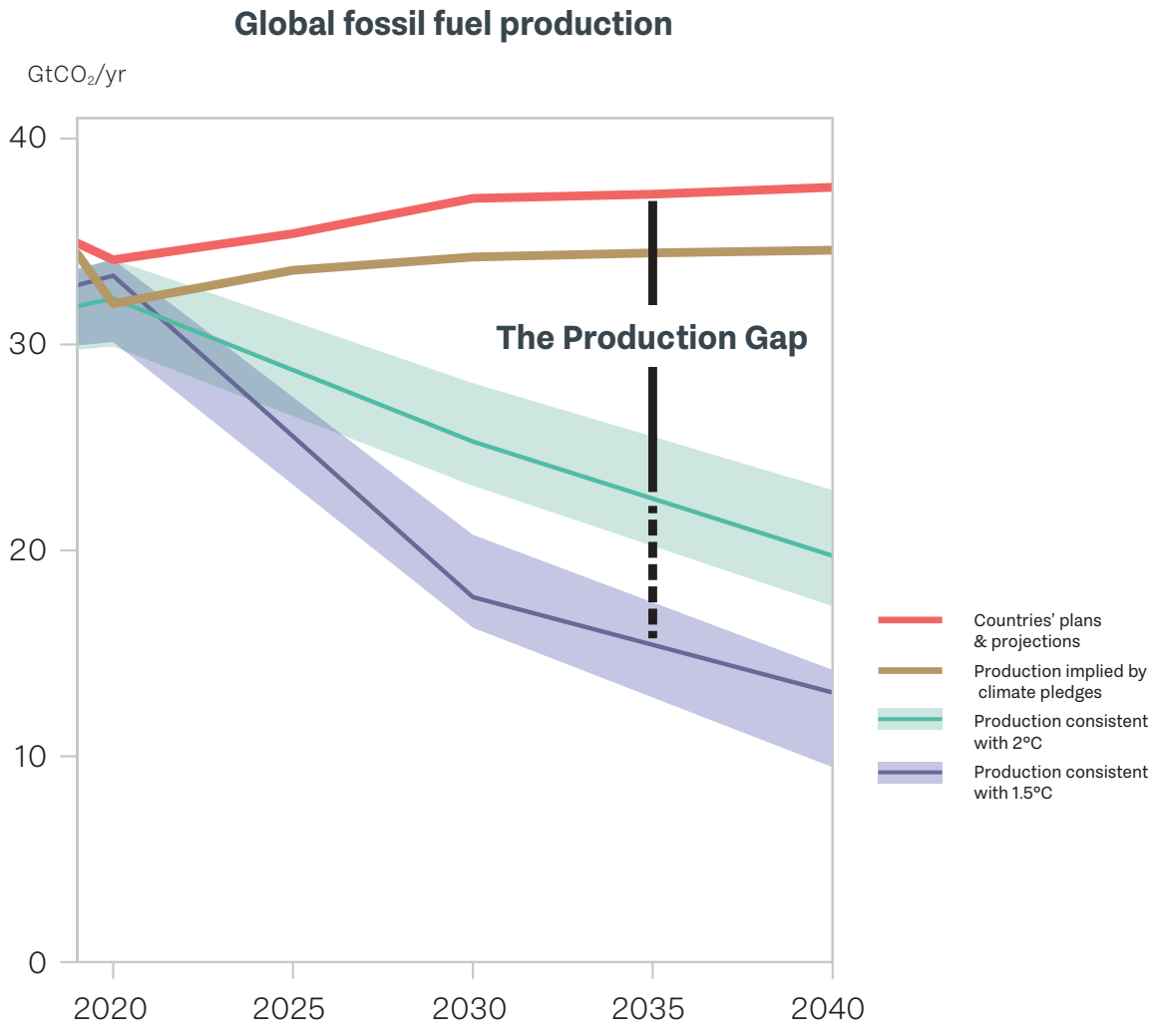
To be consistent with limiting warming to 1.5°C, global coal, oil, and gas production would have to *decrease* by around 11%, 4%, and 3%, respectively, each year between 2020 and 2030.[7] However, governments are collectively projecting an *increase* in global oil and gas production, and only a modest decrease in coal production, from 2020 onwards (as shown by the "countries' plans and projections" pathways in Figure 2.2). By 2030, this would lead to 240% more coal, 57% more oil, and 71% more gas than consistent with the median 1.5°C-warming pathway, and to 120% more coal, 14% more oil, and 15% more gas than consistent with the median 2°C-warming pathway. The production gaps grow much wider by 2040 under both temperature limits.

In other words, the production gap is proportionally largest for coal, with countries planning on producing coal at levels vastly incommensurate with the goals of the Paris Agreement. In aggregate, countries are planning on producing 5.3 billion tonnes more coal in 2030 than would be consistent with the median 1.5°C-warming pathway (with an interquartile range of 5.0 billion–6.0 billion tonnes relative to all 1.5°C pathways analysed). To put this excess amount into context, it is roughly equivalent to 75% of current levels of global coal production.

The production gap for oil is also substantial, especially compared to the 1.5°C-warming pathway. Nations are, in aggregate, planning on producing around 40 million

Figure 2.1

Global fossil fuel production under four pathways from 2019 to 2040, denominated in extraction-based CO_2 emissions in units of billion tonnes of CO_2 per year ($GtCO_2$/yr). This reflects the amount of CO_2 emissions expected to be released from the combustion of extracted coal, oil, and gas. For the 1.5°C- and 2°C-consistent pathways, the median and 25th–75th percentile range (shaded) of all analysed scenarios are shown.



[7] As explained in our previous production gap reports, a global wind-down of fossil fuel production that would be consistent with limiting warming to 1.5°C or 2°C could be achieved by a different mix of decline rates for coal, oil, and gas. The median trajectories shown in Figure 2.2 are dependent on the underlying assumptions of the integrated assessment models.

barrels per day (Mb/d) more oil than would be consistent with the median 1.5°C pathway in 2030 (with a range of 26–56 Mb/d). This excess is roughly equivalent to half of current global oil production.

Similarly, for gas, countries are in aggregate planning on producing around 2 trillion cubic meters (Tcm) more in 2030 than would be consistent with the median 1.5°C-warming pathway (with a range of 1.3–2.5 Tcm). This excess is roughly equivalent to half of current global gas production.

Our analysis shows that continued, long-term expansion in gas production is inconsistent with the goals of the Paris Agreement. Moreover, the models that generate the 1.5°C- and 2°C-consistent pathways include assumptions that may not pan out, meaning gas production would need to decline even more quickly than shown in Figure 2.2. Namely, these models assume that methane emissions associated with producing, transporting, and distributing gas can be minimized, and also rely on substantial levels of carbon capture and storage (CCS) for gas-based energy from 2040 onwards (installed, for example, at gas power plants or hydrogen facilities) (Rogelj et al., 2018). Should these outcomes not be plausible because of technical and public perception issues (Bruckner et al., 2014), the role of gas in low-carbon pathways would be even more limited than that shown in Figure 2.2.

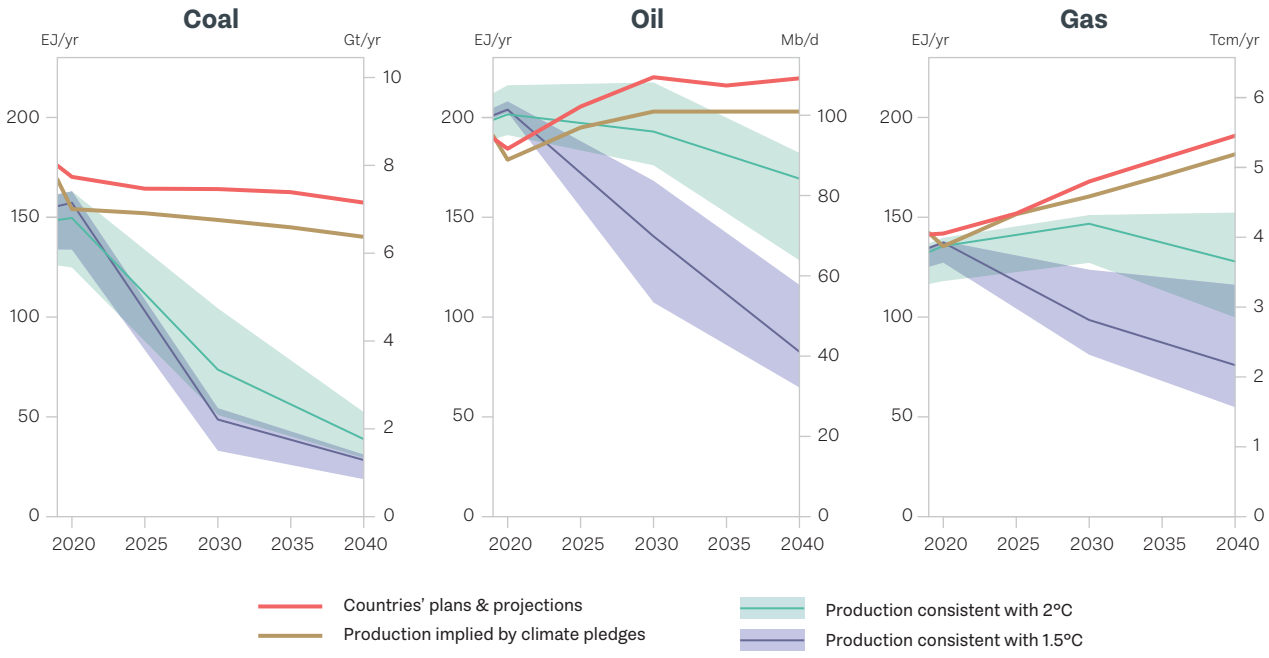
2.2 A breakdown of the "countries' plans and projections" pathway

In this section, we explore trends in major producer countries that underlie the global coal, oil, and gas "countries' plans and projections" (CPP) pathway, and then describe how these pathways have changed compared to our 2019 assessment.

This year's analysis of the CPP pathway comprises an evaluation of the most recent government plans and projections from the eight major fossil-fuel-producing countries we assessed in our 2019 report, as well as from seven additional countries. This year's analysis thus relies on the plans and projections of 15 major producer countries (countries added this year are denoted with an asterisk*): Australia, Brazil*, Canada, China, Germany*, India, Indonesia, Kazakhstan*, Mexico*, Norway, Russia, Saudi Arabia*, the United Arab Emirates (UAE)*, the United Kingdom (UK)*, and the United States (US). On an energy basis, these producer countries accounted for 75% of global fossil fuel production in 2020 (IEA, 2020). Within these 15 countries, 8 had government plans and

Figure 2.2

Global coal, oil, and gas production (denominated in exajoule or EJ per year) under four pathways from 2019 to 2040. Physical units are displayed as secondary axes: billion tonnes per year (Gt/yr) for coal, million barrels per day (Mb/d) for oil, and trillion cubic meters per year (Tcm/yr) for gas. For the 1.5°C- and 2°C-consistent pathways, the median and 25th–75th percentile range (shaded) of all analysed scenarios are shown.



projections for coal (accounting for around 90% of global production), 14 had projections for oil (70%), and 13 had projections for gas (65%).

Figure 2.3 shows the individual contributions of these 15 countries to the global coal, oil, and gas CPP pathways, denominated in units of energy and extraction-based CO_2 emissions. The global values (shown by the red lines, which are equivalent to the pathways shown in Figure 2.2) are estimated by scaling the aggregated production levels of the 15 countries shown, based on their future shares of global coal, oil, and gas production as modelled in the IEA STEPS (IEA, 2020) (see online Appendix B for further details on this approach).

As previously described, the CPP pathways show global oil and gas production continuously rising out to 2040, after a small dip in 2020, while coal declines slightly throughout this period. Specifically, under the CPP pathways, annual coal production is projected to be 12 EJ lower (-7%) in 2030 than in 2019, while oil production is 31 EJ higher (+16%), and gas production is 28 EJ higher (+19%).

The decline in coal is led by today's largest two coal producers, China and the US, which foresee drops of 13 EJ and 4 EJ, respectively, over this period. However, this decline is partially counteracted by projected increases in India, Russia, and Australia.[8]

The projected increase for oil is led by Saudi Arabia, Brazil, and the US, each of which project oil production to be 5–7 EJ higher in 2030 relative to 2019. Of the other 11 countries assessed, 8 also foresee smaller increases (while the UK, Russia, and Indonesia see small decreases).

For gas, the planned increase is led by Saudi Arabia, Russia, China, and the US, each of which project gas production to be more than 5 EJ higher in 2030 than in 2019. Australia, Brazil, Canada, India, and Mexico also foresee smaller increases (while the UK, Norway, Indonesia, and Kazakhstan foresee small decreases).

As shown in Figure 2.3, according to the outlooks from governments and affiliated institutions, today's largest producers will dominate the global total cumulative production between 2019 and 2040. Between one and four countries will account for around half of the projected global total of each fuel: China for coal; the US, Saudi Arabia, Russia and Canada for oil; and the US, Russia, China, and Saudi Arabia for gas.

Compared to our 2019 analysis, this year's assessment of the global CPP pathways is more comprehensive, since it includes government plans and projections from seven additional countries. This expanded scope makes it difficult to directly compare the CPP pathways in our 2021 assessment to those in our 2019 assessment; the lack of regular, standardized reporting across countries on planned domestic fossil fuel production, and a general lack of transparency, also complicates the comparison.[9]

Nevertheless, in aggregate, we find that the size of the production gap has remained largely unchanged compared to our 2019 assessment (see Figures B.1 and B.2 and further details online Appendix B).[10]

This broadly stagnant gap includes slight changes for oil production. The COVID-19 pandemic has played some role in lowering the CPP pathway for oil in the near term. The sharp decrease in travel associated with the response to the pandemic pushed down oil demand forecasts (and, in turn, investment levels in new oil supply). However, these economic effects are projected to be short-lived (IMF, 2021). By 2030, plans for oil production grow to the same levels foreseen in our 2019 analysis, before flattening out by 2040 to levels about 9% below our previous analysis. Still, we find that global planned oil production will exceed levels consistent with limiting warming to 1.5°C by 57% in 2030 and by 170% in 2040.

For coal, projections under the CPP pathway in 2030–2040 have decreased slightly compared to our 2019 analysis. Still, governments' planned coal production will vastly exceed global levels consistent with limiting warming to 1.5°C — by 240% in 2030 and by 450% in 2040.

For gas, the global level of production estimated under the CPP pathway in 2030–2040 has remained largely unchanged since our 2019 analysis. Governments' planned gas production will exceed the levels consistent with limiting warming to 1.5°C by 71% in 2030 and by 150% in 2040.

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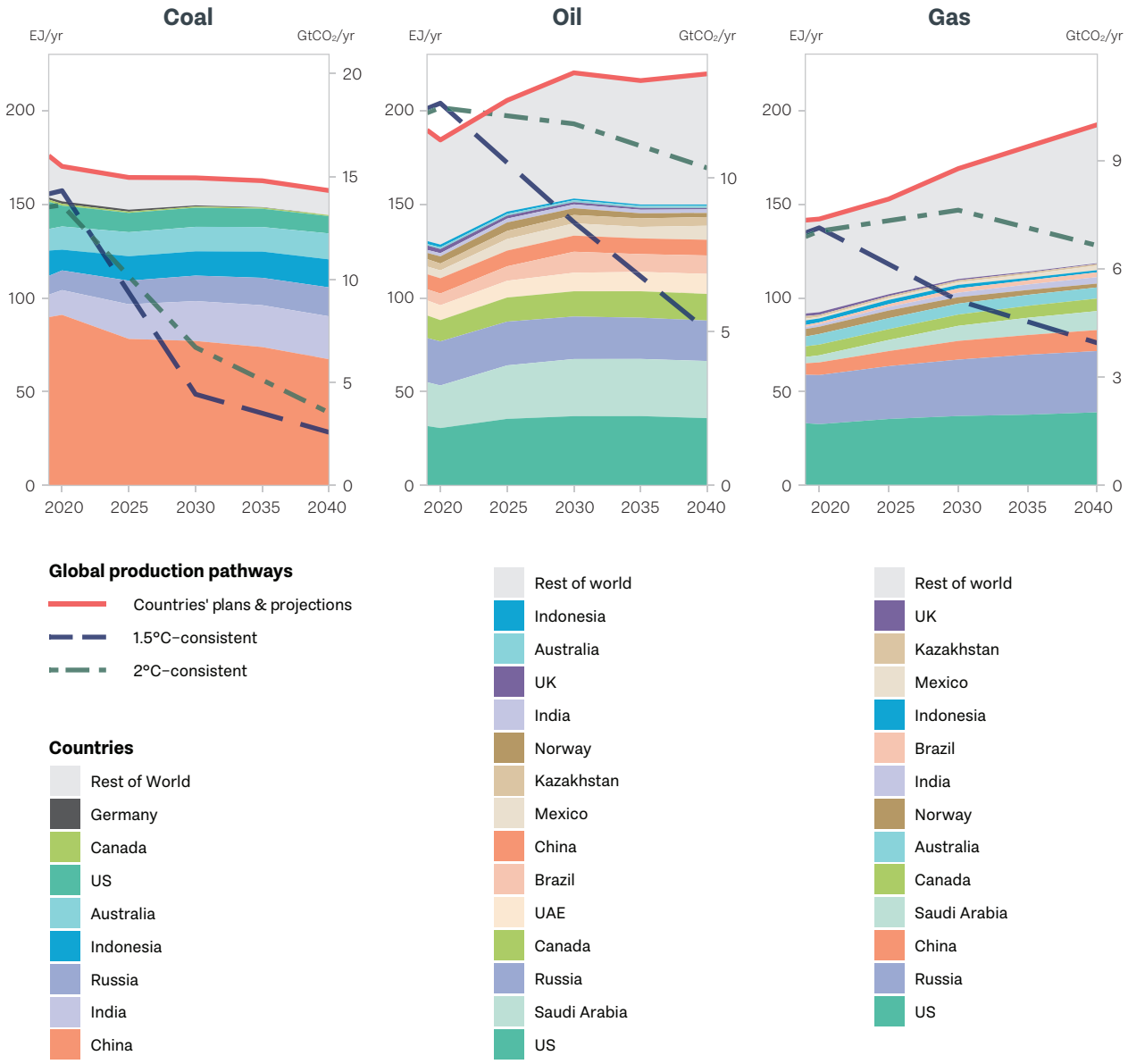
[8] For India, government projections end in 2024. To extrapolate to 2040, we use the percent change in India's coal production as modelled under the IEA's *Stated Policies Scenario* (STEPS) in the *World Energy Outlook 2020* (IEA, 2020). STEPS is a scenario that reflects existing and announced climate policies as of 2020; thus, this is likely a conservative extrapolation approach, given that global production estimated under our CPP pathway is higher than those under the STEPS (as shown in Figures 2.1–2.2). See online Appendix B for further details.

[9] For example, some governments issue long-term national energy outlooks annually, which enables a direct, year-to-year comparison of their projections. However, many countries do not. In some cases, countries provide projections in different government documents, which makes comparison over time more difficult (see online Appendix B for details).

[10] Our 2019 report found that governments are planning to produce around 52% more fossil fuels in 2030 than would be consistent with a 2°C pathway and 120% more than would be consistent with a 1.5°C pathway. Upon re-analyzing the source data for that calculation, it appears that we misinterpreted the units of India's coal projections given in "coal-equivalents" in the government source document analysed (NITI Aayog, 2017, p. 27). When we account for our new interpretation of India's projections, our 2019 coal CPP pathway would have been slightly lower. Consequently, the size of the production gap in 2030 would have been around 110% relative to the 1.5°C pathway and 46% relative to the 2°C pathway (see details in online Appendix B). All reported results are rounded to 2 significant figures.

Figure 2.3

Individual countries' contributions to global production estimated under the "countries' plans and projections" pathways. For each fuel, countries are plotted in order of decreasing cumulative 2019–2040 production, from bottom to top. Global production under the median 1.5°C- and 2°C-warming pathways are overlaid. Annual coal, oil, and gas production are shown in energy units (exajoules, or EJ) on the primary axes, and in units of extraction-based CO_2 emissions on the secondary axes. (To allow for these two units to be shown on the same plot, globally averaged, extraction-based emission factors for each fuel are applied to all countries here. See online Appendix B for details on each country's plans and projections.)



Altogether, the largely unchanged outlooks for global coal, oil, and gas production under the CPP pathways in 2030 means that our estimate of the overall production gap has remained almost the same for that year. In 2040, small reductions in the levels of oil and coal under the CPP pathways translate to a very small narrowing of the overall gap (by 3%).[11]

2.3 Implications of mitigation pathways on the production gap

As discussed in Section 2.1, one of two major elements we use to estimate the size of the production gap is the future pathways of global fossil fuel production that would be consistent with limiting warming to 1.5°C or 2°C. Our analysis relies on the set of mitigation pathways assembled by the IPCC SR1.5 (IPCC, 2018b). Each model scenario has its own estimates for how quickly coal, oil, and gas have to be phased down in order to meet the 1.5°C- and 2°C-warming limits of the Paris Agreement.[12] We use the median values across scenarios to calculate the production gap, but this is not the only way this estimate could be made (Huppmann et al., 2018). For example, it is possible that certain groups of scenarios — or even individual scenarios on their own — are more plausible than the median values. There are also very different conceptions of how the low-carbon transition might unfold.

Accordingly, in this section, we explore how the size of the production gap might differ under the four "illustrative pathways" of the IPCC SR1.5 (IPCC, 2018b; Rogelj et al., 2018), as well as under IEA's recently released *Net Zero by 2050* pathway (NZE) for the energy sector (IEA, 2021). Since these pathways are all designed to limit long-term warming to 1.5°C, we focus on this temperature limit in this section. Figure 2.4 shows how global fossil fuel production differs among different 1.5°C-consistent pathways, and how these six pathways compare to the "countries' plans and projections" pathway. We include the median pathway used to calculate the production gap, as well as the four IPCC SR1.5 illustrative pathways (termed P1, P2, P3, and P4) and the IEA NZE pathway.

IPCC chose the four illustrative pathways to demonstrate "the spectrum of CO_2 emissions reduction patterns consistent with 1.5°C", which range from very rapid decreases, facilitated by efficiency and demand-side measures, to relatively slower reductions that lead to a temperature overshoot and necessitate large carbon dioxide removal (CDR) deployment later in the century (Rogelj et al., 2018, p. 99).[13] CDR refers to various approaches to removing carbon dioxide from the air, including afforestation, reforestation, BECCS, direct air capture (DAC), enhanced weathering of minerals, and ocean fertilization (Minx et al., 2018). The two CDR methods most often included in the IPCC SR1.5 scenarios are BECCS and afforestation (Rogelj et al., 2018).

Figure 2.5 shows how four key model variables that could substantially affect the size of the production gap differ among the P1–P4 and NZE scenarios. These are: (a) CO_2 emissions from fossil fuel burning that can be captured and stored (fossil CCS); (b) CO_2 emissions that can be captured and stored from bioenergy use from biomass (BECCS); (c) CO_2 emissions from agriculture, forestry, and other land use (AFOLU); and (d) methane emissions.[14]

The P1 pathway warrants special mention. This pathway was designed to reflect a mitigation approach that relies much more on reducing energy demand and electrifying end uses than on deploying CDR technologies (Grubler et al., 2018). As shown in Figure 2.4, the P1 scenario relies on lower levels of fossil fuels as a source of primary energy than either the *Production Gap Report* (PGR) median or any of the other pathways. Relatedly, as shown in the Figure 2.5 panels (a) and (b), the P1 scenario uses no CCS, either with fossil fuels or biomass, while relying on similar amounts of forest carbon sequestration as our PGR median pathway (panel c).

Accordingly, this P1 pathway illustrates a key finding of this sensitivity exercise: the less CDR and CCS that can be deployed at scale in future years, the faster that fossil fuel supply and demand must decline, and the wider the production gap. Specifically, under the P1 pathway,

[11] We quantify the overall production gap (Figure 2.1) in terms of the amount of CO_2 emissions expected to be released from the combustion of extracted coal, oil, and gas. Because coal is the most carbon-intensive, changes in its individual production gap will have a larger influence on the overall production gap than those in oil or gas.

[12] The mitigation pathways are generated by integrated assessment models that are typically run to achieve a specific temperature outcome while minimizing costs — but not necessarily minimizing other objectives, such as air pollution reduction or the attainment of other sustainable development goals (Rogelj et al., 2018, p. 98).

[13] Briefly, P1 is a sustainability-oriented scenario with "lower energy demand up to 2050 while living standards rise, especially in the global South", and with afforestation as the only CDR option. P2 has "a broad focus on sustainability." P3 is a "middle-of-the-road scenario in which societal as well as technological development follows historical patterns, and there is more of a focus on changing energy production than on reducing demand." P4 is "a resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles", and where most emission reductions are achieved through technology, including CDR (IPCC, 2018a). For more details, see page 16 of IPCC (2018a).

[14] We focus on the variables shown here because, of all those in the IPCC SR1.5 database, these ones vary (on a CO_2-equivalent basis) by 20% or more as compared to the PGR median 1.5°C-consistent values in 2030 or 2040. In other words, besides coal, oil, and gas consumption, these are the most important variables to consider when evaluating how the production gap could be different under different conceptions of the low-carbon transition. The terminology for these four variables in the IPCC SR1.5 database (Huppmann et al., 2018) are Carbon Sequestration|CCS|Fossil (which includes CCS in the industrial sector), Carbon Sequestration|CCS|Biomass, Emissions|CO2|AFOLU, and Emissions|CH4. Methane emissions are converted to CO_2-equivalent units using its 100-year time horizon Global Warming Potential value of 28, following the IPCC Fifth Assessment Report (Myhre et al., 2013, p. 731).

the production gap in 2030 would be 23 instead of 19 $GtCO_2$ — or 21% larger than when using the median 1.5°C-warming scenario, as shown in Figure 2.4.

The opposite is also true: with more CDR and/or CCS assumed to take place, more fossil fuels could be produced and burned in 2030, as the P3, P4, and NZE pathways illustrate. As shown in Figure 2.5a-b, the P3 pathway assumes that much more emissions from fossil fuel burning can be captured and stored (as does the NZE, but to a lesser extent), while the P4 pathway assumes much more BECCS. This higher reliance on CCS and/or BECCS leads to a smaller production gap than that relative to our median pathway. This observation deserves a major caveat, however: the P4 scenario's use of land for both afforestation and biomass (and, by extension, biomass used in CCS) is higher than levels considered to be plausibly sustainable by the IPCC itself (Rogelj et al., 2018). Using this much land (and associated nutrient and chemical inputs) for afforestation and biomass could lead to unsustainable levels of water use and pollution and pose additional sustainability risks for agriculture and food systems and biodiversity (Calvin et al., 2021; Fuss et al., 2014, 2018; Minx et al., 2018; Nemet et al., 2018; Robledo-Abad et al., 2017; Séférian et al., 2018; Smith et al., 2016, 2019). Consequently, we consider the production gap implied by the P4 scenario to also be implausible, at least on the basis of land requirements. In fact, we did not use the P4 scenario in our calculation of the median 1.5°C-warming pathways, as it exceeded the BECCS and AFOLU constraints we imposed to select our scenario set (see Table B.4 in the online Appendix for a list of all scenarios included).

The P2 pathway offers some more nuanced insights about how different forms of emissions abatement can substitute for each other. It shows how, even if CDR technol-

Figure 2.4

Comparison of global 2020–2040 fossil fuel production under the "countries' plans and projections" pathway and six different 1.5°C-warming pathways. As in Figure 2.1, fossil fuel production modelled in energy terms are denominated here in extraction-based CO_2 emissions. The 1.5°C-warming pathways shown include the median and 25th–75th percentile range (shaded) used in this report (i.e. Figure 2.1), plus four "illustrative pathways" from the IPCC SR1.5 (P1-P4) and the IEA's Net Zero by 2050 pathway (NZE). The P4 and NZE pathways are not included in the scenario set used to calculate the median 1.5°C-consistent pathway in this report.

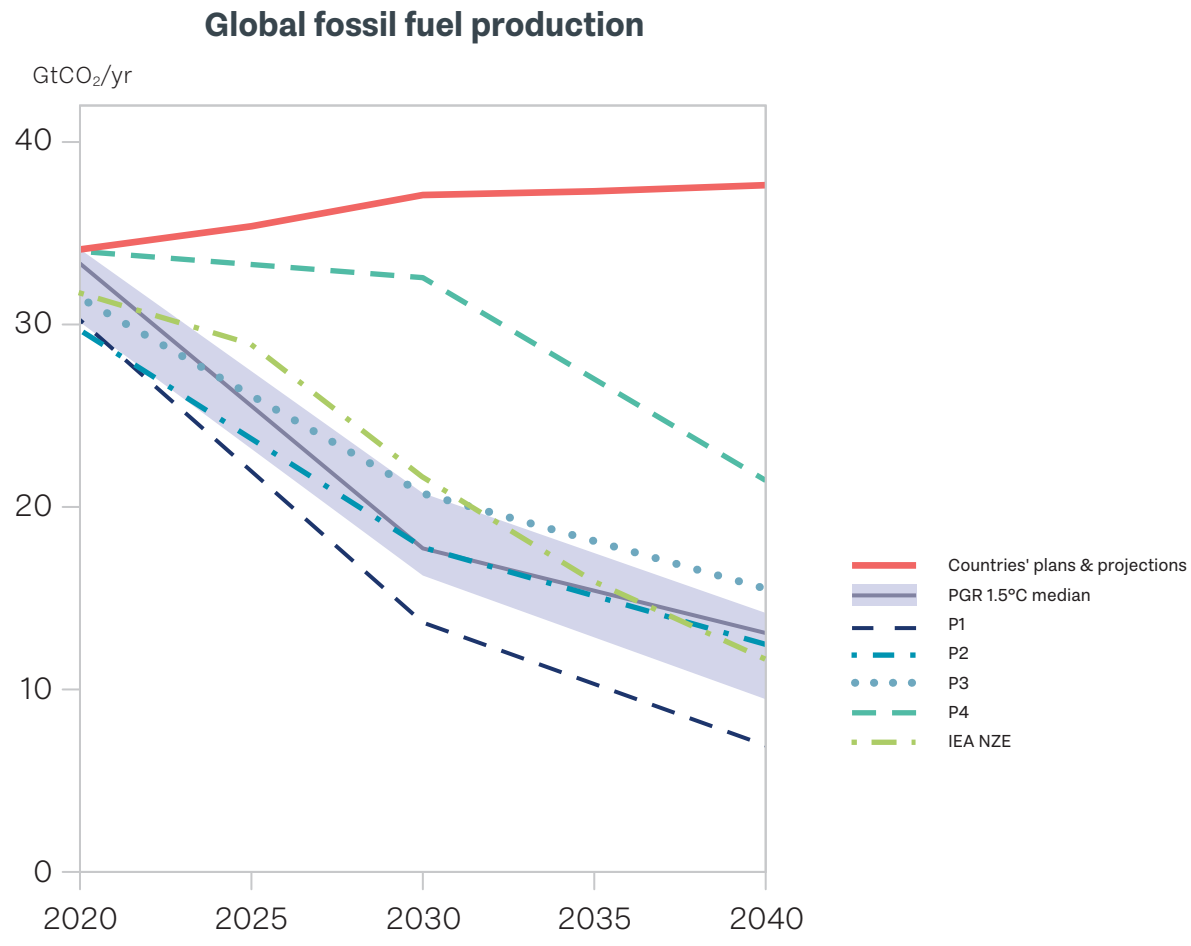
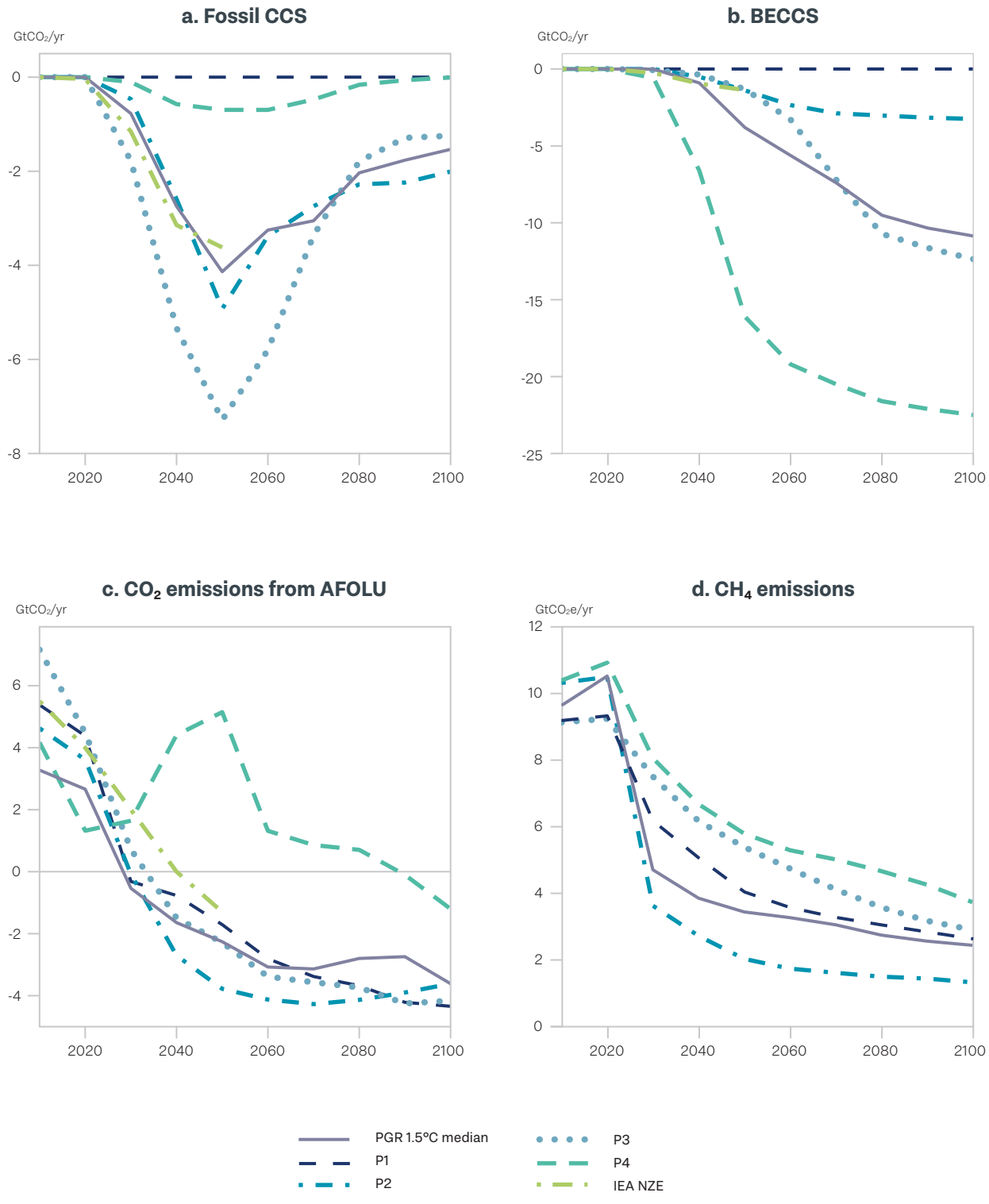


Figure 2.5

Key model variables underlying different 1.5°C-warming pathways, 2010-2100: a) the amount of CO_2 emissions from fossil fuel burning that can be captured and stored, fossil CCS ($GtCO_2$/yr); b) the amount of CO_2 emissions that can be captured and stored through bioenergy from biomass, BECCS ($GtCO_2$/yr); c) CO_2 emissions from agriculture, forestry, and other land use, AFOLU ($GtCO_2$/yr); and d) methane emissions from all sources ($GtCO_2$-equivalent/yr). Negative emission values represent carbon storage or sequestration. The six pathways are as shown in Figure 2.4. (For the NZE pathway, data for the model variables are only available to 2050; total methane emissions are not provided, so NZE is omitted from panel d).



ogies develop more slowly than in the median scenario, other forms of mitigation could achieve a similar level of emissions reduction. Specifically, while the P2 pathway relies on less BECCS than the PGR median pathway (Figure 2.5b), it relies on greater methane emissions reduction (Figure 2.5d) and carbon sequestration in land (Figure 2.5c). Consequently, the size of the production gap in 2030 relative to the P2 pathway is nearly the same as that relative to the median 1.5°C pathway (Figure 2.4).

These trade-offs between different means of reducing or removing emissions should not be surprising, since climate change is driven largely by cumulative total carbon dioxide emissions (IPCC, 2018b). Thus, different options for reducing or removing emissions can, in some cases, substitute for each other, depending on assumptions about — among other factors — non-CO_2 warming effects, the interpretation of the required timing of the Paris Agreement temperature goals (Schleussner et al., 2019), and the effectiveness and social acceptability of CDR and its associated risks for land, food, water, and biodiversity, as discussed above.

These observations have important implications for the production gap. First, even under implausibly high levels of BECCS in the P4 pathway, there would still be a sizeable production gap, and fossil fuel production would still need to start declining between now and 2030 (Figure 2.4).

Second, CDR technologies may fail to develop at large scale due to technical and economic viability and/or social constraints (Anderson & Peters, 2016; Fuss et al., 2018; Grant et al., 2021; Smith et al., 2016). Thus, a precautionary approach would demand that fossil fuel production and use decline even more rapidly than in our median 1.5°C-warming pathway (Figure 2.4, P1 scenario). From this perspective, our calculation of the production gap is conservative, since it assumes more than 5 billion tonnes of CDR annually in the latter half of the century, a level at which the "multiple feasibility and sustainability concerns" noted by the IPCC (IPCC, 2018a, p. 19) — such as intense land competition, and water pollution and biodiversity risks — may present themselves (Fuss et al., 2018; Rogelj et al., 2018).

Lastly, relying on other emission-reduction strategies, such as reduction of methane, to compensate for the delayed availability of CDR strategies also poses some risks. As shown in Figure 2.5d, the IPCC 1.5°C-consistent scenarios (P1, P2, P3 and P4) all show steep declines in methane emissions over the next 20 years, including by aggressive measures to minimize methane emissions at fossil fuel production sites (UNEP & CCAC, 2021). However, global methane emissions from human activities have been increasing and are expected to continue to increase under current policies; methane emissions from gas and oil production alone is expected to increase by around 280 million tonnes of carbon dioxide equivalent each year ($MtCO_2e/yr$) (Saunois et al., 2020; UNEP & CCAC, 2021).[15] Ongoing efforts to reduce methane emissions from the extraction and distribution of fossil fuels are essential for slowing the rate of near-term warming (Ocko et al., 2021), and represent one of the most cost-effective, emission-reduction strategies (UNEP & CCAC, 2021). Nevertheless, a focus on reducing methane and other "upstream" emissions, as advocated by some fossil fuel producers and industry partnerships, is not a substitute for the need to wind down fossil fuel production itself in line with the Paris Agreement's goals.

There are also other decarbonization roadmaps for limiting warming to 1.5°C beyond the model scenarios analysed and discussed here. For example, other researchers have explored pathways that do not assume continued growth in gross domestic production and do not rely on CDR technologies (Keyßer & Lenzen, 2021). Others have also pointed out that low-carbon pathways with limited CDR deployment and a faster phase out of fossil fuels will bring additional air pollution reduction and public health co-benefits (Shindell et al., 2018). Among all these models, the peak dates and decline rates in coal, oil, and gas production and use vary, depending on their assumptions. However, they all share one common outcome for meeting the temperature limits of the Paris Agreement: a global, long-term wind down of coal, oil, and gas production and use.

[15] Here we convert an increase of 10 $MtCH_4/yr$ in UNEP & CCAC (2021) to $MtCO_2e/yr$ using its 100-year time horizon Global Warming Potential value of 28, following the IPCC Fifth Assessment Report (Myhre et al., 2013, p. 731).

2.4 Conclusions

Our assessment of the most recent government plans and projections for fossil fuel production reveals that the world's governments plan on producing around 110% more fossil fuels in 2030 than would be consistent with the median 1.5°C-warming pathway, and 45% more fossil fuels than would be consistent with the median 2°C-warming pathway. The production gap has remained largely unchanged since our 2019 analysis. The gap remains proportionally largest for coal, even as governments plan small production decreases in aggregate. Meanwhile, governments plan to increase oil and gas production until at least 2040, leading to large production gaps for these fuels as well.

As shown in this chapter's analysis of modelled scenarios assembled by the IPCC, global coal, oil, and gas production (and consumption) have to start declining immediately to be consistent with limiting warming to 1.5°C. Global coal and oil also have to decline immediately to be consistent with a 2°C limit, while gas production must decline no later than 2030. However, current government plans and outlooks for fossil fuel production would take the world in the opposite direction, creating an ever-widening production gap that is vastly inconsistent with the Paris Agreement's goals.

This disconnect could be even worse than our analysis implies. As explored in this chapter, our estimate of the size of the production gap partly depends on model assumptions and conceptions of how the energy sector can be decarbonized, such as how much carbon dioxide emissions can be captured and stored or sequestered, or how much methane emissions can be reduced in the near term. If CDR technologies fail to develop at large scale, a precautionary approach would demand that fossil fuel production and use decline even more rapidly than in our median 1.5°C- and 2°C-consistent pathways. Similarly, relying on other near-term, emission-reduction strategies to compensate for the delayed availability of CDR technologies, such as minimizing methane emissions from fossil fuel extraction and distribution, is not a substitute for a sustained wind-down in fossil fuel production and use.



3

Government support and policies for fossil fuel production

Key Messages

Governments continue to commit more funds to fossil fuels than to clean energy through their COVID-19 recovery plans.

Since the adoption of the Paris Agreement, public finance institutions have spent at least USD 294 billion supporting fossil fuels overseas.

Major multilateral development banks (MDBs) and G20 countries have significantly decreased new international public finance for production since 2017. MDBs and G20 development finance institutions (DFIs) holding a total of over USD 2 trillion in assets have adopted policies that exclude fossil fuel production activities from future finance.

Governments have an opportunity to reduce production through their leverage in state-owned companies, which control 50% of global oil and gas production and 55% of global coal production. However, current trends instead show an increase in government support for fossil fuel production and infrastructure.

Seven of the 15 major fossil-fuel producing countries analysed in this report have made net-zero emissions pledges. At the same time, most still plan on increasing their oil and gas production until at least 2030, in contradiction with the global production declines needed to limit warming to 1.5°C or 2°C.

3. Government support and policies for fossil fuel production

Governments have injected trillions of US dollars into the economy to respond to the consequences of the COVID-19 pandemic. Many governments have committed to using some of these funds to "build back better," including through public investment in low-carbon development, high-quality clean energy jobs, and a just transition for all. However, the policies, investments, and measures adopted so far have yet to match up with this "build back better" commitment.

Since the start of the pandemic, many governments have added to their long-standing support for domestic and overseas fossil fuel production through tax breaks, direct government spending, public finance, and support for state-owned enterprises (SOEs) (Geddes et al., 2020; Sanchez et al., 2021). This increase in support stands in contrast with the declines in production necessary to meet the Paris Agreement's goals as shown in Chapter 2, as well as with the International Energy Agency's recent report that found that "there is no need for investment in new fossil fuel supply" in a scenario that limits warming to 1.5°C (IEA, 2021b, p. 21).

This chapter reviews both the way in which the COVID-19 pandemic has influenced new public support for fossil fuels and the mixed trends in government institutions' efforts to shift public support away from fossil fuel production.



3.1 Plans, targets, and projections

Governments are key entities in driving future fossil fuel production. Not only do SOEs control more than half of global fossil fuel production (Beaton & Roberts, 2019; Nelson et al., 2014; NRGI, 2021), but governments also influence the decision-making of private fossil fuel companies and investors, including through their plans, targets, and projections for fossil fuel production. The future trajectory of fossil fuels is also being shaped by the unprecedented levels of COVID-19-related investment that many governments are injecting to boost their economies. The IEA and International Monetary Fund (IMF) now both project strong rebounds in oil demand and supply in coming years (IMF, 2021; IEA, 2021a).

At the same time, a growing number of countries have announced targets to achieve net-zero emissions by mid-century. As of July 2021, 53 countries and the European Union, representing more than two thirds of global GHG emissions and 93% of global GDP, have pledged net-zero emissions targets (Climate Watch, 2021; Energy & Climate Intelligence Unit, 2021).[16] Seven of the 15 major fossil fuel producers profiled in Chapter 4 have adopted such commitments. Meeting these targets will require declines in fossil fuel production alongside reductions in consumption. Yet, as illustrated in Figure 3.1, and described in more detail in Chapter 4, most producer countries with net-zero targets still plan on increasing their oil and gas production, as do most who lack such targets. Indonesia, Norway, and the UK do project declines in the long term. But such trends are primarily a reflection of natural resource depletion (as producing fields become exhausted), rather than the result of intentionally aligning production with a decarbonized future. All major coal-producing countries with net-zero targets also project some declines in coal production; however, among those without them, some — notably India and Russia — are still projecting significant production increases this decade.

Many countries continue to view expanding fossil fuel production as a key lever for their national development, energy security, and sovereignty (Harrison & Bang, 2021;

[16] Government net-zero targets differ in terms of standards, scope and methodology and are thus not directly comparable among themselves or to other low-emission targets (Hale et al., 2021).

Figure 3.1

Net-zero commitments and planned/projected fossil fuel production in 15 selected fossil fuel producers.

Country	Status of national net-zero commitment; net-zero target year	Planned/projected[a] change in national fossil fuel production for 2030[b] relative to 2019 (EJ)		
		Coal	Oil	Gas
Australia	No commitment	■	▲ 0.2 EJ	▲ 0.6 EJ
Brazil	Political pledge 2050	●	▲ 5.3 EJ	▲ 1.3 EJ
Canada	In law 2050	▼ 0.5 EJ	▲ 1.4 EJ	▲ 0.3 EJ
China	Political pledge 2060	▼ 9.2 EJ	▲ 0.6 EJ	▲ 3.8 EJ
Germany	In law 2045	▼ 0.6 EJ	●	●
India	No commitment	▲ 6.1 EJ	▲ 0.5 EJ	▲ 0.8 EJ
Indonesia	No commitment	■	▼ 0.7 EJ	▼ 0.2 EJ
Mexico	No commitment	●	▲ 2.4 EJ	▲ 0.5 EJ
Norway	No commitment[c]	●	▲ 0.3 EJ	▼ 0.6 EJ
Russia	No commitment	▲ 3.6 EJ	■	▲ 4.3 EJ
Saudi Arabia	No commitment	●	▲ 7.1 EJ	▲ 4.7 EJ
South Africa	In policy document 2050	No available projections	●	●
United Arab Emirates	No commitment	●	▲ 1.9 EJ	No available projections
United Kingdom	In law 2050	●	▼ 1.2 EJ	▼ 0.7 EJ
United States	In policy document 2050	▼ 4.3 EJ	▲ 5.2 EJ	▲ 3.8 EJ

[a] See Chapter 4 for details and sources of countries' fossil fuel production plans and projections, and online Appendix B for unit standardization.

[b] For India, changes shown are for 2024 relative to 2019 as projections are only available until then.

[c] Norway has committed to a "low-emission society" by 2050 in its 2018 Climate Change Act, with 90-95% emission reduction targets.

Sources: Own analysis; Net Zero Tracker, 2021; WRI Climate Watch Data, nd

▲ Denotes an increase of greater than 5% by 2030, relative to 2019 production in energy terms.

▼ Denotes a decrease of greater than 5% by 2030, relative to 2019 production in energy terms.

■ Denotes change in production by 2030 stays within 5% of 2019 production in energy terms.

● Annual production in 2019 is less than 0.5 EJ.

Strambo & González Espinosa, 2020), even though the risks of relying on production have become increasingly clear — either of stranded assets if decarbonization goals are achieved or of climate damages undermining development if they are not (IPCC, 2021; IEA, 2021b; IPCC, 2014). These views, along with projections and plans to increase fossil fuel production, provide rationales for continued national and international support for fossil fuels — support which is at odds with countries' commitments to achieve the Paris Agreement's goals.

3.2 National support mechanisms

At the national level, governments support fossil fuel production through a variety of financial, regulatory, and administrative mechanisms. In this section, we pay specific attention to financial mechanisms, including fossil fuel subsidies,[17] aid to state-owned coal and oil and gas companies, and public funding commitments approved during the COVID-19 pandemic.

COVID-19 response and economic recovery

The scale and type of COVID-19 economic responses have varied widely across countries. Many wealthier countries have been able to rapidly fund large stimulus efforts, while many low- and middle-income countries are struggling to mobilize support at scale, burdened by high levels of debt and unfavourable conditions in international markets (Kose et al., 2021; O'Callaghan & Murdock, 2021).

Several research efforts are tracking the potential climate, social, and environmental implications of economic measures approved during the COVID-19 pandemic. While they differ in scope, sectoral coverage, and methods, their findings are broadly aligned. The Global Recovery Observatory found that as of August 2021, only 23% (USD 530 billion) of announced economic recovery spending (USD 2.35 trillion) was "green spending" (Global Recovery Observatory, 2021). Another assessment found that, as of July 2021, stimulus measures in 20 of 30 countries analysed are likely to have a net negative environmental impact (Vivid Economics & Finance for Biodiversity Initiative, 2021). Focusing on energy-intensive sectors, the Energy Policy Tracker found that since January 2020, G20 countries have directed 45% (USD 297 billion) of new public money commitments towards fossil-fuel-consuming and -producing activities[18] (Energy Policy Tracker, 2021).



In late 2020, countries' proportion of expenditure toward "green" policies increased, though governments continue to commit more COVID-19 funds to fossil fuels than to clean energy (Dufour et al., 2021; Green Recovery Tracker, 2021; SEI et al., 2020; Vivid Economics & Finance for Biodiversity Initiative, 2021). This is shown in Figure 3.2.

As part of their COVID-19 responses, governments have provided support to the production of fossil fuels through new tax incentives, guarantees, regulatory changes, and other financial support, largely without accompanying social, economic, or environmental requirements (Energy Policy Tracker, 2021). Between January 2020 and June 2021, 31 countries added over USD 55 billion in support to production of fossil fuels (Energy Policy Tracker, 2021). This may be an underestimate, given the lack of data and transparency in many countries.

These types of commitments may have long-lasting impacts by locking in fossil-fuel-intensive energy systems with equipment lifetimes of 10–50 years (Erickson et al., 2015). Such commitments have included, for example, a special COVID-19 tax in Argentina, used to raise an estimated USD 479 million for new gas production (Government of Argentina, 2021; Boletin Oficial, 2020), and Canada's creation of the Oil and Gas Industry Recovery Assistance Fund, which has allocated USD 241 million (CAD 320 million) to activities such as facility maintenance and

[17] According to the World Trade Organization's definition (Agreement on Subsidies and Countervailing Measures (ASCM) Article 1.1), fossil fuel subsidies include direct transfer of government funds; tax expenditure, other revenue foregone, and underpricing of goods and services; induced transfers (price support); and transfer of risk to government. Such measures typically confer benefits to a specific industry or group of industries (ASCM Article 2) (Marrakesh Agreement 1994). Governments also provide types of support to the fossil fuel industry that go beyond fossil fuel subsidies.

[18] Data as of August 2021. G20 countries directed far less public money to clean energy (35%, or USD 229 billion) and other types of energy (20%, or USD 134 billion). Policies supporting "other types of energy" include policies not labelled as clean energy or fossil fuels, and policies that support multiple energy types, such as intertwined fossil fuels and clean energy. The Energy Policy Tracker figures do not include COVID-related wage support that was accessed by fossil fuel companies, but not targeted specifically to the industry. See www.energypolicytracker.org for further details.

upgrades for the Newfoundland and Labrador offshore energy sector (Department of Finance Canada, 2020). This latter measure was part of a larger federal stimulus package, which also included USD 1.3 billion (CAD 1.7 billion) to fund the closure and reclamation of orphan and inactive wells in Western Canada, as well as USD 559 million (CAD 750 million) to reduce emissions in Canada's oil and gas sector, with a focus on methane.

Fossil fuel subsidies

A large number of fossil fuel production and consumption subsidies predate the COVID-19 pandemic. In 2019, fossil fuel subsides totalled approximately USD 468 billion (OECD, 2021). While lower fossil fuel prices have driven a recent decline in fossil fuel consumer subsidies,[19] fossil fuel producer subsidies have been on the rise (OECD, 2021).

In 2019, subsidies supporting the production of fossil fuels increased by 30% compared to 2018 levels, reaching a total of USD 53 billion, according to the data collected on 50 OECD members, non-OECD G20 members, and economies in the European Union's Eastern Partnership (OECD, 2021).[20] The surge in production subsidies among OECD countries was driven by attempts to alleviate corporate debt and promote investment in fossil fuel infrastructure — trends that the COVID-19 pandemic exacerbated in 2020 (OECD, 2021). The increase was particularly prominent in North America, due in part to Mexican government efforts to shore up its heavily indebted state-owned oil company, Pemex, and to automatic increases in long-standing US subsidies as oil prices declined and production increased (OECD, 2021).

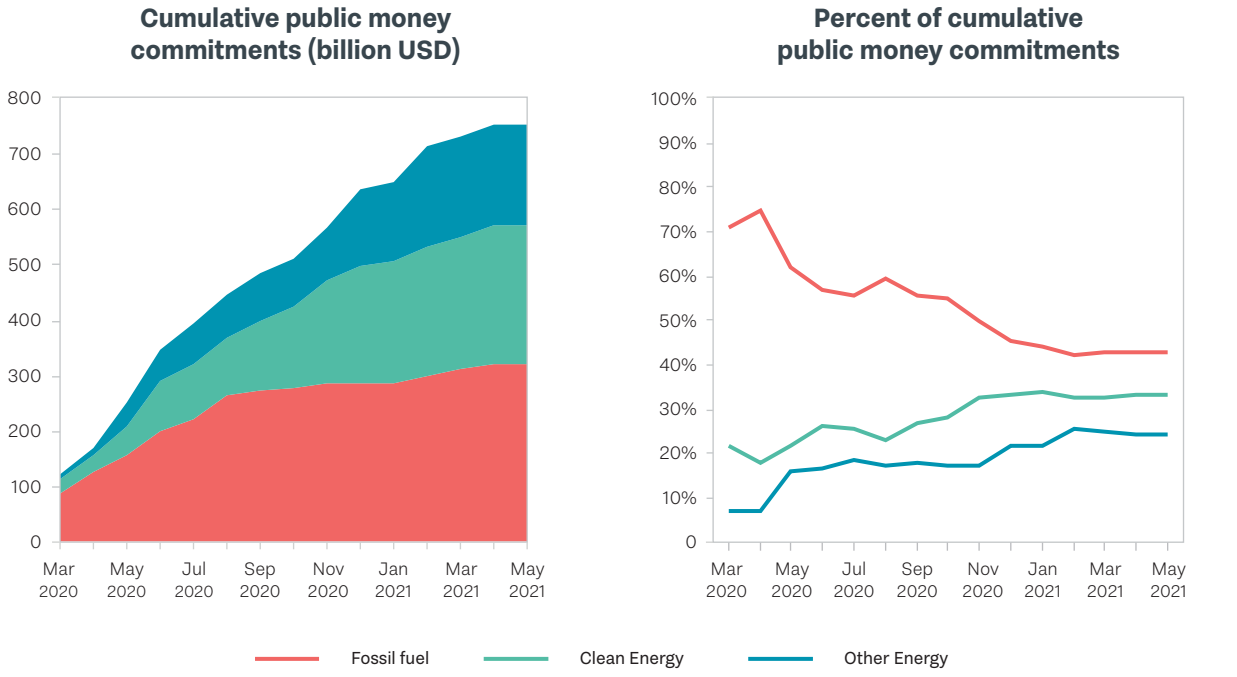
This trend is at odds with the commitment made by G20 countries in 2009 to "rationalise and phase out over the medium term inefficient fossil fuel subsidies that encourage wasteful consumption, while providing targeted support for the poor" (G20, 2009), and the reaffirmed G7 commitment to "eliminating inefficient fossil fuel subsidies by 2025" (G7, 2021). The lack of progress in reforming fossil fuel subsidies is a lost opportunity, as such reforms could free up scarce public resources to build back better from the pandemic (IISD, 2021).

State-owned coal and oil and gas companies

Support channelled into fossil fuel production and infra-

Figure 3.2

Cumulative public money for energy producing and consuming activities approved in 31 major economies during the COVID-19 pandemic (2020-2021). Source: Energy Policy Tracker www.energypolicytracker.org



[19] Most consumption subsidies cover the gap between domestically regulated prices and the international price benchmark: the smaller the gap, the lower the subsidy. Therefore, as oil prices declined in 2020, the value of consumption subsidies shrank accordingly.

[20] If we consider only the 44 OECD advanced and emerging economies, the increase in production subsidies between 2018 and 2019 would be equal to 38% (instead of 30%) and the overall increase in consumption and production subsidies would be 10% (instead of 5%) (OECD, 2020a). A larger share of the increase was driven by OECD members and emerging economies.

structure through state-owned enterprises (SOEs) — specifically, national oil, gas, and coal companies — also plays a prominent role in the evolution of the production gap. National oil and gas companies (NOCs)[21] are responsible for more than 50% of global oil and gas production, and national coal companies control around 55% of global coal production.[22] NOCs account for 40% of total investment in oil and gas worldwide, making them one of the largest vehicles steering public revenues toward fossil fuel production (Manley & Heller, 2021).

Governments have traditionally justified investments by NOCs and national coal companies by pointing to the central role fossil fuel extraction has played in government revenue, jobs, and energy security (Mahdavi, 2020; Victor et al., 2011). However, the risks of investing in fossil fuel extraction are rising amid the global energy transition. An increasing number of public finance institutions, investors, and insurance companies are reluctant to finance upstream fossil fuels (see Section 3.3). Meanwhile, NOCs are expected to invest almost USD 2 trillion over the next decade,[23] predominantly on projects that may break even only if global oil and gas consumption exceeds the carbon budget compatible with limiting global temperature rise to 1.5°C or well below 2°C (Manley & Heller, 2021).

Moreover, NOCs tend to react to price changes more slowly than private companies when it comes to oil and gas investments, because their public ownership serves as a buffer from the effects of markets. When their revenues fall, NOCs cut governments' dividends and taxes faster than the capital they invest back into the oil sector.[24] This not only results in governments having fewer funds for public services — including diversification — it also allows NOCs to sustain spending longer on new exploration and production. As oil prices fell between 2014 and 2016, for example, NOCs' share of global upstream oil and gas investment increased from 36% to 44% (IEA, 2018), indicating that NOCs' spending cuts were less than those of international oil companies. This suggests that NOCs may sustain production even if private companies turn away from some of their new fossil fuel investments (Adams-Heard et al., 2021; Cahill, 2021; Eschenbacher & Jessop, 2020). This tendency does not bode well for the resilience of NOC-dependent countries under a global energy transition, where long-term global oil demand and prices fall. In addition to making demand-side policy less effective by dampening market signals, it risks both greater stranding of assets and fewer resources to prepare workers and economies for the transition.

Presently, NOCs show the least comprehensive plans to shift to a low-carbon economy compared to other types of companies (World Benchmarking Alliance, 2021). This trend suggests that the barriers outweigh the opportunities for state-owned oil and coal companies to transition away from fossil fuels production (Box 3.1), slowing down changes in a sector whose investments and support contribute significantly to the production gap.

3.3 Multilateral and bilateral finance

International finance plays a significant role in supporting fossil fuel production. We focus here on international public support provided by governments through bilateral export credit agencies (ECAs), development finance institutions (DFIs), and multilateral development banks (MDBs). This finance — in the form of loans, grants, equity, insurance, and guarantees — is often provided at prefer-



[21] NOCs and national coal companies are defined as companies fully or majority-owned by a national government.

[22] Authors' calculation using data from Rystad Energy UCube. See Manley and Heller (2021). SOEs dominate oil and gas production in almost all major Gulf producers, as well as in China and Latin American countries, including Brazil and Mexico (NRGI, 2021). SOEs account for almost all of the coal production in China, 90% in India, and smaller shares in Indonesia and Poland (IEA, 2019, p. 242). These countries respectively account for 47%, 9%, 5% and 1% of global coal production (BP, 2020).

[23] This is according to Rystad Energy's baseline scenario, cited in Manley and Heller (2021).

[24] The Natural Resource Governance Institute's National Oil Company Database, which uses published financial reports by NOCs, shows that between 2011 and 2019, on average, a 10% year-on-year change in company revenue (e.g. due to a change in oil prices) was associated with a 3.3% change in capital expenditure, and a 6.5% change in transfers to government (NRGI, 2021). For a description of the methodology for calculation, see Heller and Mihalyi (2019, pp. 40–51, 66–67).

Box 3.1 Opportunities and barriers for transitioning state-owned enterprises away from fossil fuel production

Opportunities: SOEs generally have lower financing costs than privately owned companies, and access to grants and other forms of government support, all of which can help in a transition (Prag et al., 2018). Some NOCs — such as those based in China and Colombia — have explicit social missions that could provide the framework to ensure social policies are integrated into any business plans as part of a just transition (Bridle et al., 2017). Governments also can direct SOEs to reduce production. This occurred in 2020, when OPEC+ countries required NOCs to meet agreed production cuts (OPEC, 2020). In that case, the national interest was economic, not climate mitigation, with OPEC+ aiming to increase prices and reduce oversupply; however, a government that committed to wind down production to achieve climate goals could use its NOC as a lever to do so.

Barriers: The entrenched interests of NOCs and national coal companies, especially in countries that are highly dependent on revenues from fossil fuels, can prevent many of these companies from reducing production (Alsharif et al., 2017; Muttitt & Kartha, 2020; Stevens et al., 2015). They are less subject to short-term competition and market pressures than private companies, meaning they also tend to be less commercially efficient and organizationally nimble (Eller et al., 2011; Phi et al., 2019; Wolf & Pollitt, 2008); this can make it harder to pivot to new lines of business. Most NOCs have an explicit legal mandate to extract fossil fuels and manage the large revenues they generate as their main or sole objective — an additional obstacle that stands in opposition to the goals of a low-carbon transition.

ential below-market rates and has a significant impact on what projects get implemented by leveraging substantial additional commercial investment; international private finance has provided trillions of US dollars to fossil fuels since the adoption of the Paris Agreement (Rainforest Action Network et al., 2021). Public finance institutions (PFIs) also shape the energy landscape by signalling government priorities, providing political cover and pre-investment support (OECD, 2017; Tucker et al., 2020).

Scale of finance

Governments have committed to making finance flows "consistent with a pathway towards low GHG emissions and climate-resilient development" (Paris Agreement, 2015 Art. 2.1(c)). Since the adoption of the Paris Agreement, however, international PFIs have continued to support fossil fuels significantly, totalling USD 294 billion since 2016. From 2017 to 2019, international public finance for fossil fuels from major MDBs[25] and G20 countries averaged USD 62 billion a year, including USD 28 billion for fossil fuel extraction, distribution, and processing (OCI, 2021).

As shown in Figure 3.3, international public finance for fossil fuel extraction from major MDBs and G20 countries has decreased significantly since 2017, which may reflect the increasing number of commitments to exclude, or limit, future investments in fossil fuels, referred to here as "exclusion policies" and discussed below. However, since some historically significant funders of fossil fuel extraction have not excluded upstream finance, this trend could ultimately be reversed.

For coal, international public finance from the G20 countries and major MDBs[26] totalled USD 14 billion each year from 2014 through 2017; this dropped to an average of USD 8 billion per year in 2018 and 2019. International coal finance should continue to fall, following the G7 commitment to end "new direct government support for unabated international thermal coal power generation by the end of 2021" and China's commitment to not build new coal-fired power plants abroad (G7, 2021; Xi, 2021).[27] Oil finance, however, stayed relatively stable over the 2014–2019 period, and gas finance has continued to grow.

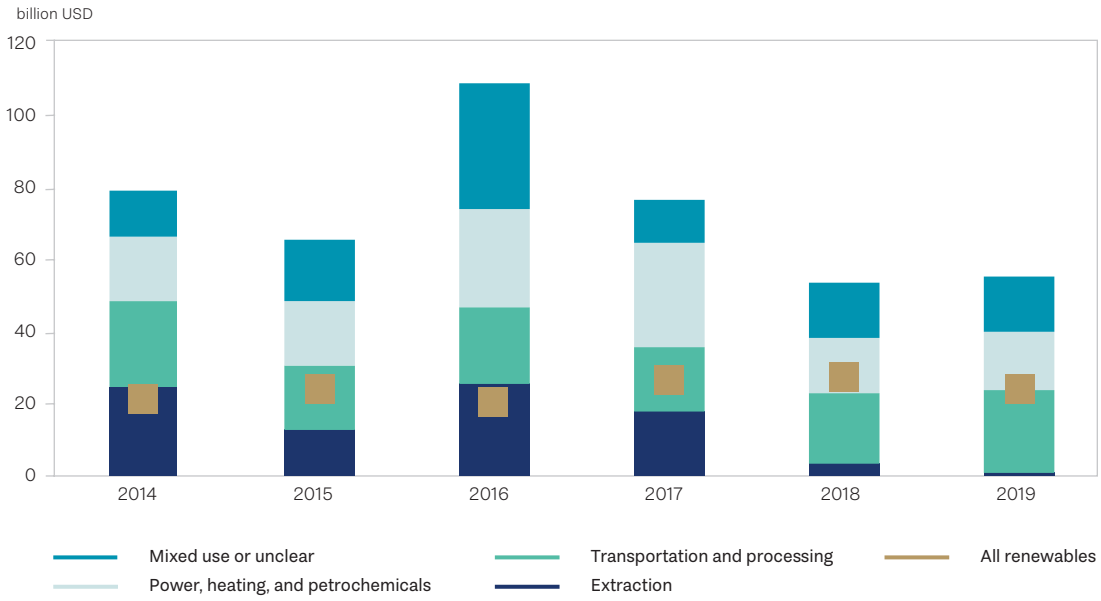
[25] Including the African Development Bank (AfDB), the Asian Development Bank (ADB), the Asian Infrastructure Investment Bank (AIIB), the EU Bank for Reconstruction and Development (EBRD), the European Investment Bank (EIB), the Inter-American Development Bank (IDB), the Islamic Development Bank (IsDB), the New Development Bank (NDB) and the World Bank Group (WBG).

[26] See Footnote 25.

[27] At the Climate and Energy Ministerial meeting in July 2021, the G20 Presidency also stated that "the large majority of [G20] members acknowledged that unabated coal power plants and their international public funding are incompatible with the transition to net-zero emissions" (G20 Presidency, 2021).

Figure 3.3

International public finance for fossil fuels and renewable energy reported by major MDBs and G20 trade and development finance institutions, 2014-2019. Source: Oil Change International (2021). Shift the Subsidies Database. http://priceofoil.org/shift-the-subsidies/



Note: Public finance to "renewables" includes investments in energy efficiency and renewable energy coming from naturally replenished resources such as sunlight, wind, small hydropower, rain, tides, green hydrogen, and geothermal heat.

Gas received more international public finance than any other source of energy from 2017 to 2019, averaging USD 16 billion each year (Muttitt et al., 2021). Levels of international public finance may be underestimated, given the lack of transparency in reporting and the increasing levels of public finance flowing through financial intermediaries (Fuchs et al., 2021; Larsen et al., 2018).

Preliminary data for 2020 suggest an overall drop in multilateral and bilateral finance for energy across all categories, following the outbreak of the COVID-19 pandemic and an outsized drop in finance for oil and gas in particular (OCI, 2021). It remains unclear whether this is representative of future trends, given the growing perception of climate risks by PFIs, or a temporary effect due to the drop in demand during the pandemic (McMonigle et al., 2020).

Fossil fuel exclusion policies

Meanwhile, a growing number of PFIs have made commitments to limit or exclude fossil fuels from their future investments and align with the Paris Agreement goals (Bhattacharya et al., 2019; Larsen et al., 2018; Finance in Common Summit, 2020; IDFC & MDBs, 2017). At the time of writing, the European Investment Bank is the only MDB to formally exclude *all* "unabated" energy fossil fuel projects (EIB, 2019, p. 4). Most other institutions with exclusion policies have limited them to fossil fuel production.

Major MDBs and DFIs from G20 countries control more than USD 6.1 trillion in public assets, and thus have a major influence on public and private investment decisions in the countries they support. MDBs and DFIs representing thirty four percent of these assets have adopted official policies limiting or excluding future financing for coal, oil, and gas production. If we also consider publicly announced policies, this proportion increases to 38% for oil and gas, and 54% for coal (see Figure 3.4). However, for some G20 DFIs and MDBs, debates on these policies are still in the early stages, or non-existent (Erzini et al., 2020; Khinmaung-Moore et al., 2020; Muttitt et al., 2021).

The majority of the world's ECAs have yet to formally exclude or limit future fossil fuel production investments (Shishlov et al., 2021; Tucker et al., 2020). A full exclusion policy on coal, oil, and gas has only been reported for the UK, which in 2021 excluded all fossil fuel production from its export credit support (UK BEIS, 2021). Other countries, like France and Sweden, are tightening their restrictions on upstream oil and gas (EKN, 2020; French Ministry for the Economy and Finance, 2020), and in 2021,

Figure 3.4

Exclusion policies for coal mining & processing and upstream oil and gas in major MDBs and G20 development finance institutions (DFIs), by asset size.



Notes: Upstream activities include all the steps involved from the preliminary exploration through the extraction of the resource. They do not cover power generation and transportation. Exclusion policies usually apply only to future investments, current assets are displayed as indicative information.

Sources: Authors own calculations using (Xu et al., 2020, Korean Development Bank, 2019, Tucker and DeAngelis, 2020, Erzini et al., 2020, E3G, nd), as well as official public finance institutions and governments announcements and updates.

China, the Republic of Korea and the G7 announced they will end financing of overseas coal-fired plants (G7, 2021; Government of Korea, 2021; Xi, 2021). Some legal experts argue that continued financing of fossil fuel production is a breach of international obligations for ECAs (Cook & Viñuales, 2021).

There can also be a perceived disconnect between the stated policies and recent actions of international finance institutions (Ramos et al., 2021). For example, in its most recent annual report, the IMF underscores the need for diversification in economies that depend on fossil fuel exports (IMF, 2020). Yet in some of its country monitoring reports — known as Article IV consultations — the IMF appears to promote expanded fossil fuel production, including for Mongolia, South Sudan, and Bolivia (IMF, 2017a, pp. 8, 54, 2017b, 2019). In another example, UK Export Finance — along with the African Development Bank and ECAs from Italy, Japan, South Africa, Thailand, and the United States — approved support for a multibillion-dollar gas project in Mozambique, just months before the UK exclusion policy was formally approved (TotalEnergies, 2020).

3.4 Conclusions

As Chapter 2 shows, global coal, oil, and gas production need to decline steeply if we are to limit global warming to 1.5°C or 2°C. In contrast, many countries continue to offer significant support to new and increased fossil fuel production — and are even increasing this support when it comes to subsidies and pandemic recovery packages. A significant course correction, including profound changes in technology deployment, policy adoption, and financing, is needed if the world is to get on track with an equitable, low-carbon recovery that is consistent with the Paris Agreement goals. In their efforts to "build back better," governments should shift their support away from fossil fuel production and towards preparing for a managed transition that equitably addresses the needs of people and communities. Some governments and international financial institutions have begun to take encouraging steps in this direction. These efforts need to deepen and more must follow.



4

Fossil fuel production and policies in key countries

Key Messages

This chapter provides an overview of the climate ambitions and fossil fuel production plans, views and policies for 15 key producer countries: Australia, Brazil, Canada, China, Germany, India, Indonesia, Mexico, Norway, Russia, Saudi Arabia, South Africa, the UAE, the UK, and the US.

These countries have announced various emission reduction targets through their nationally determined contributions (NDC) and, in several cases, have set net-zero goals. Few have assessed, at least publicly, whether their projected fossil fuel production is compatible with limiting global warming to 1.5°C or well below 2°C.

Most major oil and gas producers are planning on increasing production out to 2030 or beyond, while several major coal producers are planning on continuing or increasing production.

A few countries are beginning to discuss and enact policies towards a just and equitable transition away from fossil fuel production. However, these efforts have not yet affected the plans and strategies of major producer countries.

4. Fossil fuel production and policies in key countries

This chapter surveys government strategies, support, and plans and projections for fossil fuel production across 15 key countries. As shown in Figure 4.1, the first eight countries — China, the United States, Russia, Saudi Arabia, Indonesia, Australia, India, and Canada — are the largest global producers of fossil fuels in terms of extraction-based CO_2 emissions.[28] The remaining seven countries represent other major producers with readily available data (United Arab Emirates, South Africa, Brazil, and Mexico), as well as those with strongly stated climate ambitions (Norway, the United Kingdom, and Germany). Altogether, these 15 countries accounted for 77% of global, extraction-based CO_2 emissions in 2019.

Each of the 15 profiles in this chapter includes a summary of the country's stated national climate ambitions; available information on government views, projections, and support for fossil fuel production; and emerging policies and discussions towards a managed and equitable wind-down of production. The profiles draw on national energy plans and outlooks published by government and affiliated institutions; on studies by government, research, and intergovernmental institutions; and on other publicly available information.

These countries' plans and projections for domestic fossil fuel production underpin the global gap analysis detailed in Chapter 2. We do not provide an assessment on whether each individual country's projected level of fossil fuel production would be consistent with limiting global warming to 1.5°C or 2°C. This would require making assumptions and establishing principles for how to equitably distribute the remaining global fossil fuel extraction consistent with these temperature limits, taking into account factors including, but not limited to, countries' relative capacity to transition away from fossil fuel production, relative economic dependence on production, relative costs of production, and historical responsibility in terms of past extraction and benefits accrued (Caney, 2016; McGlade & Ekins, 2015; Muttitt & Kartha, 2020; Pye et al., 2020; SEI et al., 2020).

As one starting point for considering how to effectively and equitably align their domestic production with the Paris Agreement's goals, countries could look to *global* decline rates that would be consistent with these goals. As shown in Chapter 2, annual average decline rates of around 11% for coal, 4% for oil, and 3% for gas between



2020 and 2030 would be consistent with limiting warming to 1.5°C, based on the mitigation scenarios compiled by the Intergovernmental Panel on Climate Change (IPCC). In order to ensure a just and equitable wind-down, countries with greater capacity and lower dependency on fossil fuels will likely need to wind down their production faster than the global average. Meanwhile, countries with limited capacity will need financial, technological, and capacity-building support from the international community, as discussed in Chapter 4 of the 2020 Production Gap Report (SEI et al., 2020). Table 4.1 provides some metrics that reflect countries' dependence on, and capacity to transition away from, fossil fuel production.[29]

The countries profiled here have announced various emission reduction targets through their nationally determined contributions (NDCs) and, in several cases, have set net-zero goals (See Figure 3.1). However, this focus on emissions alone ignores their roles and responsibilities

[28] This accounting method allocates CO_2 emissions from fossil fuel combustion to the location of extraction. See online Appendix B for details.

[29] The metrics shown are intended to provide a quick overview and should not be viewed as exhaustive. For a summary of approaches to evaluating the dependence of countries on the extractives industry (including oil and gas), see Hailu and Kipgen (2017). These metrics are also discussed in Chapter 4 of the 2020 Production Gap Report (SEI et al., 2020).

in producing the predominant source of these emissions, fossil fuels. Achieving net-zero emissions globally will require countries to wind down their production of coal, oil, and gas. To date, few producer countries have assessed, at least publicly, whether their projected fossil fuel production is compatible with limiting global warming to 1.5°C or well below 2°C.

In April 2021, the governments of Canada, Norway, Saudi Arabia, and the US – along with Qatar – announced a "Net-Zero Producers Forum" with goals to "form a cooperative forum that will develop pragmatic net-zero emission strategies, including methane abatement, advancing the circular carbon economy approach, development and deployment of clean-energy and carbon capture and storage technologies, diversification from reliance on hydrocarbon revenues, and other measures in line with each country's national circumstances" (U.S. Department of Energy, 2021). Further details have not emerged since this initial announcement, and the Forum has not acknowledged or addressed the need to reduce production itself.

As this chapter illustrates, several major coal producers are planning on continuing or increasing domestic production, while most major oil and gas producers are promoting, investing in, and planning on expanding production. For the few oil and gas producers projecting long-term decreases, this largely reflects natural resource depletion rather than a managed wind-down. A few countries are now beginning to discuss — and in some cases to enact policies towards — a just and equitable transition away from fossil fuel production, but thus far, these efforts have largely been limited to coal (see e.g., Germany) and have yet to affect the plans and strategies of major producer countries.

Figure 4.1

Top 25 countries in terms of extraction-based CO_2 emissions (million tonnes CO_2, or $MtCO_2$) in 2019. The top eight producers account for 70%, and the top 25 producers account for 90%, of the global total. Countries profiled in this chapter are indicated in bold and denoted with an asterisk (Germany ranks 34th and is not shown). Coal, oil, and gas production data are from the IEA (2021); the methodology for estimating extraction-based emissions is provided in online Appendix B.

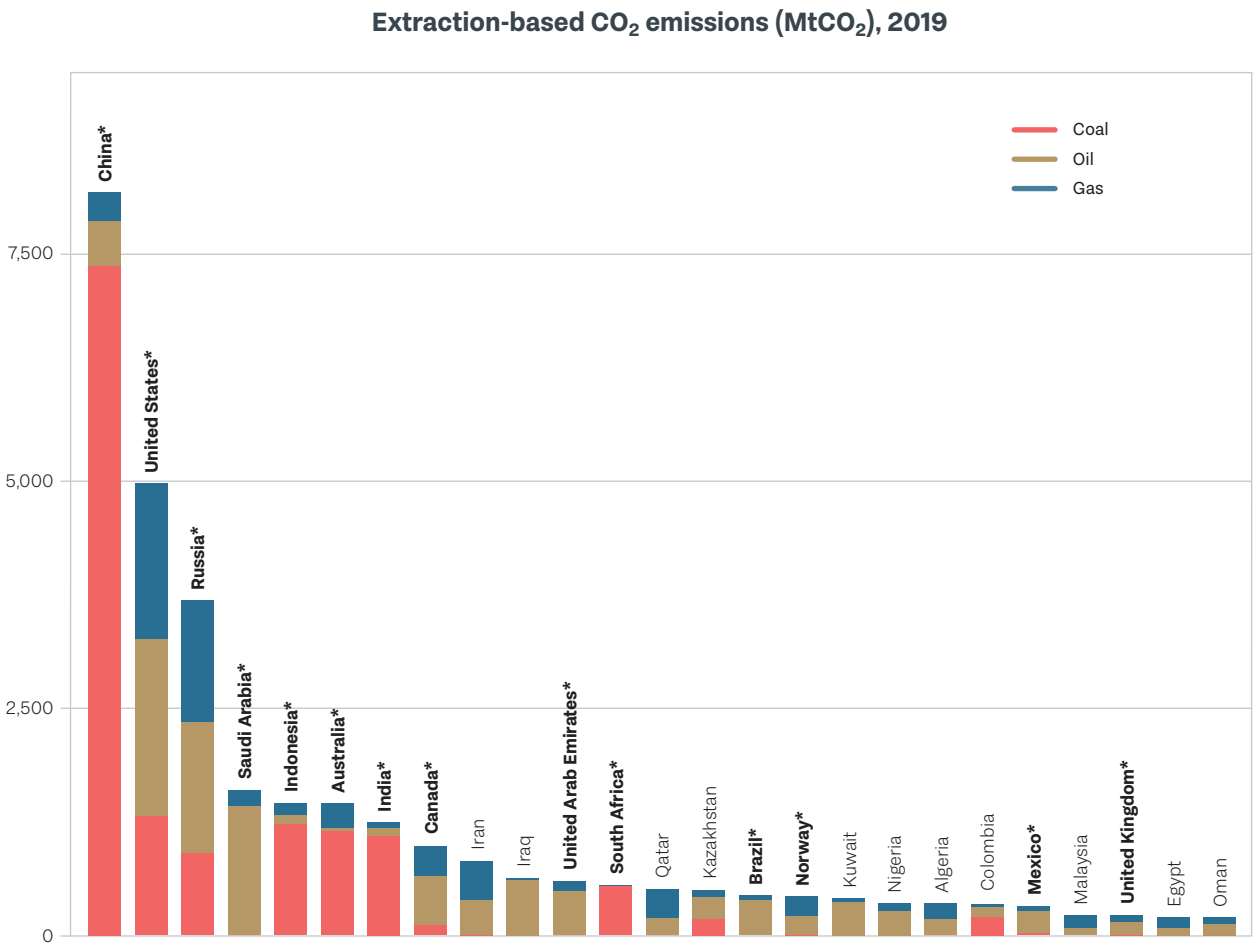


Table 4.1

Fossil fuel producer rankings, transition capacity, and dependence on fossil fuel production for the 15 countries profiled in this chapter (see footnote 29). Countries are listed in order of decreasing 2019 extraction-based CO_2 emissions. Data are shown as reported or estimated from the sources listed; there is no standardized methodological approach and thus estimates may not be fully comparable between countries. A dash (-) indicates that a country's 2019 production of that fuel is zero or below 0.5 exajoules per year (EJ/yr).

Country	Rank and share of global production in 2019 on an energy (EJ) basis (IEA, 2021)			Economic capacity for transition	Dependence on fossil fuel production		
	Coal	Oil	Gas	Income level, 2021 (World Bank, 2021b)	Coal miners per 1,000 workers*	Share of government revenue from oil and gas production	Sources
China	1st (49%)	6th (4%)	6th (4%)	Upper-middle	3.6[a]	<3%[b]	[a] 2020 estimate (CEIC, 2021b, 2021a) [b] 2017 estimate; includes coal, oil, and gas production (Gerasimchuk et al., 2019)
United States	2nd (9%)	1st (17%)	1st (23%)	High	0.3[c]	0.5%[d]	[c] 2020 estimate (U.S. Bureau of Labor Statistics, 2021) [d] 2020 estimate (US DOI, 2021b; U.S. Treasury Data Lab, 2021)
Russia	6th (6%)	2nd (13%)	2nd (18%)	Upper-middle	2.0[e]	39%[f]	[e] 2018 estimate (Grachev, 2018) [f] 2019 estimate (Government of the Russian Federation, 2021a)
Saudi Arabia	–	3rd (12%)	9th (2%)	High	-	64%[g]	[g] 2019 estimate (Saudi Central Bank, 2021)
Indonesia	3rd (8%)	22nd (1%)	13th (2%)	Upper-middle	1.0[h]	3%[i]	[h] 2014 estimate (Directorate General of Mineral and Coal, 2015; World Bank, 2021a) [i] 2020 estimate; oil and gas extraction accounts for 3% of total and 18% of non-tax government revenue (Reuters, 2020)
Australia	4th (8%)	31st (0.4%)	7th (4%)	High	3.3[j]	0.6%[k]	[j] 2015-2019 average (Australian Bureau of Statistics, 2020) [k] 2020 estimate (APPEA, 2020; Parliament of Australia, 2020)
India	5th (7%)	24th (1%)	23rd (1%)	Lower-middle	1.0[l]	1%[m]	[l] 2020 estimate (Aggarwal, 2020) [m] 2019 estimate (Ministry of Finance, 2021)
Canada	11th (1%)	5th (5%)	4th (4%)	High	0.4[n]	1%[o]	[n] 2020 estimate (Statistics Canada, 2021b) [o] 2014-2018 average (Government of Canada, 2020; Statistics Canada, 2021a)
United Arab Emirates	–	7th (4%)	15th (1%)	High	–	41%[p]	[p] 2019 estimate (Arab Monetary Fund, 2020)
South Africa	7th (4%)	–	–	Upper-middle	3.6[q]	–	[q] 2017 estimate (Montmasson-Clair et al., 2019)
Brazil	–	8th (3%)	27th (1%)	Upper-middle	–	7%[r]	[r] 2017 estimate (Deloitte, 2021)
Norway	–	14th (2%)	8th (3%)	High	–	14%[s]	[s] 2021 estimate (Norwegian Petroleum Directorate & Norwegian Ministry of Petroleum and Energy, 2021)
Mexico	–	13th (2%)	26th (1%)	Upper-middle	–	16%[t]	[t] 2020 estimate; likely includes revenues from both production and consumption (Mora-Tellez, 2021)
United Kingdom	–	19th (1%)	19th (1%)	High	–	0.1%[u]	[u] 2019 estimate (HM Revenue & Customs, 2020; Keep, 2020)
Germany	12th (1%)	–	–	High	0.3[v]	–	[v] 2019 estimate (Federal Statistical Office of Germany, 2021)

* This estimate does not include informal or indirect jobs related to the coal mining industry.

China

Announced climate ambitions

In 2020, President Xi Jinping announced China's updated 2030 NDC targets that "aim to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060" (Xi, 2020a, 2020b). As of August 2021, the government had not yet submitted its updated NDC to the UNFCCC.

Government views on fossil fuel production

President Xi recently stated that China will wind down coal consumption during the 15th Five-Year Plan period, and "control the total use of fossil fuels and take action to shift to alternative energy sources," but did not explicitly address production at these meetings (Xi, 2021a; XinhuaNet, 2021). China's heavy reliance on gas imports is driving the country's recent efforts to develop unconventional gas production (OECD, 2021g), and China's first NDC listed expanding gas production and use as one of its strategies for "building [a] low-carbon energy system" (Government of China, 2016).

Plans and projections for domestic fossil fuel production

As of August 2021, the Chinese government had not yet released sector-specific plans of its 14th Five-Year Plan. China's fossil fuel production is dominated by several large state-owned companies (G20 Peer-review Team, 2016). As shown in Figure 4.2, the China National Petroleum Corporation (CNPC)'s 2050 World and China Energy Outlook projects oil and gas production to increase by 5% and 58%, respectively, and coal production to decrease by 8%, between 2020 and 2030 (CNPC Economics & Technology Research Institute, 2020). However, a 2025 production target from the China National Coal Association (CNCA) suggests an increase in coal production through 2025 (CNCA, 2021).

Government support for fossil fuel production

- Provincial governments provided budgetary transfers for coal exploration and extraction totalling CNY 2.6 billion (USD 380 million) in 2019, according to the Organisation for Economic Co-operation and Development (OECD, 2021i).
- The central government provided CNY 8.8 billion (USD 1.3 billion) in budgetary transfers and tax expenditures for oil and gas production in 2019, including per-unit payments to coal-bed methane and shale gas producers (OECD, 2021i).
- In 2020, the central government issued a five-year special fund to support "the clean development and utilization of renewable energy, clean fossil energy, and the clean utilization of fossil energy," targeted at unconventional gas and hydropower development (China Ministry of Finance, 2020; quotations translated from Mandarin Chinese). The starting budget for 2020 is CNY 420 million (USD 61 million); to incentivize unconventional gas production, the level of "reward" will increase from year to year if production increases (China Ministry of Finance, 2020a).
- China does not release official data on its overseas development finance. According to independent estimates, in 2000-2019, the Chinese Development Bank (CDB) and Chinese Export-Import Bank (EXIM) provided a total of at least USD 169 billion in finance to international fossil fuel projects, including USD 70 billion for oil and gas exploration and extraction (Gallagher, 2021). In 2021, China committed to not build new coal-fired power plants abroad (Xi, 2021b).

Policies and discourses towards a managed wind-down of fossil fuel production

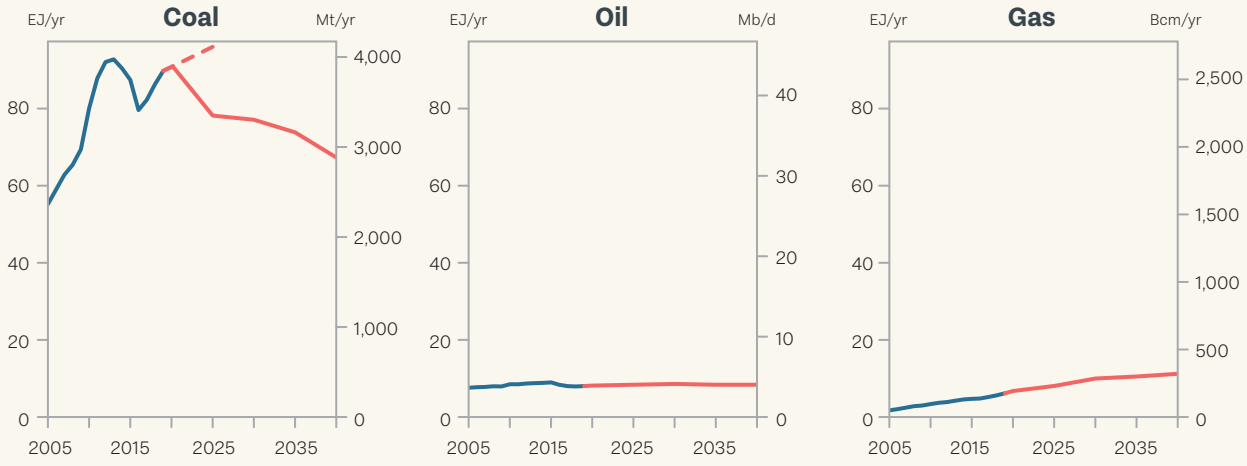
No specific discourses were identified beyond President Xi's announcement that China will reduce its coal consumption between 2026 and 2030; this has implications for production since over 90% of coal use is domestically produced (National Bureau of Statistics of China, 2019).

Policies and discourses supporting a just and equitable transition away from fossil fuel production:

In his speech at the 2021 Leaders Summit on Climate, President Xi mentioned delivering "social equity and justice in the course of green transition" (Xi, 2021a). No other government policies or discourses were identified.

Figure 4.2

Historical and projected coal, oil, and gas production for China. Sources: Projections for all fuels are from the reference scenario from the CNPC's 2050 World and China Energy Outlook (2020 Edition) (CNPC Economics & Technology Research Institute, 2020). For coal, production projections are estimated from consumption projections, assuming imports will account for around 7% of total consumption, the 2016–2020 average. A 2025 coal production target from the CNCA is also shown by the dotted red line (CNCA, 2021). Historical data are from China's National Bureau of Statistics (2019, 2021).



United States

Announced climate ambitions

In 2021, President Biden announced a goal to achieve net-zero emissions by 2050, and a new NDC target to reduce GHG emissions by 50%–52% by 2030, compared to 2005 levels (The White House, 2021b, 2021c).

Government views on fossil fuel production

The US government has long incentivized the expansion of US oil and gas production, including through support for the research and development of fracking technologies and the withdrawal of a four-decade ban on most crude oil exports (National Research Council, 2001; Rusco, 2020; Vietor, 1984; Wang & Krupnick, 2015; Warner & Shapiro, 2013). The government also has largely taken a permissive approach to fossil fuel development and supporting infrastructure, such as pipelines (Brady & Crannell, 2012; Clark, 1987; Vietor, 1984). A notable exception is the Keystone XL pipeline, which it cancelled because the pipeline "would undermine U.S. climate leadership" (The White House, 2021a). The country is now the world's largest producer of oil and gas, and second (in energy terms) in coal (IEA, 2021). In April 2021, the US joined four other countries in establishing the Net-Zero Producers Forum (see chapter introduction).

Plans and projections for domestic fossil fuel production

Projections from the U.S. Energy Information Administration (EIA) show oil and gas production increasing to 17% and 12% above 2019 levels by 2030, respectively, increases that would largely go to exports (US EIA, 2021). EIA projects that coal production will continue its decline, to 30% below 2019 levels in 2030 (US EIA, 2021).

Government support for fossil fuel production

- The federal government provides over a dozen subsidies to coal, oil, and gas production (US Government, 2015), such as the immediate depreciation of many capital expenses, worth USD 4 billion in 2019 (OECD, 2021f).
- Individual US states provide additional subsidies, including through tax exemptions (OECD, 2021f), and by levying charges for well plugging and abandonment that are much too low to cover actual clean-up costs (Achakulwisut et al., 2021; Raimi et al., 2021).
- The US leases public lands and waters for fossil fuel extraction, often at below-market rates (Rusco, 2019). About 40% of all coal (and less than 20% of all oil and gas) has been extracted from federal lands and waters in recent years (Merrill et al., 2018; US EIA, 2015).
- Over time, the US Congress has exempted fossil fuel extraction from numerous federal environmental regulations, such as hazardous waste requirements (Achakulwisut et al., 2021; Brady & Crannell, 2012; Congressional Research Service, 2020; Goldman et al., 2013; Simms, 2017).
- The US government also indirectly supports fossil fuel production through long-standing support to fossil fuel consumption, such as by constructing and expanding the extensive highway system (Dilger, 2015). Support for highways was expanded in the infrastructure legislation that passed Congress in August 2021 along with other indirect measures of support for both fossil and non-fossil energy (Infrastructure Investment and Jobs Act, 2021).

Policies and discourses towards a managed wind-down of fossil fuel production

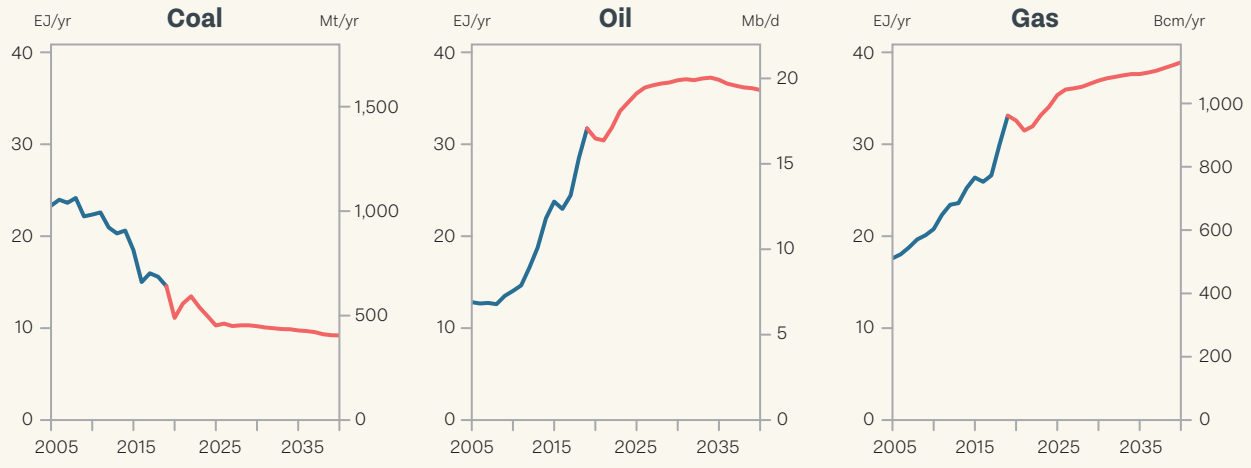
The current administration is considering aligning the leasing of federal lands for fossil fuel extraction with climate goals (US DOI, 2021a, 2021c). The State of California, historically one of the top oil-producing states, is evaluating how to phase out oil extraction across the state by 2045 as part of its climate strategy (Erickson et al., 2018; Office of the Governor, 2021).

Policies and discourses supporting a just and equitable transition away from fossil fuel production

The current administration has created a working group to "revitalize the economies of coal, oil and gas, and power plant communities" as part of decarbonizing the economy (The White House, 2021b). The group's initial recommendations have been on funding infrastructure, mine clean-up, and economic development in coal-mining communities (NETL, 2021).

Figure 4.3

Historical and projected coal, oil, and gas production for the US. Source: Reference scenario from the EIA Annual Energy Outlook 2021 (US EIA, 2021).



Russia

Announced climate ambitions

Russia's 2020 updated NDC reiterated its 2015 NDC goal of reducing net greenhouse gas emissions to 30% below 1990 levels by 2030 (Ministry of Economic Development of the Russian Federation, 2020).

Government views on fossil fuel production

In June 2020, Russia approved its new Energy Strategy to 2035 (Ministry of Energy of the Russian Federation, 2020a). While recognizing shifts in global energy markets, the strategy relies heavily on the production and export of fossil fuels as "stimulating infrastructure" for development and diversification of the Russian economy, particularly for gas and coal.

Plans and projections for domestic fossil fuel production

Under the Russian Energy Strategy's "Optimistic" scenario, gas and coal production increase by 38% and 52%, respectively, from 2018 to 2035, and by 18% and 10%, respectively, under its "Pessimistic" scenario, as shown in Figure 4.4 (Ministry of Energy of the Russian Federation, 2020a). In contrast, the strategy projects relatively flat (Optimistic) or declining (Pessimistic) production for oil.

Government support for fossil fuel production

- Russia is investing heavily in liquefied natural gas (LNG) infrastructure (RUB 11.5 trillion, or USD 158 billion, by 2030), with LNG exports expected to account for most of the growth in gas production over the coming decade (Ministry of Energy of the Russian Federation, 2020a; RBC, 2021). Similarly, Russia is expanding its seaport terminals and other coal export infrastructure, with an eye to increasing coal exports across the Asia-Pacific Region (Ministry of Energy of the Russian Federation, 2020a).
- Tax breaks and budget expenditures for fossil fuel production totalled RUB 713 billion in 2019 (USD 9.8 billion), nearly three times the amount in 2015, with the vast majority associated with exemptions or reductions of extraction taxes for oil and gas development (OECD, 2021d). By one prior estimate, not adjusted for new and removed exemptions, the government could forego RUB 2.3 trillion (USD 32 billion) in revenue by 2033, by under-taxing oil extraction (RBC, 2019).
- In response to the major drop in oil and gas revenues in 2020, the Russian government removed certain tax breaks for the industry, including repealing prior exemptions of some petroleum fields from mineral extraction tax and export duties (Official Portal of Legal Information, 2020b, 2020a). The government also adopted measures to support fossil fuel producers and other "systemically important enterprises", providing for potential state guarantees, deferral and instalment plans for the payment of taxes, and preferential loans (Ministry of Energy of the Russian Federation, 2020b). It granted new exemptions from the mineral extraction tax to promote new oil and gas development in the Arctic regions, as well as LNG production and exports. It also launched a program to subsidize the use of Russian oil and gas equipment, allowing advance payments to be reduced by up to 30% (Government of the Russian Federation, 2020).

Policies and discourses towards a managed wind-down of fossil fuel production

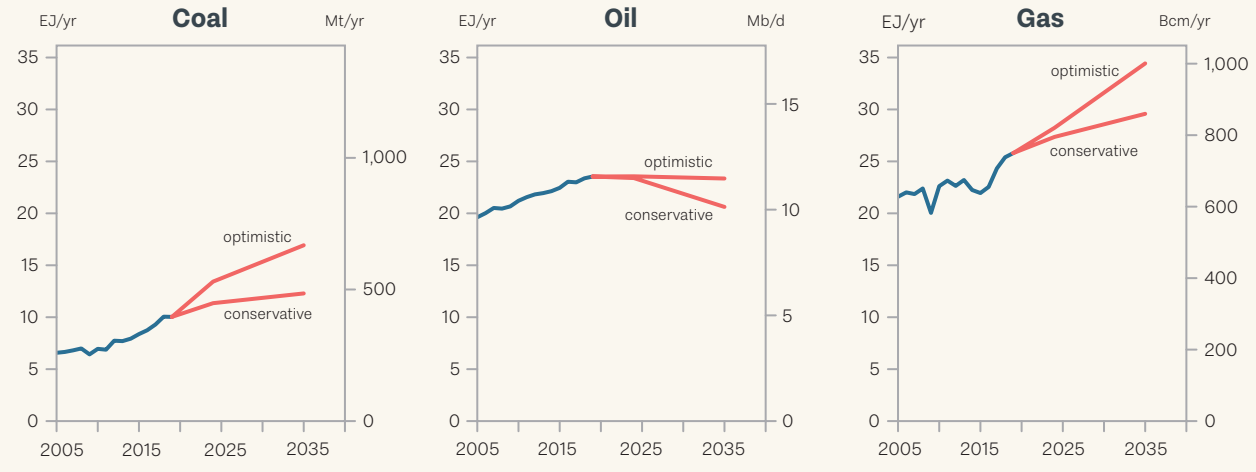
Over the past year, the Russian president has issued a federal decree to reduce GHG emissions (President of the Russian Federation, 2020), the government has drafted a law to limit emissions (Government of the Russian Federation, 2021b), and the Bank of Russia has launched a consultation process to consider climate risks and disclosure (Bank of Russia, 2021). However, there are no publicly available indications that Russian authorities and state-owned energy companies have discussed the need to prepare for a managed wind-down in fossil fuels (Grushevenko et al., 2021; Korppoo et al., 2021)

Policies and discourses supporting a just and equitable transition away from fossil fuel production

No such government policies or discourses were identified.

Figure 4.4

Historical and projected coal, oil, and gas production for Russia. Sources: The 2024 and 2035 projections under two scenarios, "optimistic" and "conservative", are from Russia's Energy Strategy to 2035 (Ministry of Energy of the Russian Federation, 2020a). Historical data are from the IEA (IEA, 2021).



Saudi Arabia

Announced climate ambitions

Saudi Arabia's first NDC, issued in 2015, seeks to reduce emissions by 130 million tonnes of carbon dioxide equivalent ($MtCO_2e$) by 2030 (no baseline indicated), contingent on "an increasingly diversified economy and a robust contribution from oil export revenues" (Kingdom of Saudi Arabia, 2015, p. 1).

Government views on fossil fuel production

Saudi Aramco, the state-owned enterprise responsible for oil and gas exploration and extraction, holds 17% of the world's proven petroleum reserves. It has indicated its intention to remain the "last man standing" among major producers, even under a global transition to low-carbon energy, given that its oil is among the world's cheapest and least GHG-intensive to extract (Blas, 2021; Krane, 2021; McQue, 2021). In April 2021, Saudi Arabia joined four other countries in establishing the Net-Zero Producers Forum (see chapter introduction).

Plans and projections for domestic fossil fuel production

There are few publicly available government documents that reveal planning assumptions or government intentions for future domestic oil and gas production. A notable exception is Saudi Aramco's bond prospectus, first issued in 2019. As illustrated in Figure 4.5, it forecasts that Saudi oil production will increase by 37% from 2020 to 2040 under a scenario where global oil demand levels off by 2035, and by 31% over the same period under a more rapid transition scenario where demand declines by the late 2020s (Saudi Aramco, 2020d). In March 2020, the Saudi Ministry of Energy directed Saudi Aramco to raise maximum production capacity from 12 to 13 million barrels per day, which is expected by 2024 (Kawar, 2021; Saudi Aramco, 2020b). Saudi Aramco also plans to double its natural gas production and export gas for the first time by 2030, with an aim to be one of the world's top three natural gas producers (Saudi Aramco, 2020c). Saudi Arabia has recently approved the world's largest gas development project; the offshore Jafurah shale gas field costs USD 110 billion and will also be used to produce blue hydrogen (with carbon capture and storage) for export (Kimani, 2021; Saudi Aramco, 2020a).

Government support for fossil fuel production

No information is publicly available on tax expenditures or other measures that support fossil fuel production in Saudi Arabia.

Policies and discourses towards a managed wind-down of fossil fuel production

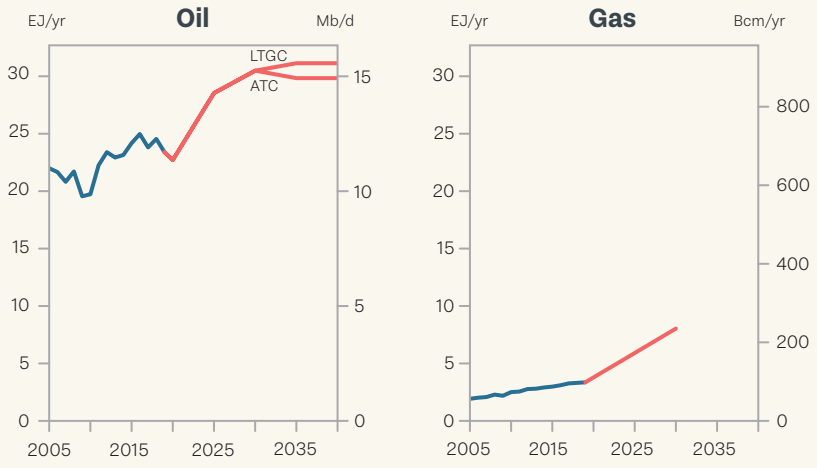
No such government policies or discourses were identified.

Policies and discourses supporting a just and equitable transition away from fossil fuel production

While economic diversification lies at the core of Saudi Arabia's Vision 2030 planning framework (Kingdom of Saudi Arabia, 2021), no government policies or discourses to prepare and support workers and communities for a just transition away from fossil fuels were identified.

Figure 4.5

Historical and projected oil and gas production for Saudi Arabia. Saudi Arabia does not produce coal. Sources: For oil projections, two scenarios — "long term growth case" (LTGC) and "accelerated transition case" (ATC) — are taken from Saudi Aramco's Global Medium Term Note Programme, Base Prospectus (Saudi Aramco, 2020d, p. 87). Gas projections are from Saudi Aramco's 2019 Prospectus (Saudi Aramco, 2020c). Historical data are from the IEA (IEA, 2021).



Indonesia

Announced climate ambitions

Indonesia's NDC, first issued in 2016 and updated in 2021, sets an unconditional emission reduction target of 29% by 2030, against a business-as-usual scenario, and a reduction target of up to 41% conditional on international support (Republic of Indonesia, 2016, 2021). The state-owned electric monopoly utility, Perusahaan Listrik Negara (PLN), has pledged carbon neutrality by 2050 (Rahman, 2021) .

Government views on fossil fuel production

The central government has undergone a paradigm shift from viewing oil and gas as export commodities to seeing them as strategic domestic resources (Braithwaite & Gerasimchuk, 2019).

Plans and projections for domestic fossil fuel production

As shown in Figure 4.6, the most recent government outlook provides short-term projections under various scenarios to account for the effects of the pandemic on Indonesia's energy sector (PPIPE & BPPT, 2020). Longer-term projections from the government's 2019 outlook foresee coal production growing at 1% per year, on average, through 2050, with around three-quarters destined for export (PPIPE & BPPT, 2019). In contrast, the long-term strategy (LTS) that Indonesia recently submitted to the UNFCCC projects coal production to peak around 2025 and decline about 1% annually thereafter in its current policy scenario, and 3% per year in its low-carbon scenario (Indonesian Ministry of Environment and Forestry, 2021). These latter projections, however, have not yet been integrated into national energy outlooks and thus are not depicted in Figure 4.6. According to the government's 2019 outlook, crude oil oil and gas production are projected to decrease by around 5% and 3% per year, respectively, between 2019 and 2040 (PPIPE & BPPT, 2019).

Government support for fossil fuel production

- Indonesia provided subsidies for oil and gas production valued at IDR 4.4 trillion (USD 320 million) in 2019, according to the OECD (OECD, 2021c). These subsidies include special treatment for import duties and taxes, value-added tax, income tax, capital goods and equipment taxes, and land and building taxes (MEMR & MoF, 2019), as well as other fiscal benefits such as investment credit, domestic market obligation (DMO) holidays, and accelerated depreciation (PPIPE & BPPT, 2019).
- The 2020 Job Creation Act provided a royalty exemption to coal producers who expand their businesses into coal derivatives, such as coal gasification as an alternative fuel to liquefied petroleum gas (LPG) (Kementerian Sekretariat Negara, 2020). One study estimates the resulting forgone revenue to be USD 1.1 billion in royalties and USD 1.2 billion in taxes (Peh, 2020).
- In 2020, the government created automatic contract extensions for coal mining areas and relaxed environmental regulations related to spatial planning (Harsono, 2020). For example, the Job Creation Act reduced public engagement during the environmental impact assessment process and eliminated the requirement of an environmental license (Kementerian Sekretariat Negara, 2020).

Policies and discourses towards a managed wind-down of fossil fuel production

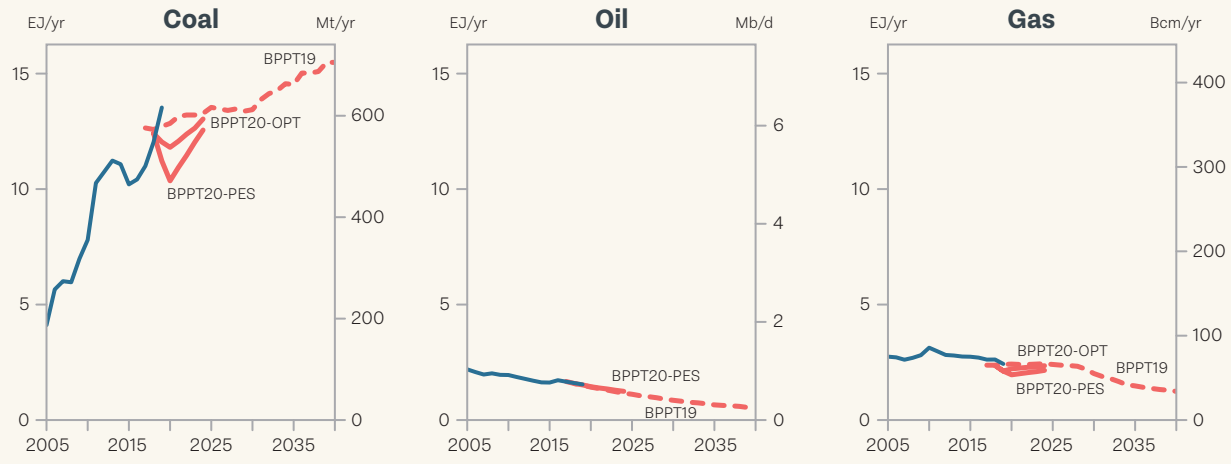
No such government policies or discourses were identified.

Policies and discourses supporting a just and equitable transition away from fossil fuel production

Indonesia's LTS identifies future policies and interventions that are needed to ensure a just transition of the work force, gender equality, intergenerational equity, and the protection of vulnerable people (Indonesian Ministry of Environment and Forestry, 2021).

Figure 4.6

Historical and projected coal, oil, and gas production for Indonesia. Sources: Three projected scenarios are shown from the Agency for the Assessment and Application of Technology (BPPT): BPPT19 shows 2017–2040 projections from BPPT's Indonesia Energy Outlook 2019 (PPIPE & BPPT, 2019); BPPT20-OPT and BPPT20-PES show 2018–2024 projections under the optimistic and pessimistic scenarios, respectively, from BPPT's Indonesia Energy Outlook 2020 (PPIPE & BPPT, 2020). Historical data are from the IEA (IEA, 2021).



Australia

Announced climate ambitions

Australia's first and updated NDCs both set the same emission reduction target of 26%–28% below 2005 levels by 2030 (Government of Australia, 2016, 2020).

Government views on fossil fuel production

The federal government promotes its fossil fuel industry, emphasizing the economic importance of its coal and gas sectors (Minister for Energy and Emissions Reduction, 2020; Prime Minister of Australia, 2021). As shown in Fig 4.7, coal and gas production have grown rapidly since 2010, driven by the major expansion of coal exports and a newly established liquefied natural gas (LNG) export industry. Australia is now the world's largest coal exporter and the second largest LNG exporter (Australian Department of Industry, Science, Energy and Resources, 2021a; IEA, 2021).

The federal government has promoted a "gas-fired recovery" from the COVID-19-related economic slowdown, including by providing substantial new public funding to unlock new gas basins, supporting the expansion of the gas transport network, and using various measures to boost gas supply and domestic gas use (Australian Department of Industry, Science, Energy and Resources, 2020b, 2021b; Prime Minister of Australia, 2020).

Plans and projections for domestic fossil fuel production

As illustrated in Figure 4.7, the Australian government projects increases in coal, oil, and gas production of 4%, 32%, and 12%, respectively, from fiscal year 2019 to 2030 (Australian Department of Industry, Science, Energy and Resources, 2020a).

Government support for fossil fuel production

- Australia's fiscal regime for oil and gas production allows some operators of major projects to pay little or nothing in royalties or resource rent taxes (Bruce, 2019; Butler, 2021; Campbell, 2020).
- Australia exempts fuel used in mining from fuel taxes through the fuel tax credit system, which is also available to other sectors of the economy (Australian Taxation Office, 2017).
- The Queensland State government has expedited approval for proposed large coal mine developments in the Galilee basin (Bavas, 2019; Wahlquist, 2019), as well as agreed to defer royalty payments on a concessional basis (Swann, 2018; Thornhill, 2020; Zillman & Horn, 2020). However, market conditions, limited access to financing, and recent Chinese import restrictions have delayed, limited, or stalled these developments (Australian Department of Industry, Science, Energy and Resources, 2021a).
- Export Finance Australia provided between AUD 1.6 and 1.7 billion (USD 1.1 to 1.2 billion) in finance to fossil fuel projects from mid-2009 to mid-2020, including AUD 0.3 billion (USD 0.2 billion) to a LNG facility and coal export terminal (Rui & Strachan, 2021).

Policies and discourses towards a managed wind-down of fossil fuel production

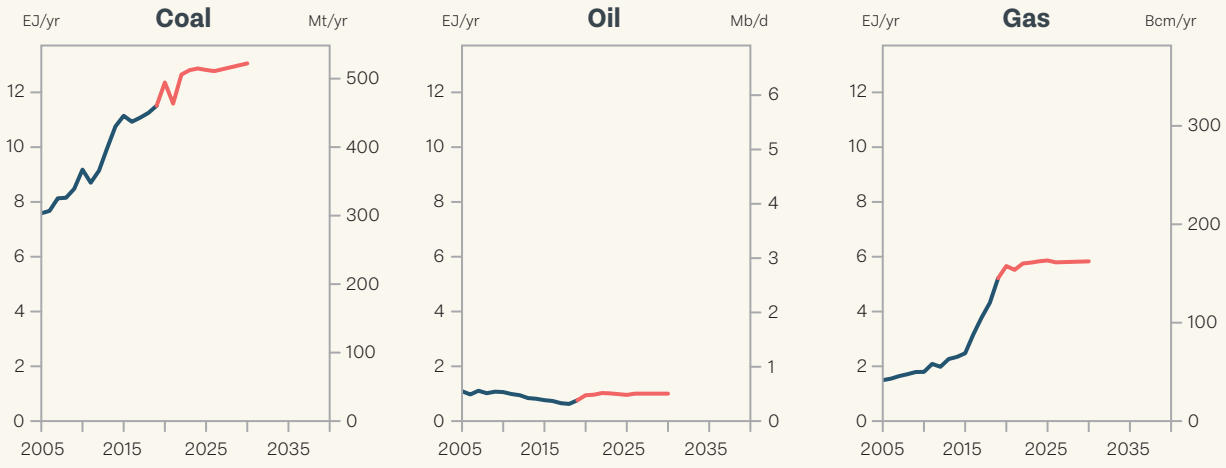
No such government policies or discourses were identified.

Policies and discourses supporting a just and equitable transition away from fossil fuel production

Policies and discourses have been limited to transition assistance at the local level, related to coal plant closure in the Latrobe Valley, as well as some early considerations for how to handle future coal plant closures in the Hunter Valley (Green, 2019; Wiseman et al., 2020).

Figure 4.7

Historical and projected coal, oil, and gas production for Australia. Sources: Historical data and 2020–2026 projections are from the Resources and Energy Quarterly, March 2021 (Australian Department of Industry, Science, Energy and Resources, 2021a); 2030 projections are from Australia's emissions projections 2020 (Australian Department of Industry, Science, Energy and Resources, 2020a).



India

Announced climate ambitions

India's first NDC, issued in 2016, pledged a 33%–35% reduction in the "emissions intensity" of its economy by 2030, compared to 2005 levels (Government of India, 2016).

Government views on fossil fuel production

Under the Aatma Nirbhar Bharat (Self-Reliant India) campaign, the government seeks to "unleash the power of coal" and become self-reliant by 2023–24 (Press Information Bureau of the Government of India, 2020c), and commits to "augment production through government companies" (Indian Ministry of Coal, 2021a). The government articulated this as "a paradigm shift in the approach from being oriented to maximum revenue from coal to making maximum coal available in the market at the earliest" (Press Information Bureau of the Government of India, 2020b).

Plans and projections for domestic fossil fuel production

In 2020, several ministries jointly produced a vision and action plan for developing India's resources. The plan outlines measures to expand coal production by nearly 60% from 2019 to 2024 (from 730 to 1,149 million tonnes), including through the removal of barriers to land acquisition and building capacity for exploration (Indian Ministry of Coal, 2021b). India also aims to increase total oil and gas production by over 40% in the same period through measures such as accelerated exploration licensing, faster monetization of discoveries, and gas marketing reforms (Indian Ministry of Coal, 2021b; Ministry of Petroleum and Natural Gas, 2020).

Government support for fossil fuel production

- India provided tax breaks and budget expenditures for fossil fuel production worth INR 11.8 billion (USD 168 million) in 2019, according to the OECD (OECD, 2021b). Another report, considering a wider range of government support measures, estimates that subsidies for coal production totalled INR 17.5 billion (USD 249 million) and those for oil and gas production totalled INR 29.3 billion (USD 417 million) in 2020 (Garg et al., 2021). Fiscal support for coal production is small in comparison with the fiscal revenue collected from coal.
- In response to the COVID-19 crisis, the government provided a 50% rebate on revenue payable to the government for coal extraction projects (Bhaskar, 2021).
- As part of structural reforms announced in 2020 amid the Self-Reliant India campaign, the government committed INR 500 billion (USD 7.1 billion) for coal extraction infrastructure (Press Information Bureau of the Government of India, 2020a).
- In 2020, India opened up its coal mining sector to private and foreign investment, offering financial incentives and organizing large auctions of coal mining blocks. A 2020 auction included mines that would add an estimated 225 million tonnes at peak production, representing around 15% of India's projected coal output for 2025 (Press Information Bureau of the Government of India, 2020d, p. 41). It was opposed by the states of Jharkhand, Chhattisgarh and Maharashtra, with concerns about potential social and environmental impacts (Indian Ministry of Coal, n.d.; Jamwal, 2020). A second auction took place in 2021.
- Over the past decade, the Ministry of Environment, Forest and Climate Change has narrowed the public consultation process for coal mine projects (Ministry of Environment, Forest and Climate Change, 2019; Aggarwal, 2021).

Policies and discourses towards a managed wind-down of fossil fuel production

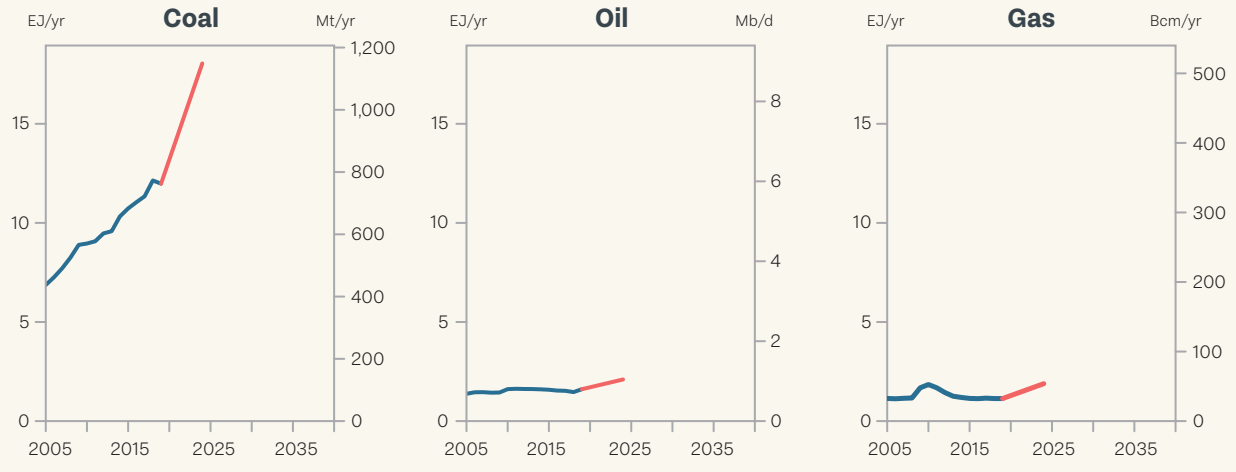
No such government policies or discourses were identified at the federal level.

Policies and discourses supporting a just and equitable transition away from fossil fuel production

No such government policies or discourses were identified at the federal level.

Figure 4.8

Historical and projected coal, oil, and gas production for India. The 2024 oil and gas production projections are estimated from the total reported in the source document, assuming the oil-to-gas ratio remains constant at 2019 values. Sources: 2024 projections from the Five Year Vision Document 2019–2024 (Indian Ministry of Coal, 2021b). Historical data are from India's Bureau of Mines (2021).



Canada

Announced climate ambitions

Canada released its updated NDC in mid-2021, pledging to reduce emissions 40%–45% from 2005 levels by 2030 and confirming its 2019 commitment to reach net-zero domestic emissions by 2050 (Government of Canada, 2021; Prime Minister of Canada, 2021). In 2021, Canada also passed climate accountability legislation that enshrines the net-zero target in law (Parliament of Canada, 2021).

Government views on fossil fuel production

The federal government views fossil fuel exports as critical for Canada's economic growth and prosperity and to funding the transition to a low-carbon economy (McSheffrey, 2017; O'Regan, 2021). In particular, it has emphasized the need to expand export infrastructure, such as pipelines and LNG (Jang, 2019; Rabson, 2020). In April 2021, Canada joined four other countries in establishing the Net-Zero Producers Forum (see chapter introduction).

Plans and projections for domestic fossil fuel production

In the 2020 Canada's Energy Future report, the government changed its primary scenario from the "reference" scenario to a new "evolving" scenario, with assumptions of greater global climate action and lower future oil prices (Canada Energy Regulator, 2020a). It projects lower oil and gas production than the report's updated "reference" scenario. As shown in Figure 4.9, under the evolving scenario, oil and gas production increase by 18% and 17% respectively from 2019 to 2040, as compared with increases of 43% and 38% respectively under the reference scenario (Canada Energy Regulator, 2020a).

Government support for fossil fuel production

- National and subnational subsidies for fossil fuel production amounted to CAD 1.4 billion (USD 1 billion) in 2019, according to the OECD (OECD, 2021a). Other estimates, which include direct transfers made by governments, suggest national and subnational subsidies are much higher, totalling over CAD 4.8 billion (USD 3.6 billion) per year pre-pandemic, mostly for production (Corkal & Gass, 2019, 2019; Environmental Defence & IISD, 2019; Equiterre & IISD, 2018; OECD, 2021a; Touchette et al., 2017).
- In 2020, as part of its COVID-19 economic response efforts, the Government of Canada allocated CAD 320 million (USD 240 million) for an Oil and Gas Industry Recovery Assistance Fund to support the Newfoundland and Labrador's offshore oil industry. It also allocated CAD 1.7 billion (USD 1.3 billion) for provincial governments to clean up orphan and inactive oil and gas wells that the private sector has not remediated on their own, and CAD 750 million (USD 560 million) for an Emissions Reduction Fund for oil and gas companies (Department of Finance Canada, 2020; Department of Natural Resources Canada, 2021; Prime Minister of Canada, 2020).
- During the 2018–2020 period, the Governments of Canada and Alberta provided at least CAD 23 billion (USD 17 billion) in public finance to three fossil fuel pipelines (Corkal, 2021).
- Since 2016, Export Development Canada (EDC) has provided a yearly average of over CAD 13 billion (USD 10 billion) in public finance for fossil fuels (EDC, 2021a, 2021b).

Policies and discourses towards a managed wind-down of fossil fuel production

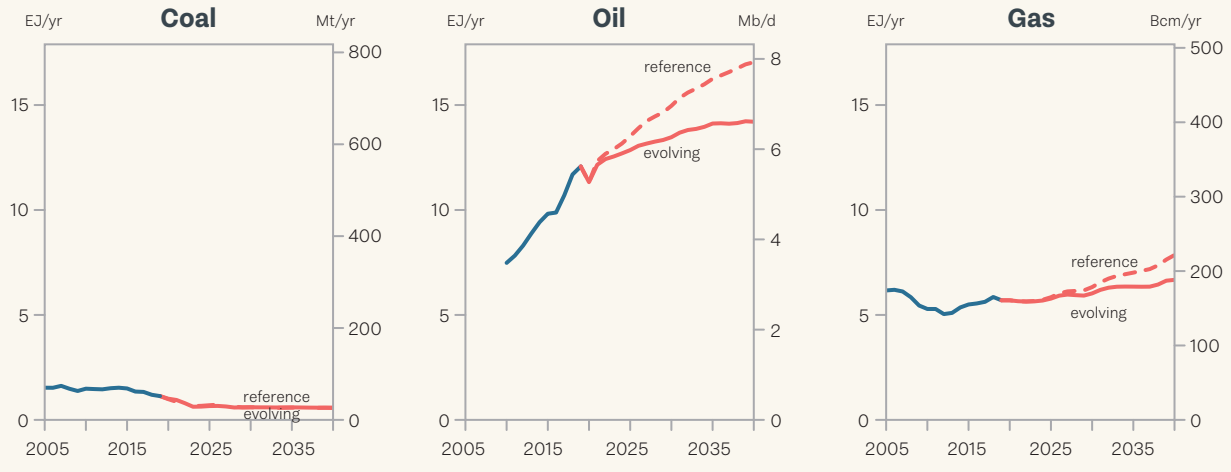
No such government policies or discourses were identified.

Policies and discourses supporting a just and equitable transition away from fossil fuel production

In 2018, the Canadian government created a Task Force on Just Transition for Canadian Coal Power Workers and Communities. Its 2018 and 2019 budgets allocated CAD 35 million (USD 26 million) for worker transition centres and CAD 150 million (USD 110 million) for economic diversification in affected communities, over five years (Department of Finance Canada, 2019).

Figure 4.9

Historical and projected coal, oil, and gas production for Canada. The 2020 edition of Canada's Energy Future introduced a new "evolving" scenario as its main scenario. Sources: Canada's Energy Future 2020 (Canada Energy Regulator, 2020b).



United Arab Emirates

Announced climate ambitions

The UAE announced its second NDC in December 2020, committing to reduce GHG emissions by 23.5% below business-as-usual in 2030 (Government of the United Arab Emirates, 2020). The NDC also notes that in 2020, the state-owned Abu Dhabi National Oil Company (ADNOC) announced a target to reduce the GHG emissions intensity of oil and gas production by 25% by 2030.

Government views on fossil fuel production

The UAE government views oil and gas, the mainstay of its economy, as key to the country's future socio-economic growth (Government of the United Arab Emirates, 2020), with the stated objective to maximize export revenues from its hydrocarbon sector for the longest time possible (United Arab Emirates Ministry of Energy & Industry, 2019). In parallel, the country has stepped up efforts over the past decade to position itself within the Middle East as a "green hub", promoting clean energy and freeing up domestic fossil fuel production for export.

Plans and projections for domestic fossil fuel production

The UAE has ambitious plans to ramp up oil and gas production in the near term, reflecting increasing pressure to reconcile long-term profit maximization with global climate action and the risk that oil and gas assets could become stranded in the future (Cahill, 2021; Faucon et al., 2021; Meyer, 2021). ADNOC, which produces nearly all of the country's hydrocarbons, plans to increase the UAE's crude oil production capacity from 4 million barrels per day (Mb/d) in 2020 to 5 Mb/d by 2030, relying on enhanced oil recovery (EOR) in existing oil fields, as well as output from around 22 billion barrels of unconventional reserves newly confirmed in 2020 (Kerr, 2020). To support this aim, the UAE government has pledged USD 122 billion in capital expenditure for its national oil company between 2020 and 2025 (Kerr, 2020). With the intent of ensuring self-sufficiency and becoming a net exporter once again, the country has also announced plans to invest aggressively in gas production, including significant unconventional gas resources (ADNOC, 2018a, 2018b). ADNOC plans to add 3 billion cubic feet (Bcf) per day of new gas production this decade, an increase of 50% over current production levels (6 Bcf/day).

Government support for fossil fuel production

No information is publicly available on tax expenditures or other measures to support fossil fuel production in the UAE.

Policies and discourses towards a managed wind-down of fossil fuel production

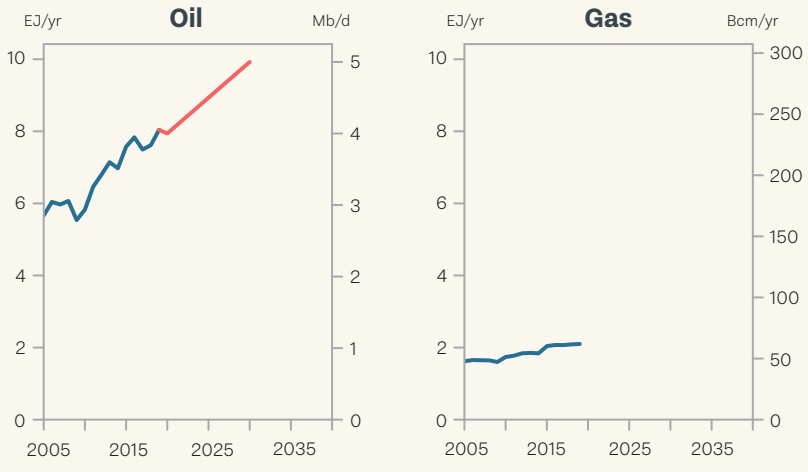
No such government policies or discourses were identified.

Policies and discourses supporting a just and equitable transition away from fossil fuel production

No such government policies or discourses were identified, though UAE has invested in workforce training for energy efficiency, renewable energy, and other low-carbon technologies.

Figure 4.10

Historical oil and gas and projected oil production for the UAE. The UAE does not produce coal; gas projections are not available. Sources: Oil projections are based on ADNOC's plans as reported by Kerr (2020). Historical data are from the IEA (IEA, 2021).



South Africa

Announced climate ambitions

South Africa released a draft of its enhanced NDC in March 2021, proposing to limit the country's annual emissions to 398–440 $MtCO_2e$ by 2030 (Government of South Africa, 2021a); the country's 2017 emissions were around 513 $MtCO_2e$/yr (Government of South Africa, 2021b). In its long-term, low-emissions development strategy (LT-LEDS), South Africa mentioned that it will "ultimately mov[e] towards a goal of net zero carbon emissions by 2050" (Government of South Africa, 2020).

Government views on fossil fuel production

Coal mining has been central to the industrialization of South Africa (Burton et al., 2018). Coal currently accounts for around 77% of South Africa's primary energy mix and is historically viewed as key to the country's economy (Department of Mineral Resources and Energy, 2021), though this view is increasingly contested (The Presidency of the Republic of South Africa, 2021). Coal production has historically had relatively secure demand from users such as Eskom, South Africa's state-owned electricity utility, and from the country's large coal-to-liquids industry (Burton et al., 2018). Eskom recently "committed in principle to net zero emission[s] by 2050" (Ramaphosa, 2021).

Plans and projections for domestic fossil fuel production

To date, the government has not published national projections or targets for coal production. South Africa's 2019 Integrated Resource Plan sets a target for reducing coal's contribution to installed power sector capacity — from 72% in 2018 to 45% in 2030 — but does not address production (Department of Mineral Resources and Energy, 2019).

Government support for fossil fuel production

- The coal sector has historically received significant direct and indirect support via regulatory measures, state-owned enterprises, and subsidies to large users such as Eskom and Sasol (a minority state-owned, coal-to-chemicals producer) (Bridle et al., 2020; Burton et al., 2018). While indirect support remains substantial, direct subsidies for coal mining are now smaller than in the past (Bridle et al., 2020; Burton et al., 2018; OECD, 2021l). In 2019, the government still provided direct budgetary transfers worth an estimated ZAR 760 million (USD 53 million) to projects that supply water to power stations and to coal mines (OECD, 2021l).
- South Africa's state-owned development finance institutions, the Development Bank of Southern Africa (DBSA) and the Industrial Development Corporation of South Africa (IDC), support coal production through their investment holdings (Halim & Omar, 2020). For example, the IDC holds shares in the New Largo proposed coal mine project, which is intended to supply Eskom's under-construction plant, Kusile (Seriti, 2019).

Policies and discourses towards a managed wind-down of fossil fuel production

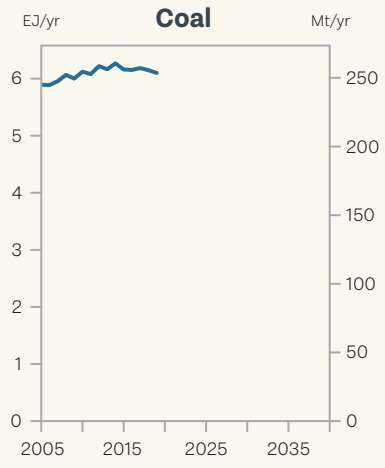
No policies or discourses to actively phase out coal production were identified.

Policies and discourses supporting a just and equitable transition away from fossil fuel production

South Africa's first NDC mentioned the broad concept of a just transition (Government of South Africa, 2015). Its draft updated NDC elaborates on this issue, noting that the country "will need to put measures in place that plan for… diversifying coal dependent regional economies, and developing labour and social plans as and when ageing coal-fired power plants and associated coal production infrastructure are decommissioned" (Government of South Africa, 2021, p. 4). Many high-level political discourses are actively taking place on the importance of, and how to implement, a just transition to a low-carbon, resilient, and inclusive economy and society, including for the coal mining and power sector (Department of Environmental Affairs, 2018; GreenCape, 2021; Joubert, 2019; The Presidency of the Republic of South Africa, 2020, 2021; TIPS, 2020).

Figure 4.11

Historical coal production for South Africa. Government projections are not available. Oil and gas production are small (<0.5 EJ/yr) and not shown. Source: IEA (2021).



Brazil

Announced climate ambitions

In its updated NDC, released in 2020, the Brazilian government maintained its earlier targets of reducing GHG emissions by 37% and 43% from 2005 levels by 2025 and 2030, respectively, and stated that it is considering a long-term goal of achieving climate neutrality in 2060 (Government of Brazil, 2020).

Government views on fossil fuel production

With the oil and gas sector making up an estimated 13% of Brazil's GDP, the government views oil exports as critical for economic development, which has resulted in many regulatory changes since 2017 to "encourage new investments" and expand production (ANP, 2018a). In the face of global decarbonization efforts and potential near-term peak oil demand, the Brazilian government intends to boost domestic production in the coming years to maximize the "monetization" of its domestic oil and gas reserves (ANP, 2019; Mariano et al., in press).

Plans and projections for domestic fossil fuel production

The National Energy Plan 2050, approved by the Ministry of Mines and Energy in 2020, shows that the Brazilian government intends to attract investments and ramp up oil and gas production to "become one of the five largest producers in the world" (Ministério de Minas e Energia, 2020c). As shown in Figure 4.12, the Plan foresees production of oil and gas increasing by 60% and 110%, respectively, between 2020 and 2030.

Government support for fossil fuel production

- The country's tax expenditures and direct budgetary transfers to incentivize oil and gas production were around BRL 10 billion (USD 2.5 billion) in 2019, according to the OECD (OECD, 2021h). The overwhelming majority (99%) of this value comes from one tax break: Repetro, a tax exemption for equipment used in the research and mining of oil and gas. Originally created in 1999, it was set to expire in 2020 but was renewed until 2040 (Delgado & Cals, 2017; Pedra, 2020; PPI, 2017).
- The Revitalization of Onshore Oil and Gas Exploration and Production Activities ("REATE") program, first launched in 2017 and updated in 2020, aims to double onshore oil and gas production over the next 10 years (Ministério de Minas e Energia, 2020a).
- In 2018, the government approved a reduction in the royalty rate from 10% to 5% or less on the incremental production from mature fields, to be applied from 2020 onwards, designed to promote exploration, development, and production (ANP, 2017, 2018b).
- In 2019, Brazil introduced a new "Open Acreage" program that consists of a continuous offer of exploration blocks (ANP, 2018a, 2021a), designed to attract new private investments, expand exploration and production, and increase government revenues from the hydrocarbon sector (Mariano et al., in press).
- The Brazilian Development Bank (BNDES) has historically provided extensive support to its domestic oil and gas industry; between 2008 and 2013, it provided loans worth a total of BRL 46 billion (USD 24 billion) (Oliveira, 2015). These loans, including to Petrobras (a state-controlled oil company), have enabled the ramp-up of oil production in Brazil's new frontier basins over the last five years (Barbosa, 2013; Ministério de Minas e Energia, 2019).

Policies and discourses towards a managed wind-down of fossil fuel production

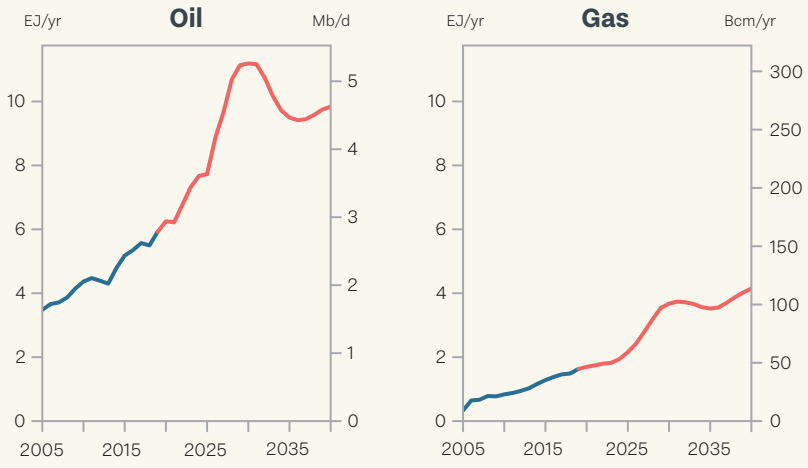
No such government policies or discourses were identified.

Policies and discourses supporting a just and equitable transition away from fossil fuel production

No such government policies or discourses were identified.

Figure 4.12

Historical and projected oil and gas production for Brazil. Brazil's coal production is small (<0.5 EJ/yr) and not shown. Brazil's reported gas production (as shown) includes fractions that are re-injected, self-consumed, and flared, which accounted for around 40% of total production in 2019. Sources: 2021–2025 projections are from the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP, 2021b); 2026–2040 projections are from the 2050 Energy Plan (Ministério de Minas e Energia, 2020b). Historical data are from the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP, 2021c).



Norway

Announced climate ambitions

In its updated NDC, Norway increased its emission reduction targets to 50%–55% by 2030, and 90%–95% by 2050, compared to 1990 levels (Government of Norway, 2020).

Government views on fossil fuel production

With oil and gas making up about half of the total value of Norway's exported goods, the government views oil and gas as "the most important export commodities in the Norwegian economy" (Norwegian Petroleum Directorate, 2021a). The government recently stated that it will "facilitate profitable production of oil and gas in a long-term perspective within the framework of Norway's climate policy," which includes intentions to "continue to pursue its exploration policy with regular concession rounds to ensure that new areas for exploration are made available to the industry" (Norwegian Ministry of Petroleum and Energy, 2021a, 2021d). So far in 2021, the government has issued 61 production licenses and offered 84 new blocks for exploration on the Norwegian Continental Shelf (Norwegian Ministry of Petroleum and Energy, 2021b, 2021c). In April 2021, Norway joined four other countries in establishing the Net-Zero Producers Forum (see chapter introduction).

Plans and projections for domestic fossil fuel production

Due to recent large discoveries, oil production is set to increase for the next few years, before an expected longer-term decline, as shown in Figure 4.13. The government recently argued that its forecasted oil and gas production is compatible with the Paris Agreement's 1.5°C limit, as the projected decline (65% from 2020 to 2050) is broadly in line with the median declines in oil and gas consumption in the IPCC 1.5°C scenarios (Sanner & Bru, 2021). However, the declines reflect the expected resource depletion rates rather than a planned transition (Norwegian Ministry of Petroleum and Energy, 2021a), and Norway's projected production out to 2030 "have consistently been adjusted upwards" (Norwegian Ministry of Finance, 2021a, p. 85; translated from Norwegian).

Government support for fossil fuel production

- Norway's oil tax scheme for oil is characterized as "investment friendly" by the government. The estimated amount of forgone government revenue in 2020 is NOK 16 billion (USD 1.7 billion), due to a system for accelerated depreciation and high uplift and interest deductions (Norwegian Ministry of Finance, 2020).
- The government covers significant investments in exploration and field development. For example, exploration costs are fully deductible, with cash refunds available for companies that are in a negative tax position (Norwegian Petroleum Directorate, 2021b). The government also provides funds for geological surveys and for research and development activities. This amounted to NOK 660 million (USD 75 million) in 2019 (OECD, 2021k).
- In response to the oil price fall in 2020, the government passed several interim tax measures, including deferred taxation on new projects. The total value of these tax breaks is estimated to be around NOK 8 billion (USD 850 million). (Norwegian Ministry of Finance, 2021c).

Policies and discourses towards a managed wind-down of fossil fuel production

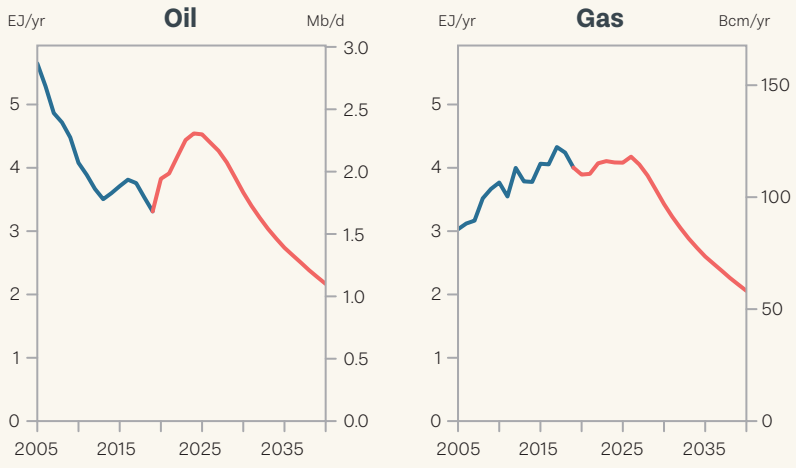
There is increasing awareness that international climate policy may pose economic risks to Norway's oil and gas production (Bang & Lahn, 2019). To date, the most direct response measure has been the divestment of Norway's USD 1 trillion sovereign wealth fund from coal and certain upstream oil and gas companies (Norwegian Ministry of Finance, 2019; Norwegian Parliament, 2015). The government will also require oil and gas companies to disclose climate risk in development plans for new projects (Norwegian Ministry of Petroleum and Energy, 2021a, p. 161).

Policies and discourses supporting a just and equitable transition away from fossil fuel production

No specific government policies were identified beyond Norway's general system of workers' rights, including financial and retraining assistance.

Figure 4.13

Historical and projected oil and gas production for Norway. Coal production is small (<0.5 EJ/yr) and not shown. The 2026-2040 oil and gas projections are estimated from the source document's reported total, assuming the liquids-to-gas ratio remains constant at average 2020–2025 values. Sources: 2026–2050 are from the Norwegian Ministry of Finance (2021). 2021–2025 projections and historical data are from the Norwegian Petroleum Directorate (2021c).



Mexico

Announced climate ambitions

Mexico's updated NDC, submitted in 2020, maintained the same targets as its 2015 NDC — a 22% (unconditional) and 36% (conditional) reduction of greenhouse gas emissions by 2030 relative to business-as-usual — while it increased the business-as-usual value for 2030 from 973 $MtCO_2e$ to 991 $MtCO_2e$ (Government of Mexico, 2015, 2020).

Government views on fossil fuel production

Pemex, a state-owned enterprise, accounts for 97% of Mexico's oil and gas production (Sistema de Información de Hidrocaburos, 2021). In March 2021, Pemex published its Business Plan for 2021–2025, signalling its intent to boost oil and gas production and reverse the significant decline of the past 15 years (PEMEX, 2021). This is in line with the current government's priorities of "energy sovereignty" and increased oil production as a lever for national development (Government of Mexico, 2019a, 2019b).

Plans and projections for domestic fossil fuel production

The Ministry of Energy's most recent annual outlooks on oil and gas production, last updated in 2018, provide production projections under a "maximum" and "minimum" scenario (Secretaría de Energía SENER, 2018b, 2018a). As shown in Figure 4.14, under the maximum scenario, oil and gas production would increase by 66% and 89%, respectively, from 2018 to 2032. Under the low scenario, oil production would decline by 3% and gas production would increase by 25% over the same period.

Government support for fossil fuel production

- Mexico provides tax allowances and relief for oil and gas production, which totalled MXN 31 billion (USD 1.6 billion) in 2019 (OECD, 2020). Most of this is attributed to an increase in the tax deduction cap from 12.5% to 40% of the value of onshore production (35% for offshore) (Diario Oficial de la Federación, 2019a)
- In 2019, the Mexican Congress reduced Pemex's minimum mandated dividend to the federal government for oil and gas extraction activities, from 65% to 58% in 2020 and to 54% in 2021 and onwards (Diario Oficial de la Federación, 2019b). Pemex has estimated that this reduction will grant savings of up to MXN 45 billion (USD 2.3 billion) in 2020 and MXN 83 billion (USD 4.3 billion) in 2021, which would be used to boost hydrocarbon extraction (PEMEX, 2019).
- In response to the drop in global oil prices at the beginning of 2020, the Mexican government provided a tax credit for oil producers for the 2020 fiscal year of up to MXN 65 billion (USD 3 billion), to account for lost profits (Diario Oficial de la Federación, 2020). In early 2021, the tax credit was extended for the 2021 fiscal year, though at a lower rate, with a maximum credit set at MXN 73 billion (USD 3.7 billion) (Diario Oficial de la Federación, 2021).

Policies and discourses towards a managed wind-down of fossil fuel production

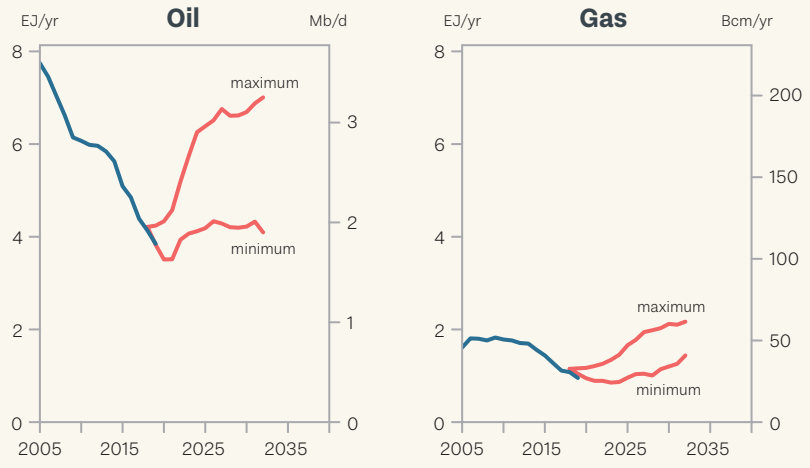
No such government policies or discourses were identified.

Policies and discourses supporting a just and equitable transition away from fossil fuel production

No such government policies or discourses were identified.

Figure 4.14

Historical and projected oil and gas production for Mexico. Mexico's coal production is small (<0.5 EJ/yr) and not shown. Two scenarios, "maximum" and "minimum", are reported in the 2018 Outlooks. Mexico's reported gas projections likely include natural gas liquids (NGLs). The raw data are therefore reduced by 20% in this figure, which is the fraction of NGLs between 2016–2021 reported by the government of Mexico (Sistema de Información de Hidrocaburos, 2021). Sources: 2018–2032 projections are from the 2018 Oil Outlook (Secretaría de Energía SENER, 2018b, p. 60) and the 2018 Gas Outlook (Secretaría de Energía SENER, 2018a, p. 71). Historical data are from the IEA (IEA, 2021).



United Kingdom

Announced climate ambitions

In its latest NDC, the UK pledged to reduce its emissions by 68% by 2030, compared to 1990 levels, with a further announcement in 2021 of 78% reductions by 2035 (UK Government, 2020a, 2021b). In 2019, the country set a target of net-zero greenhouse gas emissions by 2050 (UK Government, 2019).

Government views on fossil fuel production

Oil and gas policy is governed by a statutory duty to "maximise economic recovery" (UK Parliament, 2015, Section 41), and the government has indicated its aim to "extract every drop of oil and gas that it is economic to extract" (UK Parliament, 2017). Climate change concerns have featured prominently in deliberations around the local approval of a new coal mine in the north of England; the national government launched an inquiry to consider whether to uphold the approval given its climate change impact (Ministry of Housing, Communities & Local Government, 2021).

Plans and projections for domestic production

After peaking at the turn of the century, UK oil and gas production dropped steeply until 2014. In response to a government-commissioned report on maximizing oil and gas recovery (Wood, 2014), the UK government instituted regulatory changes and tax cuts to spur production, and production grew steadily from 2014 to 2019. According to the UK's Oil and Gas Authority (OGA), these changes are expected to lead to 30% more oil and gas production from 2016 to 2050 than would have otherwise occurred (OGA, 2018). While the OGA projects oil production to decline by 58% for oil and by 70% for gas from 2021 to 2040 (OGA, 2021a), as shown in Figure 4.15, its 2035 Vision, described in OGA's 2019 Corporate Plan, is for production to exceed these and prior projections (OGA, 2019, p. 7).

Government support for production

- In 2019, the UK provided tax allowances and relief for oil and gas production totalling GBP 3.7 billion (USD 5.1 billion) (OECD, 2021e).
- Between 2020 and 2065, the UK will provide an estimated GBP 18.3 billion (USD 25.3 billion) in tax relief to oil companies for the costs of decommissioning offshore infrastructure (OGA, 2021b). As of December 2020, the UK government had signed 98 Decommissioning Relief Deeds with oil companies, providing companies with certainty on the level of tax relief they will receive on future decommissioning (UK Treasury, 2021, p. 380).
- In 2020, UK Export Finance approved GBP 300 million (USD 420 million) in loans and GBP 850 million (USD 1.2 billion) in guarantees to a major LNG project in Mozambique, a decision that is under judicial review (Friends of the Earth, 2021). Five months later, in 2021, the UK ended all new bilateral public finance for fossil fuel production overseas, the first G20 government to do so (UK Government, 2020b).

Policies and discourses towards a managed wind-down of production

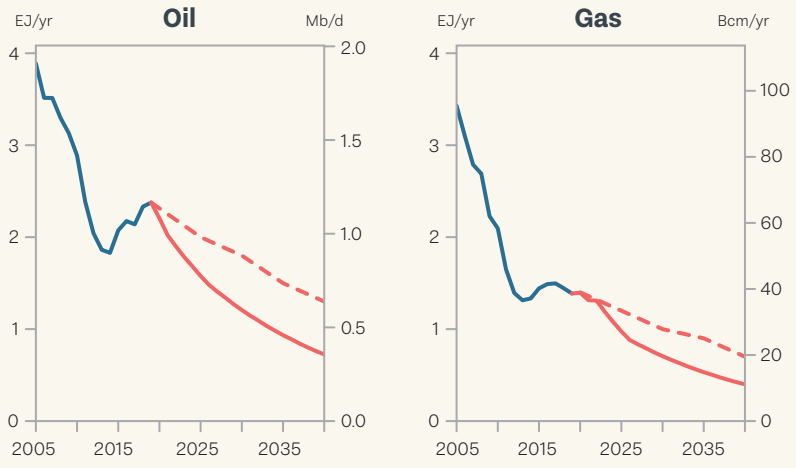
In March 2021, the UK Government announced a North Sea Transition Deal with its offshore oil and gas industry that will not stop national fossil fuel exploration or production (BEIS & OGA UK, 2021; Brooks, 2021). The government announced that a new climate compatibility test will be conducted before future exploration and production licensing rounds, to ensure licenses awarded are "aligned with wider climate objectives, including net-zero emissions by 2050" (UK Government, 2021a).

Policies and discourses supporting a just and equitable transition

The North Sea Transition Deal will invest in skills and job training oriented around CCS and hydrogen, complementing continued oil and gas production and with no plans for a wind-down in production. The Scottish Government has appointed a Just Transition Commission (Just Transition Commission, 2021).

Figure 4.15

Historical and projected oil and gas production for the UK. The UK's coal production is small (<0.5 EJ/yr) and not shown. Sources: Historical data and projections are from the UK Oil & Gas Authority's February 2021 oil and gas production projections (OGA, 2021). OGA also published a combined oil and gas production target in its "2035 Vision" document (OGA, 2019, p. 7); individual oil and gas pathways under this scenario are shown by the dotted red lines, assuming that the oil-to-gas ratios projected by OGA (2021) also apply here.



Germany

Announced climate ambitions

In May 2021, the German parliament enhanced the ambitions of the Climate Change Act — the country's first major climate law that entered into force in 2019 — with a goal to reach carbon neutrality by 2045 instead of 2050, and by increasing the 2030 target for GHG emission cuts from at least 55% to at least 65%, relative to 1990 levels (BMU, 2021).

Government views on fossil fuel production

Germany phased out hard coal production in 2018, but remains the world's largest producer of lignite, the most carbon-intensive type of coal (IEA, 2021). In 2020, the German parliament finalized the Coal Phase-out Act, with an end date of 2038 at the latest for both hard coal and lignite power generation (BMWi, 2019). This has implications for lignite mining since 100% of supply is currently domestically consumed (IEA, 2021).

Plans and projections for domestic fossil fuel production

Figure 4.16 shows the estimated declines of Germany's fossil fuel production out to 2030, as modelled in the 2019 Integrated National Energy and Climate Plan (NECP) (BMWi, 2019, pp. 176–177). Coal and gas production are projected to decrease by around 50%, and oil by 24%, between 2020 and 2030. This figure does not yet reflect the more ambitious climate goals recently adopted by Germany and by the EU's 2030 Climate Target Plan (European Commission, 2021a). The NECP is expected to be revised in 2024.

Government support for fossil fuel production

- National and subnational subsidies for lignite production amounted to EUR 309 million (USD 346 million) in 2019, according to the OECD. This includes exemptions from mining royalties and water fees for existing production (22% of the total subsidy amount), as well as financing for lignite mine rehabilitation in East Germany (78%) (LMBV, 2017; OECD, 2021j).
- Germany's development bank, KfW, is Europe's top national development finance institution for international oil and gas financing, providing a total of USD 1.4 billion in 2015–2018 (Erzini et al., 2020). It supports conventional oil and gas and unconventional gas investments, and actively promotes gas imports as being a "bridging technology on the path to climate neutrality" (Pflume & Römer, 2021; translated from German). In 2019, KfW excluded financing for new projects related to the exploration and extraction of coal and unconventional oil (KfW, 2019).
- In 2019, Germany's export credit agency provided EUR 1.3 billion (USD 1.5 billion) of support for international fossil fuel projects (Euler Hermes Aktiengesellschaft, 2021). Although there is a lack of transparency on which and what types of projects were supported, the agency's latest policies exclude new coal plants and oil production with routine flaring (Investitionsgarantien, 2021).

Policies and discourses towards a managed wind-down of fossil fuel production

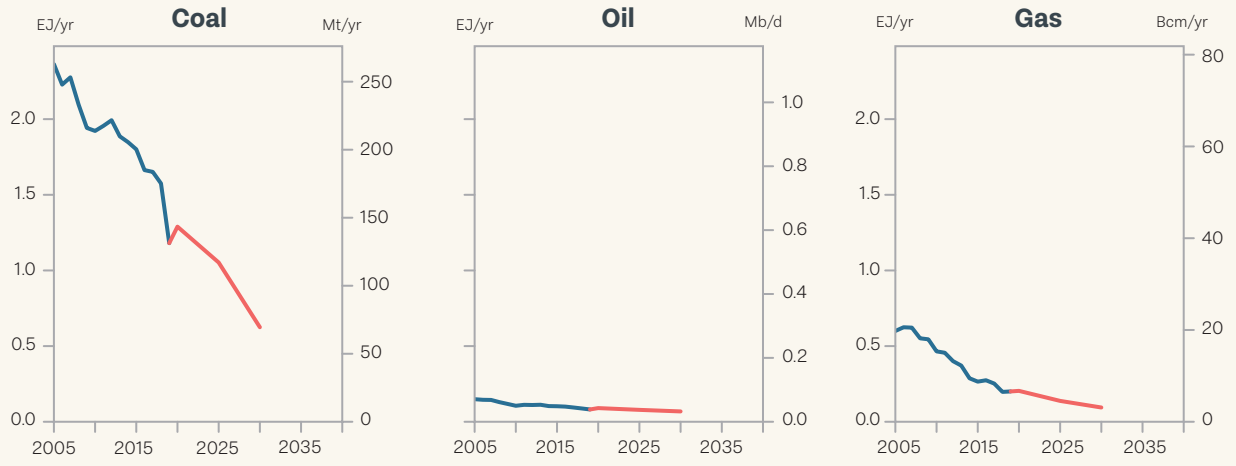
Germany's 2019 NECP considered the implications of the country's and the EU's climate goals on domestic fossil fuel production out to 2030 (BMWi, 2019, pp. 176–177). The Coal Phase-out Act further commits power generation from coal to be phased out by 2038 at the latest, but does not explicitly mention production (BMWi, 2019).

Policies and discourses supporting a just and equitable transition away from fossil fuels

Germany passed the Structural Development Act alongside the Coal Phase-out Act to provide up to EUR 40 billion (USD 46 billion) between now and 2038 for directly affected coal-mining areas (Government of Germany, 2020). This includes close-down premiums for hard-coal-fired power plant operators and direct compensation payments totalling EUR 4.35 billion (USD 5 billion) for lignite-fired power plant operators. These contracts remain a subject of conflict, with the European Commission currently investigating whether compensation for forgone profits has been kept to the minimum necessary, as required by EU state aid rules (European Commission, 2021b; Heilmann & Popp, 2020).

Figure 4.16

Historical and projected coal production for Germany. Sources: Projections are from the "climate action plan scenario" from the 2019 National Energy and Climate Plan (BMWi, 2019). Historical data are from the IEA (IEA, 2021).





5

The critical role of transparency in addressing the production gap

Key Messages

Verifiable and comparable information on fossil fuel production and support — from both governments and companies — is essential to addressing the production gap.

Existing transparency initiatives shed some light on fossil fuel production and its implications for meeting climate goals, but available information is incomplete, often inconsistent and scattered across various, mostly voluntary, government-driven and non-governmental efforts.

Governments should strengthen transparency by disclosing their fossil fuel production plans and projections, and how these align with climate goals. They should do this in their published national climate and energy plans, including in their nationally determined contributions (NDCs) and their long-term, low-emission development strategies under the Paris Agreement.

Governments should require that both private- and state-owned fossil fuel companies disclose their spending, project plans, emissions, and climate-related financial risks, and do so in a consistent manner across countries.

5. The critical role of transparency in addressing the production gap

The public disclosure of verifiable and comparable information by governments and corporations is key to addressing the fossil fuel production gap. Such information can reveal the extent to which governments are supporting fossil fuel production, and provide insights into how countries can wind down production in light of the Paris Agreement's goals.

Transparency strengthens climate and energy policy-making in several ways. It helps policymakers better understand the scope of a problem, clarifying the social, economic, and environmental consequences at stake. Openness and disclosure can also encourage more inclusive and participatory decision-making. Moreover, transparency can help hold governments, companies, and other actors accountable, driving them to modify their behaviour by facilitating market pressure, public shaming, or litigation. When countries seek to simultaneously expand fossil fuel production and achieve greenhouse gas (GHG) emissions targets, transparency can highlight the inconsistencies in these domestic policies, and draw attention to the risk of stranded assets and communities.

Transparency further matters for international climate cooperation. It can reveal whether collective climate goals are being met, help identify which actors are making progress, which ones are lagging, and which ones require support, and facilitate learning between countries (Gupta & Mason, 2014; Hale, 2008). Moreover, countries tend to be more willing to increase policy ambition when their performance is verified by other countries (Bell et al., 2012; Chayes & Chayes, 1998; Victor, 2011). In the context of the production gap, transparency entails reporting production levels, plans, and support, in addition to the emissions-focused information covered by the international climate regime under the United Nations Framework Convention on Climate Change (UNFCCC).

This chapter highlights transparency initiatives and information gaps relevant to fossil fuel production (Section 5.1), and discusses how governments, companies, and other actors can strengthen transparency around fossil fuel production (Section 5.2).

5.1 Existing transparency initiatives and information gaps

Transparency is central to many international initiatives related to fossil fuels. International organizations such as the International Energy Agency (IEA) emerged with the



specific aim of improving information sharing and collective action among fossil fuel consumer countries (Van de Graaf, 2015). The growing number of transparency and data collection efforts (summarized in online Appendix C) have diverse rationales and objectives for improving fossil fuel transparency, including: reducing fossil fuel price volatility through more accessible production data (e.g. the Joint Organisations Data Initiative, or JODI); removing fossil fuel market distortions (such as through data collection on fossil fuel subsidies by various international organizations); and improving extractive industry governance (e.g. the Extractive Industries Transparency Initiative, or EITI).

These transnational initiatives have not, historically, focused on climate change. More recently, however, non-governmental organizations (NGOs) and the private sector have launched initiatives that can help to better understand the impacts of fossil fuel production on the climate. This has included the development of frameworks to assess climate-related financial risks through the Taskforce for Climate-Related Financial Disclosures (TCFD), understand fossil fuel industry emissions through the Climate Change Reporting Framework of the Inter-

national Petroleum Industry Environmental Conservation Association (IPIECA), and monitor infrastructure development through trackers such as those developed by the non-profit Global Energy Monitor.

Governments are slowly beginning to take up various transparency initiatives related to fossil fuels and climate. For instance, G20 and other governments have begun to report their fossil fuel subsidies, while the EITI board (which includes government representatives) has resolved to advance work on the transparency of climate and energy transitions (Bradley, 2020; Clark, 2020).

Existing transparency initiatives already capture a lot of information relevant for assessing and addressing the production gap (see online Appendix C). However, this data is spread across an array of initiatives and is often not standardized or comparable; it also only exists for a portion of fossil fuel producers (for example, the EITI does not include several major fossil fuel producers among its implementing countries). Moreover, these initiatives are largely voluntary, making it challenging to assess progress on aligning fossil fuel production with climate goals, and to identify transition needs.

To better understand the extent of the production gap, improved transparency about fossil fuel production is urgently needed, including the disclosure of information on:

- **National plans and policies for fossil fuel production,** including: production data; licensing of fossil fuel resource exploration or extraction; plans and policies for future production, including underlying economic and technological assumptions; production levels implied by climate targets; GHG emissions embedded in fossil fuel exports; plans for decommissioning existing fossil fuel infrastructure; and assessments of whether production plans are equitable in the context of global climate objectives.
- **Government support for production,** including: fossil fuel production subsidies; domestic and international public finance for fossil fuel infrastructure; and other non-fiscal measures to promote or expedite production (e.g. fast-track approvals and regulatory exemptions).
- **Fossil fuel companies' plans and strategies,** including: information on the economic viability of fossil fuel reserves under different price conditions; details on investment and production plans and strategies, including underlying assumptions; end-use emissions from the coal, oil, and gas produced; and exposure to climate-related financial risk.

In addition, further information is necessary to enable a well-managed and equitable transition away from fossil fuel production, including on: laws and policies to manage



future fossil fuel production; estimates of the revenues that may be needed to replace lost fossil fuel rents and royalties; and data on the scale of the economic transition at national and subnational levels, including specific data on workforce transition needs. Information is also needed on the costs and liabilities associated with decommissioning fossil fuel production sites, and on the benefits of the transition (such as cost savings and public health benefits).

5.2 Strengthening transparency

If governments strengthened transparency around their fossil fuel production, they would facilitate the assessment of whether and how production plans align with climate goals. Moreover, such transparency can benefit a country's own citizens (see Box 5.2). In this section, we outline how governments can boost transparency by:
1) publicly releasing plans and policies for fossil fuel production, 2) reporting financial and non-financial support to production, and 3) mandating the disclosure of fossil fuel companies' plans and strategies, to assess their (mis)alignment with climate goals (see Figure 5.1).

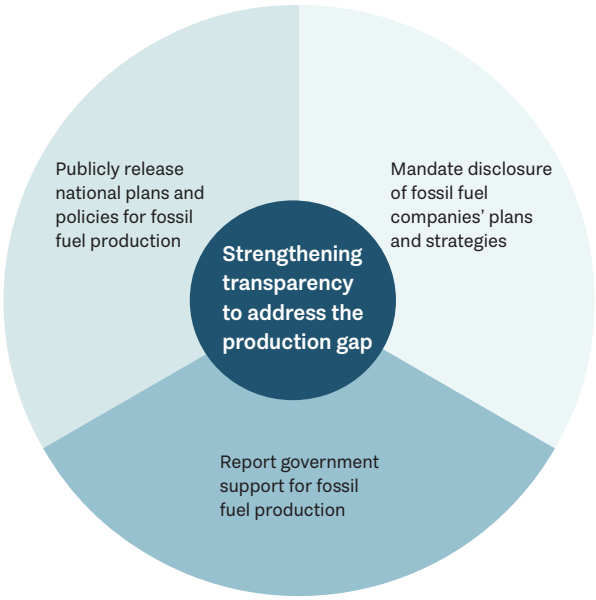
Transparency of national plans and policies for fossil fuel production

At present, only a handful of small producer countries have spelled out a strategy for aligning domestic fossil fuel production with international climate goals in their national climate and energy plans (Jones et al., 2021). There is a need for governments to provide clearer information in these plans about current and future fossil fuel production, and how they will manage the energy transition away from fossil fuels. Ideally, comprehensive climate and energy plans would include: details on historical and planned fossil fuel production; clear targets and timelines for bringing production in line with agreed climate goals; descriptions of planned or enacted policies to wind down fossil fuel production; measures introduced to support a just transition and economic diversification; and information on international cooperation to wind down fossil fuel production.

Governments have already committed to reporting climate-related information as part of the Paris Agreement, and thus could include information on fossil fuel production through the same reporting process (see Box 5.1). Governments could further strengthen transparency through initiatives outside of the UNFCCC process. For instance, the EITI could be used as a mechanism for governments to disclose intended production plans, along with the assumptions underlying these plans; this would provide citizens with a better understanding of the relative

Figure 5.1

Governments can help to assess and address the production gap by strengthening transparency for three types of information.



levels of risks governments are incurring. Requirement 5.3.c of the EITI Standard already encourages governments to disclose information about assumptions related to projected fossil fuel production and commodity prices; extractive sector revenue forecasts; and the proportion of future fiscal revenues expected to come from fossil fuels (EITI, 2019). The multi-stakeholder nature of the EITI also makes the initiative a possible forum for discussing plans for a just transition away from fossil fuel production. Another option — which would provide a more targeted focus on fossil fuels and climate change — would be for governments to jointly create an independently managed registry, through which they can report and review information on fossil fuel production plans and policies (Byrnes, 2020).

There is also a need for transparent information on fossil fuel projects and infrastructure. NGOs have begun to track the development of fossil fuel production infrastructure, which is relatively easy to monitor and verify (Green & Kuch, 2021). However, more and better information from governments would boost transparency. The need for public information about new or expanded fossil fuel production infrastructure is especially acute. Such transparency would mean governments publishing information on each new project, including: the project proponents; expected and permitted annual production volumes; the expected and permitted project lifetimes; GHG emissions, including end-use emissions from the fossil fuels

Box 5.1 Reporting on fossil fuel production under the UNFCCC process

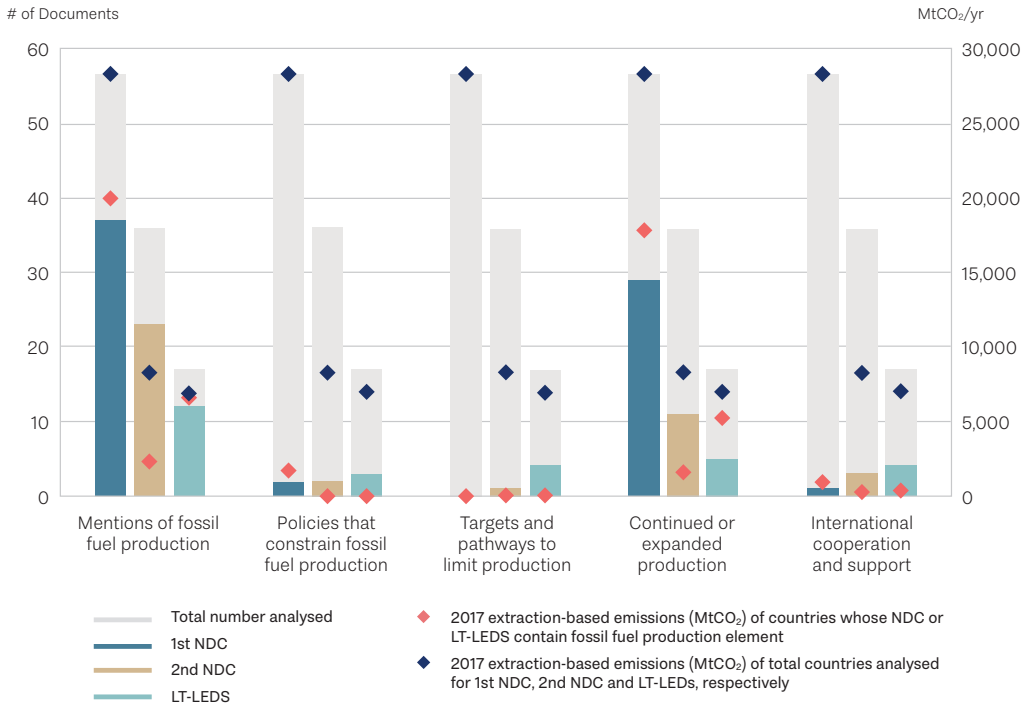
The UNFCCC is a key forum through which governments can inform the international community about their fossil fuel production plans and supporting policies. Parties to the Paris Agreement can include existing production plans and projections, as well as targets and policies to wind down fossil fuel production, in their nationally determined contributions (NDCs), their long-term, low-emission development strategies (LT-LEDS), and their progress reports on implementing and achieving their NDCs.

More countries are beginning to include fossil-fuel-supply-focused policies, measures, targets, and pathways in their NDCs and LT-LEDS. Of the NDCs and LT-LEDS submitted by fossil-fuel-producing countries to date, 34 of the 56 new and updated NDCs and 13 of the 20 LT-LEDS include a mention of fossil fuel production, although many of these reference plans to continue or increase production, as seen in Figure 5.2. Eight Parties (including the EU) have included measures to constrain or disincentivize fossil fuel production in their NDCs or LT-LEDS — six more than in 2019 (Jones et al., 2021). However, these Parties are responsible for considerably less production than those that reference continued or expanded production (see red and purple diamonds in Figure 5.2).

Parties can also report on production in the biennial transparency reports that must be submitted from 2024 onwards under the Paris Agreement's enhanced transparency framework. They could use these reports to share information on their fossil fuel production levels and expected growth; their policies and public finance that support fossil fuel production; and their plans to wind down and transition away from fossil fuel production. Doing so would provide other governments and stakeholders with insights into the alignment of fossil fuel production with a country's NDC and the Paris Agreement goals (Piggot et al., 2018; SEI et al., 2019).

Figure 5.2

Inclusion of supply-side elements in relevant UNFCCC documents. Each set of three bars indicates the total number of 1st NDCs, 2nd NDCs, and LT-LEDS that includes the respective element shown on the x-axis (e.g. mentions of fossil fuel production), relative to the total number of documents analyzed, as measured on the left y-axis. The diamonds show the total extraction-based emissions, as measured in $MtCO_2$/yr on the right y-axis. Figure and data are updated from Jones et al. (2021) and include all NDCs and LT-LEDs published as of 31 July 2021.



produced; the total amount of capital invested; and the assumptions about future resource prices, carbon prices, and other variables on which the investment was made. Since governments also need to wind down existing fossil fuel production to meet climate goals, transparency on existing production sites and infrastructure would likewise be important, including: the expected or scheduled wind-down rate and closure date; the emissions implications of the infrastructure's remaining operational life; and the estimated costs and assignment of liabilities associated with closure and site decommissioning (Eisen et al., 2021). International standardization of all such information could pave the way to a global registry of fossil fuel production sites and infrastructure, building on NGO-driven initiatives (Byrnes, 2020).

Transparency of government support for fossil fuel production

Governments also can strengthen transparency around their financial support for fossil fuel production, which they provide through government finance ministries, national development banks, export credit agencies (ECAs), and other public finance institutions. Very few of these institutions publicly report project-level information. ECAs, for example, do not provide comprehensive and fully comparable data for fossil fuel projects, nor are there universal definitions of sectors and financial support metrics (Shishlov et al., 2020). Multilateral development banks (MDBs), by contrast, are more transparent, with many providing project-level information and a joint commitment in recent years to report on how bank activities help countries meet and exceed their climate goals (E3G, 2020; MDBs, 2019).

It can be difficult to obtain a full picture of public finance investments in fossil fuel projects, due to data gaps and limited accessibility of ECA and MDB data. For example, researchers were unable to include any ECA transactions for Argentina, Saudi Arabia, or Turkey for 2016–2018 in a recent study on the G20 governments' financing for fossil fuels (Tucker et al., 2020). Moreover, neither ECAs nor MDBs provide reliably accessible information about their funding of fossil fuel production through financial intermediaries, despite intermediaries channelling a large and increasing portion of development finance (E3G, 2020; Tucker et al., 2020). The International Finance Corporation (IFC), the World Bank Group's private-sector lending arm, has started to address this by asking financial intermediary clients to voluntarily disclose high-risk sub-projects, and in March 2020 the Bank itself committed to disclosing certain categories of sub-projects. However, the IFC has not yet done that consistently across projects and years when reporting to the Organisation for Economic Co-operation and Development's (OECD) Development Assistance Committee (E3G, 2020). Moreover, voluntary disclosure — while enabling the rapid diffusion of reporting frameworks — nevertheless risks pre-empting regulatory requirements that would be stricter.

It is therefore vital for public finance institutions to publicly share the total amounts of finance by fossil fuel, production stage, and type of financing mechanism. Ideally, they would use their annual reports to disclose project-level data, as well as activities that receive financing through the main bank and their financial intermediaries. This reporting could draw on existing frameworks, such as the EU's sustainable finance taxonomy (European Commission, 2020) or the OECD format for reporting development finance (OECD, 2021a).

Governments also must provide greater transparency on fiscal support and other subsidies to fossil fuel production. Several efforts to strengthen transparency are already underway. Members of the OECD and several other countries report tax expenditures and budgetary transfers in support of fossil fuel production, as summarized in Chapter 3 (OECD, 2021b). However, as the country profiles in Chapter 4 show, some countries do not report this at all (such as Saudi Arabia and UAE), while other countries do not report all forms of support. The information collected by the OECD on subsidies, along with that gathered by the IEA and the International Monetary Fund, is collated through the Fossil Fuel Subsidy Tracker to provide a global picture of subsidies directed towards fossil fuels (Coady et al., 2019; Fossil Fuel Subsidy Tracker, 2021; IEA, 2021). A small number of countries have further chosen to submit their fossil fuel subsidies to a voluntary peer review by other countries, in the context of commitments made under the G20 and the Asia-Pacific Economic Cooperation (APEC) (Verkuijl & van Asselt, 2020). World Trade Organization (WTO) members are required to report ("notify") subsidies that meet the definition of the WTO Agreement on Subsidies and Countervailing Measures and are specific to certain enterprises. However, notification rates on subsidies have generally been low, and the WTO's surveillance mechanism rarely leads to questioning (Casier et al., 2014; Collins-Williams & Wolfe, 2010). Governments can also report fossil fuel production subsidies on a voluntary basis under Sustainable Development Goal (SDG) target 12.c.

Despite these efforts, transparency on fossil fuel production subsidies remains problematic in many countries (Skovgaard & van Asselt, 2018). Governments can therefore strengthen the effectiveness of these transparency arrangements by: providing comprehensive information

on fossil fuel production subsidies through the voluntary reports submitted under SDG 12, following the methodology created by UNEP et al. (2019); strengthening their notifications to the WTO, and using the WTO's Trade Policy Review Mechanism to draw attention to their own or other Members' production subsidies; and undergoing a voluntary self- or peer-review of their fossil fuel subsidies (van Asselt & Moerenhout, 2020).

Transparency of fossil fuel companies

Notwithstanding some positive steps forward, fossil fuel companies — including publicly traded companies and state-owned enterprises (SOEs) — still exhibit major gaps in their transparency around their investment and production plans and, more generally, their climate-related financial risks. Governments can play a key role in improving and enhancing the transparency of fossil fuel companies.

Fossil fuel companies have faced calls for transparency from civil society and investor groups, such as Climate Action 100+. More recently, calls for mandatory disclosure and reporting have come from market regulators, including governments and international organizations. The EU's Non-Financial Reporting Directive, for example, has sought to shed light on whether the business practices of fossil fuel companies are sustainable. Furthermore, G20 central banks (through the TCFD) have pointed to individual company transparency as a starting point in addressing the potential economic impact of unabated climate change and an abrupt and disorderly transition away from fossil fuels. This has led to calls to incorporate the TCFD standards into national corporate reporting regimes, including by the G7 (G7, 2021b), as well as a call for the establishment of a new "International Sustainability Standards Board" that would develop baseline rules for climate-related reporting (G7, 2021a).

A closer look at current disclosures by companies, as well as civil society recommendations to regulatory bodies such as the U.S. Securities and Exchange Commission, reveals fruitful areas for regulators to explore (SEC, 2021). Regulators could insist that fossil fuel companies disclose the emissions associated with the end-use of their products. They could also provide greater clarity on what constitutes a fossil fuel reserve, which is subject to a range of subjective assumptions and uncertainties, yet forms a critical part of oil and gas companies' *financial* reporting (Green & Kuch, 2021). Some regulators, such as the SEC, already define "proven reserves", whereas other jurisdictions allow firms to rely on industry classification systems. Overall, regulators must ensure that climate constraints are considered in evaluating potential reserves, which are supposed to represent geologically and economically producible resources. Regulatory standards for evaluating reserves would generate comparable information regarding climate-related financial risk. It is unlikely that volun-



Box 5.2 Protecting civic space for transparent decision-making

Ambiguity about energy planning, fossil fuel project licensing, and infrastructure permitting processes can pose barriers for civil society to engage in decision-making. A lack of transparency also provides an opening for regulatory capture and corruption that could undermine climate policy objectives and a just transition (Graham et al., 2020; Sovacool, 2020). This calls for increased transparency around decision-making processes surrounding fossil fuel production.

Transparency initiatives — accompanied by appropriate participation mechanisms — would allow the public to provide input into decision-making on fossil fuel development, as well as to fully participate in planning for the low-carbon energy transition. This could include the monitoring of contracts and concessions awarded by governments to fossil fuel production firms, improved community consultations, and strengthening environmental impact assessment (EIA) laws.

Improving transparency around fossil fuel production may have limited impact if civil society lacks the capacity to engage or the power to challenge decision-making processes (Ostrowski, 2020; Sovacool, 2020). Indeed, the opportunity for civil society to contribute to decision-making around fossil fuel development is shrinking in many countries, with a wave of new regulations prohibiting protest or dissent against fossil fuel development (Nosek, 2020; Temper et al., 2020). Strengthening civil society capacity and creating open governance structures are therefore crucial to realizing the potential of transparency.

Governments also have a responsibility to provide information about fossil fuel development to affected communities, and, in particular, to the Indigenous communities inhabiting a significant portion of the land worldwide where fossil fuel reserves are held.[30] The UN Declaration on the Rights of Indigenous Peoples and International Labour Organization (ILO) Convention 169 require States to consult and cooperate in good faith with Indigenous peoples to obtain their free, prior, and informed consent (FPIC) before undertaking projects that may affect their land, territory, or resources (United Nations Declaration on the Rights of Indigenous People, 2007). While many countries have not translated FPIC into a legal requirement, almost all countries have provided for public participation under their EIA laws (Glucker et al., 2013; UNEP, 2018). However, the required level of participation varies considerably, and only a few countries' national EIA legislation includes provisions on the participation of Indigenous peoples (UNEP, 2018).

EIA is an important planning, decision-making, and management tool, through which climate change can be addressed (Mayer, 2019; Sok et al., 2011). EIA laws have led to the public highlighting the potential climate impacts of fossil fuel production, as evidenced in court rulings requiring climate impact assessments for new fossil fuel development (Aydos et al., 2020). However, public participation in the context of EIA can still be strengthened, with the scope of participation restricted and fraught with procedural challenges in many countries (UNEP, 2018).

Transparency is further needed when both governments and companies are planning for a fossil fuel wind-down, to ensure that stakeholders can participate in decision-making around reducing coal, oil, and gas production. In Germany, for example, the government formed a multi-stakeholder "coal commission" to determine how and when the country would move away from coal (Egenter & Wehrmann, 2019). Similarly, the South African government's National Planning Commission convened dialogues on pathways for a just transition (Strambo et al., 2019). Creating opportunities for civil society to weigh in on government energy plans and policies can help ensure that climate concerns — along with other social and environmental issues — play a role in the decision-making process.

[30] For example, in the United States, Native American reservations (2% of the land area), hold about 20% of the country's fossil fuel reserves, including coal, oil, and gas (Osborne, 2018). The Bowen Basin in Australia, which has the country's largest coal reserves, as well as oil and gas reserves, is a land of several Aboriginal communities (Petkova et al., 2009). In Nigeria, the Niger Delta, having the largest deposits of oil and gas and fraught with conflict, is home to numerous ethnic minorities (Naanen, 2012). In India, the largest coal deposits are in the states with the highest proportion of Scheduled Tribe population (Bhushan et al., 2020).

tary initiatives can achieve the same level of disclosure, given the low historic levels of company participation and compliance in voluntary mechanisms such as the EITI. Regulators should require the disclosure of forward-looking assumptions around, for example, future commodity prices, the useful lives of fossil fuel infrastructure, and the expected costs of complying with decommissioning obligations, since in many cases these items underpin the asset valuations presented in financial statements.

Considering the role SOEs play in fossil fuel markets, it is critical for these companies, their governments, and international initiatives to strengthen transparency standards on SOE spending, production projections, GHG emissions, and exposure to climate-related financial risk. National oil companies (NOCs) produce more than half the world's oil and gas, and invest around 40% of the total capital in the sector (Manley & Heller, 2021). They can be major players in the economies of their home countries; in at least 25 countries, NOCs collect revenues equivalent to more than 20% of all government revenues (Heller & Mihalyi, 2019).

Most NOCs report little about their operations and finances to the public. Of the 52 NOCs assessed in the 2017 *Resource Governance Index* from the Natural Resource Governance Institute (NRGI), 62% had "weak", "poor", or "failing" transparency (NRGI, 2017). Some have improved recently: Colombia's Ecopetrol and Malaysia's Petronas now release detailed information, while Saudi Aramco and the Nigerian National Petroleum Corporation have begun publishing financial reports. In addition, the EITI and the OECD's Working Party on State Ownership and Privatization Practices have strengthened standards for SOE reporting (EITI, 2019; OECD, 2019). Still, major gaps remain, including in reporting on how NOCs plan to navigate the energy transition.

As of June 2021, more than half of the 71 NOCs in NRGI's *National Oil Company Database* had not published their total capital expenditure for 2019, including major players such as the Abu Dhabi National Oil Company (ADNOC), Iraq's Basra Oil Company, and Petróleos de Venezuela, S.A. (PDVSA) (NRGI, 2021). Without this information, it is difficult to understand the drivers of the production gap and what is needed to close it, or how their spending exposes the public to climate-related financial risk. Even NOCs that do report their aggregate investments tend to disclose few details on projects or infrastructure spending, on the carbon intensity of production, or on the price required to avoid stranded assets. State-owned coal enterprises are also far from transparent. With few exceptions, the largest coal SOEs report little about their plans or expenditures, or about the impact of climate change on their viability (OECD, 2020).

5.3 Conclusions

Improved transparency plays an essential role in both assessing and closing the fossil fuel production gap. It can provide governmental and non-governmental stakehold-



ers with the needed information to support improved decision-making on fossil fuel production, infrastructure development, investment, and policies, thereby strengthening the accountability of governments' actions in light of climate goals. Moreover, transparency can facilitate international cooperation by building trust and promoting compliance with international commitments.

Various government-driven and non-governmental initiatives have begun to shed light on fossil fuel production and its impacts on climate goals. However, the available information is spotty and incomplete: many producer countries and companies have yet to participate, key types of information are not reported, the data are scattered across various initiatives, and initiatives are largely voluntary or driven by civil society. The lack of available and consistent information makes it difficult to properly assess the production gap and the extent to which governments are driving this gap, as well as identify opportunities for governments to close it.

Governments and other actors can work together to boost transparency, including by:

- disclosing plans and projections for fossil fuel production and for a just transition in NDCs, LT-LEDS, and UNFCCC national reports.
- providing information on fossil fuel infrastructure at various stages of development.
- divulging information on public finance for fossil fuels by production stage and financing mechanism.
- mandating that investor-owned and state-owned fossil fuel companies disclose their spending, project plans, GHG emissions (including end-use emissions), and climate-related financial risks.
- ensuring that the decision-making processes both for fossil fuel infrastructure and for winding down production are open and transparent, and that civil society has adequate capacity to engage.
- ensuring that relevant information on fossil fuel production is not only available, but also understandable, usable, and timely.

Governments can strengthen existing transparency initiatives, or create new ones. On the international stage, countries can make better use of existing mechanisms; for instance, they can convey information on fossil fuel



production through the UNFCCC, and improve subsidy reporting under the WTO and the SDGs. Multi-stakeholder initiatives such as the EITI can use their long-standing experience in the sector to strengthen transparency on the climate impacts of fossil fuel production, including by proposing uniform standards for information disclosure. New transparency initiatives may be warranted, however. Specifically, governments should consider establishing a dedicated platform for reporting and reviewing information on fossil fuel production, which would bring the dispersed information together in a harmonized and standardized manner, building on advances made by civil society organizations.

6

Closing the fossil fuel production gap

Key Messages

Governments have a primary role to play in closing the production gap and ensuring the transition away from fossil fuels is just and equitable.

Few countries have acknowledged the need to wind down fossil fuel production. Doing so can provide the impetus for governments to develop plans and implement policies that align their production with climate goals and commitments.

Governments can restrict fossil fuel exploration and extraction, phase out producer subsidies and public finance for fossil fuel projects, and re-direct support towards decarbonization and just transition efforts.

International cooperation can support a more effective and equitable transition away from fossil fuels.

6. Closing the fossil fuel production gap

Over 75% of global GHG emissions stem from fossil fuels (SEI et al., 2019). Meeting the agreed objectives of the Paris Agreement — and achieving net-zero emissions by mid-century — thus requires dramatic and sustained reductions in fossil fuel use and extraction. Existing national energy plans and outlooks, however, take the world in the opposite direction.

It has been six years since the adoption of the Paris Agreement. The continued presence of a wide production gap underscores the urgency with which **countries must align their fossil fuel production plans with global climate goals and commitments.** Thus far, most countries have focused their climate policies on reducing the *demand* for coal, oil, and gas, with their actions on the *supply* side of fossil fuels largely restricted to promoting carbon capture and storage and addressing emissions from extraction, processing, and distribution processes.

Governments can do much more, as they have a primary role to play in closing the production gap and in ensuring that the transition away from fossil fuels is just and equitable. State-owned enterprises (SOEs) control more than 50% of global fossil fuel production (see Chapter 3). While privately-owned fossil fuel companies also have important roles to play, and can take important steps to increase their alignment with climate objectives (Coffin, 2021; World Benchmarking Alliance, 2021), governments wield great influence: they drive private-sector exploration and extraction through their policies, permitting, and investments. The extent of COVID-19 recovery spending on fossil fuel energy since the start of the pandemic demonstrates how entrenched these industries remain.

Only a handful of countries clearly **acknowledge the need to wind down fossil fuel production to achieve the objectives of the Paris Agreement.** None are top producers. Such an acknowledgement is important: it can provide the impetus for developing plans for a managed wind-down of production and for implementing specific policy measures. Two policy areas for governments to pursue are:

- **Placing restrictions on fossil fuel exploration and extraction** to avoid locking in levels of fossil fuel supply that are inconsistent with climate goals. Examples of relevant policies include moratoria, bans, or limits on all or certain types of fossil fuel exploration and extraction (such as offshore or unconventional drilling) or infrastructure (such as oil pipelines or liquefied natural gas (LNG) terminals). Countries with higher financial and institutional capacity should lead the way with these restrictions, as they are better equipped for a rapid and sustained decline (Muttitt & Kartha, 2020; SEI et al., 2020).



- **Phasing out government support and financing for fossil fuel production.** As detailed in Chapter 3, governments continue to support domestic coal, oil, and gas production through fossil fuel subsidies, regulatory exemptions, aid to SOEs, and public funds, including those committed through COVID-19 recovery packages. In addition, support for overseas fossil fuel production provided through bilateral export credit agencies (ECAs), development finance institutions (DFIs), and multilateral development banks (MDBs) play a significant role in shaping the international energy landscape. Therefore, a key step towards closing the production gap is for governments to phase out their production support policies, ramp up the exclusion of fossil fuel projects from public finance institutions, and re-direct support towards decarbonization and just transition efforts.

Table 6.1 and Appendix A provide examples of governments and international financing institutions that have adopted these types of policies.

Table 6.1

Examples of actions that can support a managed wind-down of fossil fuel production (for a more detailed overview, see Appendix A).

	Action area	Examples
1.	Place restrictions on fossil fuel exploration and extraction	▪ Bans and moratoria on the exploration of certain fossil fuel resources have been enacted in Belize, Bulgaria, Costa Rica, Denmark, France, Ireland, the Netherlands, New Zealand, Portugal, Spain, and Zimbabwe, among other countries.
2.	Phase out government support and financing for fossil fuel production	▪ Numerous national public finance institutions and multilateral development banks have committed to ending future financing for coal, oil, or gas production projects, such as the European Investment Bank and the Agence Française de Développement Group (see Figure 3.4).
3.	Provide local and international support for diversification and a just and equitable transition	▪ Countries and regions such as the EU, Germany, Spain, and China have introduced just transition plans and measures to support affected workers, communities, and regions in transitioning away from coal, including through unemployment relief, retraining, and compensation. ▪ Canada, New Zealand, Scotland, the US, and South Africa have set up bodies to support governments in designing policies that mitigate the social repercussions of the transition away from fossil fuels.

It is also critical that governments ensure the wind-down of fossil fuel production is just and equitable, minimizing economic and social disruption for workers, enterprises, communities, and other stakeholders. In recent years, the concept of a "just transition" to a low-carbon society has gained significant traction, driven by ethical as well as strategic imperatives (Atteridge & Strambo, 2020; ILO, 2019; ITUC, 2017; Jenkins et al., 2020; UNFCCC, 2016). Indeed, a just and equitable transition is pivotal to reaching the level of consensus and social acceptability that is needed for the deep changes required to limit global warming to 1.5°C or well below 2°C (Green & Gambhir, 2019; Jakob et al., 2020; Robins, 2020; Winkler & Klinsky, 2018).

Increasingly, governments have made commitments to a just transition. The Paris Agreement formally recognized the imperative of a just transition (Paris Agreement, 2015 Preamble, Para.10), over 50 heads of state signed the Solidarity and Just Transition Silesia Declaration in 2018, and 46 countries have committed to place jobs at the heart of ambitious climate action (UNFCCC, 2018). Numerous countries have put in place national commissions, task forces, dialogues, and other policies. For example, in 2020, Germany approved the Structural Development Act, which provides financial support of up to EUR 40 billion (USD 46 billion) to mitigate the social and economic repercussions of the Coal Phase-out Act (Government of Germany, 2020). Also in 2020, South Africa established a Presidential Climate Change Coordinating Commission to advise the government on how to ensure a just and fair transition for communities and workers reliant on the coal sector (Lo, 2021; The Presidency of the Republic of South Africa, 2020). These and other examples are described in more detail in Appendix A.

Still, as the country profiles in Chapter 4 show, most major producing countries have not yet implemented strategies for workers, businesses, and communities to transition away from dependence on fossil fuel production. Given the pace of decline needed to meet climate goals, governments will need to act more swiftly and comprehensively to adopt and accelerate transition planning processes. They will need to dedicate greater resources to economic diversification and worker re-training. These steps increase the chances of a successful transition and can help to avoid leaving behind fossil-fuel-dependent workers, communities, and businesses; this includes the highly vulnerable informal sector, which is the source of many fossil fuel production jobs, especially for coal, but has yet to receive much attention in just transition efforts (see Box 6.1). Such strategies will also need to address the needs of communities that have borne the negative socio-economic and health impacts of production (Healy et al., 2019; Hernández, 2015; O'Rourke & Connolly, 2003).

Finally, **international cooperation can support a more effective and equitable transition away from fossil fuels.** Through international processes such as the UNFCCC, governments can enhance transparency and ambition by communicating plans to align their fossil fuel production and climate goals, including through their NDCs and long-term low emissions development strategies under the Paris Agreement (see Chapter 5). Additionally, countries can also engage in other forms of cooperation, such as multilateral clubs and treaties, to coordinate the winding down

of fossil fuel production (Green, 2018; Newell & Simms, 2019). Some countries, such as Costa Rica and Denmark, have begun paving the way for more ambitious, coordinated action by jointly announcing commitments to phase out fossil fuel production (Jørgensen & Murillo, 2020).

Through international cooperation, countries can also seek to ensure that declines in fossil fuel production are distributed as equitably as possible, while minimizing the risks of disruption and maximizing the participation of affected stakeholders (Achakulwisut & Erickson, 2021; Green & Denniss, 2018). International cooperation can also direct support to countries that face the most risk in a transition, due to their limited financial and institutional capacity and high dependence on fossil fuel production (SEI et al., 2020).

International financial institutions also have a key role to play: they can restrict financing for fossil fuel projects and direct it to just transition measures (SEI et al., 2020). As shown in Chapter 3, an increasing number of MDBs and bilateral DFIs are enacting or considering policies to limit or exclude financing for fossil fuel production. Countries can accelerate this process for multilateral institutions, and expand it to include export credit agencies and other vehicles for public finance.

As the impacts of climate change become even clearer and starker, citizens will be looking to their governments to put the world on a net-zero emissions trajectory as rapidly as possible. To do so, governments will need to reckon with the production gap, and in short order, take the steps needed to close it.



Box 6.1. A just and equitable transition for the informal economy

Just transition efforts to date have focused heavily on the needs of those in the formal economy, who are employed with regular hours and wages in positions subject to tax and legal requirements. However, many fossil-fuel-production-related activities take place in the informal economy. This is especially true in some coal-dependent regions of the global South. In India, for example, nearly 360,000 people work in formal coal mining operations (Bhushan et al., 2020), while over 15 million depend on coal for income (Chandra, 2019), many by gathering coal manually and selling it at local markets (Lahiri-Dutt, 2014). Informal coal mining for subsistence use and small-scale commerce is also common in South Africa, and informal employment plays a key role in the main coal-producing regions of Colombia (Burton et al., 2018; DANE, 2021).

The informal workforce is generally poorer, with lower life expectancies, fewer years of schooling, and greater socio-economic challenges than the formal workforce. Consequently, it has less capacity to adapt to the types of economic and social changes that a rapid transition away from fossil fuels would bring (Bhushan et al., 2020). Therefore, where the informal sector is a significant part of the economy, just transition efforts should place a particular focus on it, providing skills, mobility, and alternative livelihood opportunities — for example, in agriculture, forestry, and fisheries or in mine closure and rehabilitation — with pathways to join the formal economy. Engagement, through social dialogue with representatives of the informal sector, particularly the Indigenous communities and women who often make up a significant part of the informal economy, is critical to ensure that their needs are met (NSO, 2020). Addressing energy poverty and providing households with access to modern energy services, as well as providing other social and physical infrastructure, is another key step in building community resilience for the transition.



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Appendix A

Examples of actions towards a managed wind-down of fossil fuel production

Place restrictions on fossil fuel exploration and extraction			
Year	**Country**	**Jurisdiction**	**Example**
2021	Spain	National	Spain ended all new exploration and extraction of oil and gas, as well as "high volume" fracking.[A1]
2021	Denmark	Subnational	Greenland banned all future oil and gas exploration.[A2]
2021	Ireland	National	Ireland ended new licenses for oil and gas exploration and extraction, following a 2017 ban on exploration and extraction of onshore petroleum by hydraulic fracturing.[A3]
2021	United States	Local	Whatcom county in Washington State prohibited new fossil fuel infrastructure, including ports, refineries, and power plants.[A4]
2021	United States	Subnational	The State of California will stop issuing fracking permits by 2024 and is analyzing pathways to phase out oil extraction by 2045.[A5]
2020	Zimbabwe	National	Zimbabwe announced a ban on coal mining in national parks.[A6]
2020, 2018	Denmark	National	Denmark ended new licensing for oil and gas extraction and exploration in the North Sea in 2020. Previously, in 2018, Denmark banned exploration and drilling for oil, gas, and shale gas on land and in inland waters.[A7]
2020	Portugal	National	Portugal announced the end of contracts for oil and gas exploration.[A8]
2019	Costa Rica	National	Costa Rica extended its moratorium on oil exploration and extraction until 2050. The moratorium was first enacted in 2002 and extended in 2011.[A9]
2019	Brazil	Subnational	The State of Paraná prohibited the exploitation of shale gas using the fracking technique.[A10]
2019	The Netherlands	National	The Netherlands banned shale gas exploration in 2013 and is expected to complete the phasing out of gas extraction in the province of Groningen by 2022.[A11]
2018	Australia	Subnational	The State of Tasmania extended its moratorium on fracking for hydrocarbon resource extraction until March 2025.[A12]
2018	Uruguay	National	Uruguay issued a four-year moratorium on hydraulic fracturing (2018 – 2021), with proposed legislation to extend the moratorium for 10 years.[A13]
2018	New Zealand	National	New Zealand ended new offshore oil and gas exploration permits.[A14]
2018	Belize	National	Belize adopted a moratorium on offshore oil exploration and drilling.[A15]
2012	Bulgaria	National	Bulgaria adopted a ban on shale gas exploration and production, and a conditional ban on hydraulic fracturing methods.[A16]

Phase out public support and financing for domestic and overseas fossil fuel production			
Year	**Country**	**Jurisdiction**	**Example**
2021	United Kingdom	Bilateral	The UK government ended new support for overseas fossil fuel projects.[A17]
2021	Inter-governmental	Multilateral	Under a draft energy policy expected to be approved after the release of this report, the Asian Development Bank commits not to finance any fossil fuel exploration or production, nor coal-power and heat plants or facilities associated with new coal generation.[A18]
2021	United States	Multilateral	The US Treasury provided guidance restricting its support for coal and gas financing at multilateral development banks.[A19]
2019	IGO	Multilateral	The European Investment Bank Energy will no longer consider new financing for unabated, fossil fuel energy projects, including gas, from the end of 2021 onwards.[A20]
2019	France	Bilateral	France's state-owned development agency Agence Française de Développement (AFD) Group ceased new finance for coal projects and fossil fuel transport.[A21]

2019	Germany	Bilateral	Germany's state-owned development and investment bank, KfW group, ceased new finance to coal-related upstream activities, infrastructure associated with coal, and upstream activities related to bituminous shale, tar sands or oil sands.[A22]
2018	Ireland	National	Ireland's Fossil Fuel Divestment Act 2018 requires the Ireland Strategic Investment Fund (ISIF) to divest from fossil fuel undertakings.[A23]
2017	Sweden	Bilateral	Swedfund (Development Finance Institution of the Swedish government) adopted a ban on fossil fuel investments.[A24]

Provide local and international support for diversification and just, equitable transitions			
Year	**Country**	**Jurisdiction**	**Example**
2021	United States	National	The US established the White House Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization to identify and deliver resources to support workers and communities reliant on the fossil fuel sector.[A25]
2021	Spain	National	In 2018, Spain established a Just Transition Strategy (2019–2027) that includes early retirement for miners over age 48, retraining for green jobs, and environmental restoration. Spain's 2021 Climate Change and Energy Transition Act requires the government to publish a Just Transition Strategy every five years.[A26]
2021	Chile	National	The government is developing a Just Transition Strategy, with local action plans to assess the needs of coal regions, mitigate the socioeconomic repercussions of coal-fired power plant closures, and maximize the benefits of the transition in affected areas.[A27]
2021	Scotland	National	Scotland's Just Transition Commission called for the introduction of just transition plans in high-emitting industrial sectors and support measures for workers in carbon-intensive sectors.[A28]
2021	United States	Subnational	The State of California, by Executive Order mandate, is designing a Just Transition Roadmap focusing on workers and communities reliant on fossil fuel industries.[A29]
2021, 2020	United States	Subnational	The State of Colorado developed a just transition action plan in 2020, with USD 15 million committed in 2021 toward just transition of coal-dependent communities and associated workers including economic diversification efforts.[A30]
2020, 2019	South Africa	National	South Africa established a Presidential Climate Change Commission to advise the government on how to ensure a just transition for communities and workers reliant on the coal sector. South Africa also includes just transition considerations as part of its energy planning.[A31]
2020	Germany	National	Germany's Structural Development Act provides financial support for regions affected by coal phase-out of up to EUR 40 bn (USD 46 bn) to support investments in clean energy, infrastructure, research and innovation, and labour market policies.[A32]
2020	Greece	National	Greece established a Just Transition Development Plan running from 2021–2027. Assistance for coal-dependent regions includes income support, social protection policies, reskilling and entrepreneurship development.[A33]
2020	Ireland	National	Ireland established the National Just Transition Fund (JTF) with EUR 12.5 million committed to projects related to retraining and sustainable employment as of July 2021.[A34]
2020	Poland	Subnational	The region of Eastern Wielkopolska set a just transition plan assuming that coal mining will be discontinued in 2030.[A35]
2020	Inter-governmental	Multilateral	The European Bank for Reconstruction and Development's just transition initiative aims to help those whose livelihoods are affected by the transition process through reskilling and enhancing entrepreneurship, and support for regional economic development.[A36]
2019	EU	Supra-national	The EU's Just Transition Mechanism offers targeted support to regions most affected by the transition, including knowledge, technical and advisory support, and the expected mobilization of at least EUR 65-75 billion over the period 2021–2027.[A37]
2018	Canada	National	Canada established a Task Force on Just Transition for Canadian coal power workers and communities. The government dedicated CAD 35 million (USD 26 million) over five years to support skills development and economic diversification activities.[A38]
2016	China	National	China's 13th Five-Year Plan for the Coal Industry included just transition support measures such as support for workers, unemployment relief, and training and job placement services (2016–2020).[A39]

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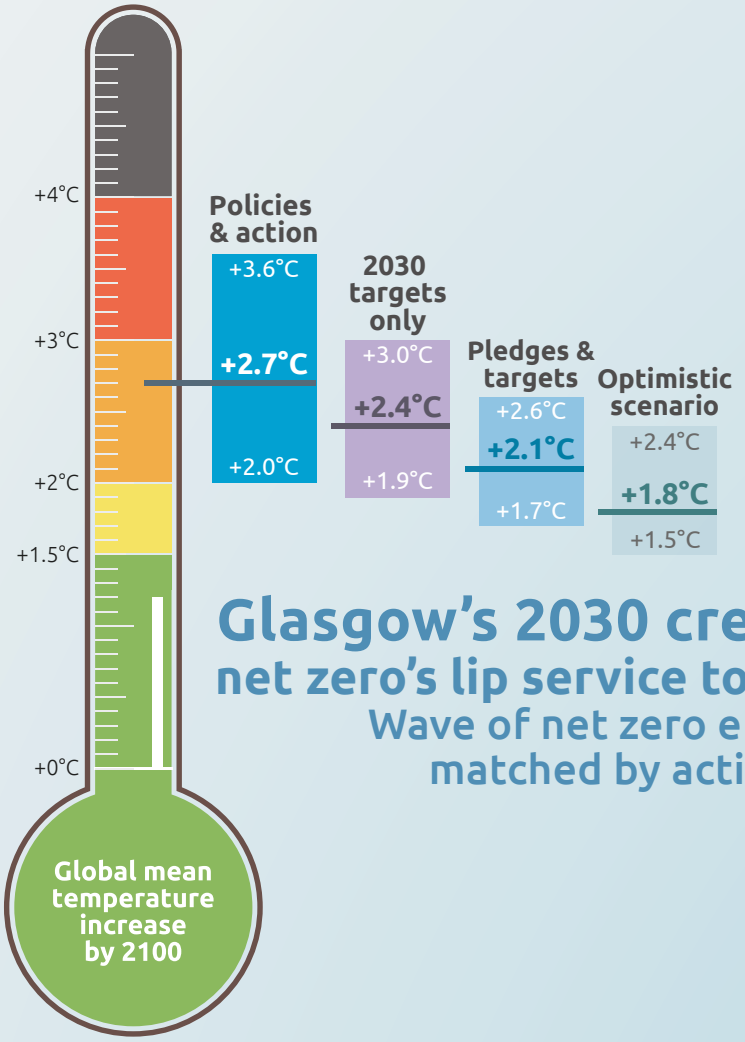
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DOCUMENT 9

Climate Action Tracker



Glasgow's 2030 credibility gap:
net zero's lip service to climate action
Wave of net zero emission goals not matched by action on the ground

Climate Action Tracker

Warming Projections Global Update

November 2021

CLIMATE ANALYTICS

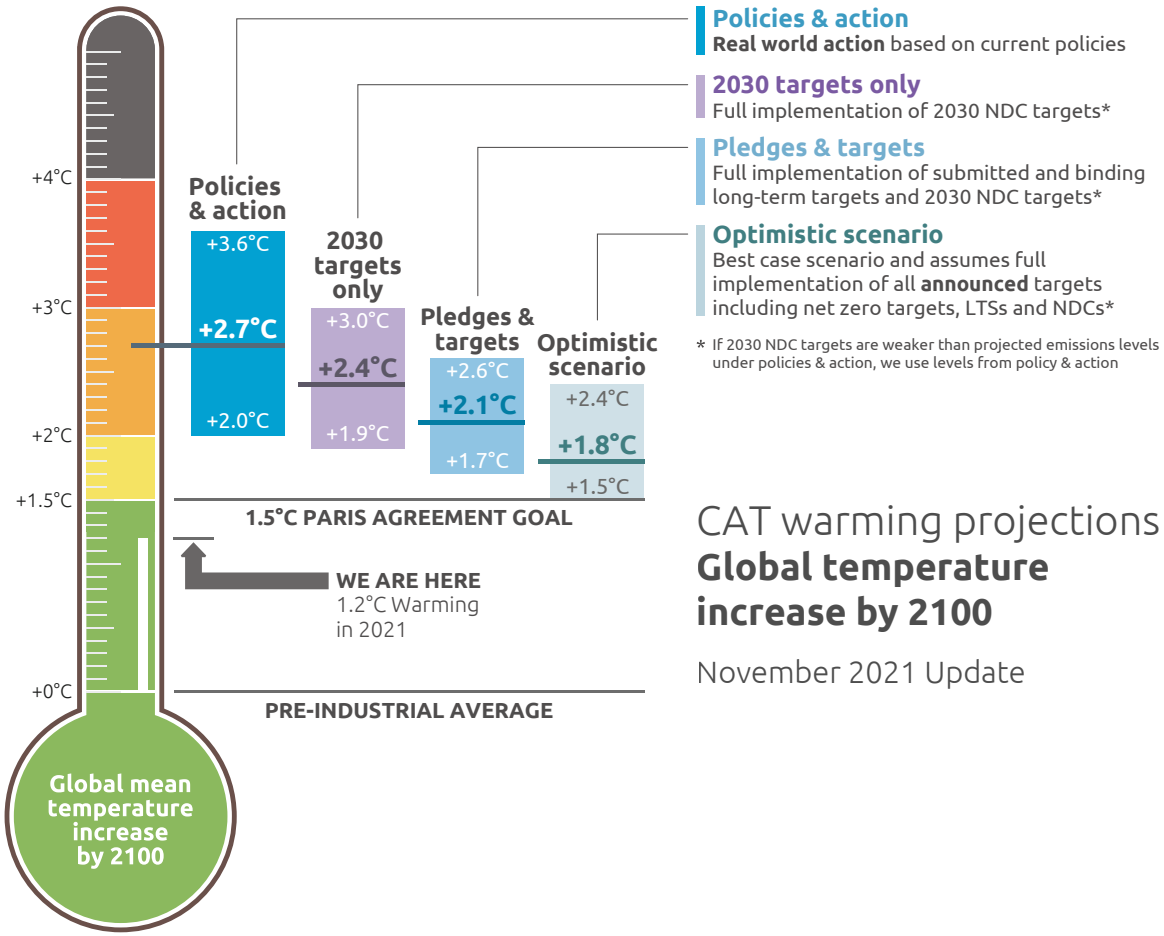
NEW CLIMATE INSTITUTE

Summary

In Paris, all governments solemnly promised to come to COP26, with more ambitious 2030 commitments to close the massive 2030 emissions gap that was already evident in 2015. Three years later the IPCC Special Report on 1.5°C reinforced the scientific imperative, and earlier this year it called a climate "code red." Now, **at the midpoint of Glasgow, it is clear there is a massive credibility, action and commitment gap** that casts a long and dark shadow of doubt over the net zero goals put forward by more than 140 countries, covering 90% of global emissions.

Policy implementation on the ground is advancing at a snail's pace. Under current policies, we estimate end-of-century warming to be 2.7°C. While this temperature estimate has fallen since our September 2020 assessment, major new policy developments are not the driving factor. We need to see a profound effort in in all sectors, in this decade, to decarbonise the world to be in line with 1.5°C.

Targets for 2030 remain totally inadequate: the current 2030 targets[1] (without long-term pledges) put us on track for a 2.4°C temperature increase by the end of the century.[2] Since the April 2021 Biden Leaders' Summit, our standard "pledges and targets" scenario temperature estimate of all NDCs and submitted or binding long-term targets has dropped by 0.3°C to 2.1°C, but this improvement is due primarily to the inclusion of the US and China's net zero targets, now that both countries have submitted their long-term strategies to the UNFCCC.



1 For weak targets, we take a country's estimated 2030 level under current policies, if that level is lower than the target.

2 Normally, the CAT bases its temperature estimates on all binding targets, including both 2030 and longer-term net zero targets; however, as more and more countries adopt their net zero targets in domestic law or submit long-term strategies to the UNFCCC, we felt the need to include this new temperature estimate to highlight the growing credibility gap between targets in 2030 and net zero targets for 2050 or later.

There has been insufficient momentum from leaders and governments to increase 2030 climate targets ahead of, and at, Glasgow: NDC improvements submitted over the last year have reduced the emissions gap in 2030 by only 15-17%. The biggest absolute contributions to this narrowing come from China, EU and the US, though other countries with lower emissions levels have also improved their NDCs.

Contrary to the Paris Agreement's requirement that each NDC update is a progression beyond the last, several governments have only resubmitted the same target as 2015 (Australia, Indonesia, Russia, Singapore, Switzerland, Thailand, Viet Nam), or submitted an even less ambitious target (Brazil, Mexico). Some have not made new submissions at all (Turkey and Kazakhstan), and Iran has yet to ratify the Paris Agreement. **Even with all new Glasgow pledges for 2030, we will emit roughly twice as much in 2030 as required for 1.5°. Therefore, *all* governments need to reconsider their targets.**

Globally, around 90% of emissions are now covered by net zero targets. While these targets are an important signal, and some have accelerated governments' climate action, the quality of most remains questionable. If all the announced net zero commitments or targets under discussion are implemented, this would bring our temperature estimate for this "optimistic scenario" down to 1.8°C by 2100, with peak warming of 1.9°C. But this is only **IF** these targets are fully implemented, and it's a big IF. Our analysis, covering 40 countries, shows only 6% of global emissions are covered by targets with an "acceptable" net zero rating for target comprehensiveness.

No single country that we analyse has sufficient short-term policies in place to put itself on track to its net zero target. The net zero CAT assessment also includes announcements made by governments which are not backed up by any national legislation, nor plans. Some lack critical information to allow for a full evaluation of the target's likely impact, including whether net-zero is defined as CO_2 only or covers all greenhouse gases. It also needs to be emphasised that **our 'optimistic' assessment of end-of-century median warming of about 1.8°C is not Paris Agreement compatible and that *warming of 2.4°C or more cannot be ruled out.***

2030 actions and targets are more often than not inconsistent with net zero goals, so that the gap between current policies and net zero goals is now 0.9°C. This, we consider, is the credibility gap that Glasgow needs to address.

The key drivers for this appalling outlook are coal and gas.

Coal

To meet the Paris Agreement's 1.5˚C warming limit, **coal must be phased out of the power sector by 2030 in the OECD, and globally by 2040**. But in spite of political momentum and clear benefits beyond climate change mitigation, there is still a huge amount of coal in the pipeline, for example in **China, India, Indonesia** and **Viet Nam**, and too many countries, including **Japan, South Korea, Australia**, still have plans centered around coal as a major contributor to electricity generation in 2030. Some also continue funding coal projects abroad. While some of these governments have committed in Glasgow to phasing out coal, we need to see that reflected on the ground at home.

Natural gas

The increasing use of natural gas is not Paris Agreement compatible, yet we are seeing the gas industry push and promote their product, supported by governments across the world. In the six years since the Paris Agreement, CO_2 emissions from gas grew by 9%, whereas emissions from coal and oil are down. Gas for electricity generation, as with coal, needs to peak in this decade, and largely be phased out globally in the coming decades, and for other applications

soon after, if the world is to reach net zero CO_2 by 2050. In Southeast Asia, heavily coal-dependent countries are now considering a switch from coal to gas (e.g. Viet Nam), rather than directly to renewables, large infrastructure for natural gas is also under development in Europe (Nord Stream 2 for imports from Russia), Canada (expansions of pipelines for export), Australia and the USA (LNG exports), and multiple African countries are promoting the increased production and use of natural gas.

Methane and forestry

Global methane and forestry initiatives announced in Glasgow support important actions, but these must go beyond existing national targets to be impactful: the Global Methane Pledge – of reducing methane emissions by 30% in 2030 – has the maximum potential to reduce the 2030 emissions gap by 14%, and warming by -0.12°C by 2100. But much of this potential is already included in existing climate pledges. The US is a prime example: the methane reduction target is already partially included in its long-term strategy, which we have already included the effect of in our 'Pledges and Targets' temperature estimate. Similarly, the Global Forestry Finance pledge can result in additional climate mitigation only if this finance is additional to the current promised funding and does not cut funding for other mitigation measures. Since the USD 100bn goal has not yet been met, the additionality of this new initiative is questionable, at best.

Glasgow must address the credibility gap

While the warming outlook has improved since Paris, the bottom line is that despite all the net zero promises, inadequate real-world action unable to deliver the kind of climate action that is aligned to the 1.5˚C temperature limit: in 2015, ahead of the Paris Agreement, the CAT estimated current policies would lead to warming of 3.6°C, and the submitted targets (NDCs) would lead to 2.7°C. Six years later, the warming from current policies has now come down to 2.7°C. If governments were to achieve their 2030 NDC targets and binding long-term targets (LTS), temperature increase could be limited to 2.1°C.

If governments are serious about the Paris Agreement's temperature limit and their own net-zero goals, they need to translate those long-term goals into net-zero aligned ambitious 2030 targets and implement the necessary policies today. Developed countries will also significantly increase the climate finance available to support the transition. Until this happens, there is no cause for celebration.

Table of Contents

Summary i

1 2030 targets are totally inadequate and put achieving 1.5°C at risk 1

2 NDCs updates are not in line with the Paris Agreement 3

3 Implementation gap is growing – and doing better is not enough 6

4 Sector and gas initiatives must go beyond existing national targets to be impactful 8

5 Net zero targets – inching closer to 1.5°C – but credibility is questionable 8

6 Warming outlook has improved since Paris 12

7 Country snapshots 13

Annex 17

A1 Scenario definition 17

A2 Detailed overview of net zero target assessments 19

A3 Optimistic Temperature Estimate Assumptions 21

A4 Differences between Climate Action Tracker, UNFCCC Synthesis Report & UNEP Gap Report 28

1 2030 targets are totally inadequate and put achieving 1.5°C at risk

The IPCC has set clear benchmarks. To keep the possibility of 1.5°C alive, we need to cut emissions by 45% below 2010 levels by 2030, in other words, halve emissions from present levels by then.

Updated NDC targets fall short, far short, of meeting this benchmark. The 2020/2021 round of NDC updates has only reduced the emissions gap in 2030 by 15-17%. Even after the new update round, global emissions in 2030 resulting from implementation of NDCs will still be twice as high as what's needed for a 1.5°C consistent pathway.

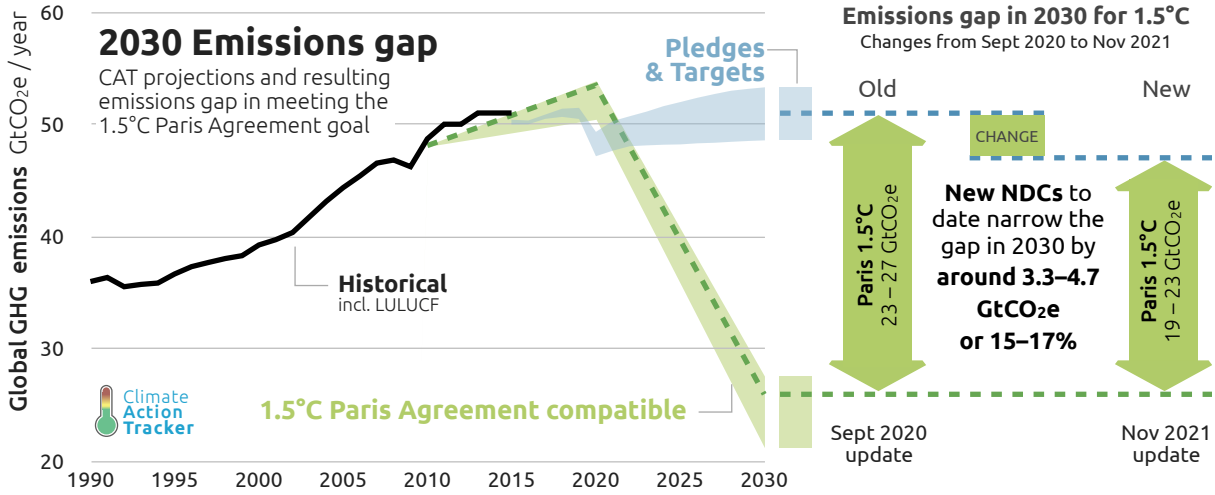


Figure 1 2030 emissions gap between NDC targets and levels consistent with 1.5°C.

If just these targets[3] are considered, end-of-century warming would be 2.4°C, almost a full degree above the Paris limit, at a time when every 0.1°C matters. Normally, the CAT bases its temperature estimates on all binding targets, including both 2030 and longer-term net zero targets; however, as more and more countries adopt their net zero targets in domestic law or submit long-term strategies to the UNFCCC, we felt the need to include this new temperature estimate to highlight the growing credibility gap between targets in 2030 and net zero targets for 2050 or later (see Figure 2).

This credibility gap grows larger when we turn our attention to policy implementation. Under current policies, end-of-century warming will be 2.7°C.[4] While this temperature estimate has fallen since our last assessment, major new policy developments are not the driving factor. It is also still well above our "2030 targets only" temperature estimate, indicating that, collectively, countries are not on track to achieve the targets they have put forward.

3 For weak targets, we take a country's estimated 2030 level under current policies, if that level is lower than the target.

4 We have updated the data for most of the countries we track since our last assessment in September 2020. See Annex I for details.

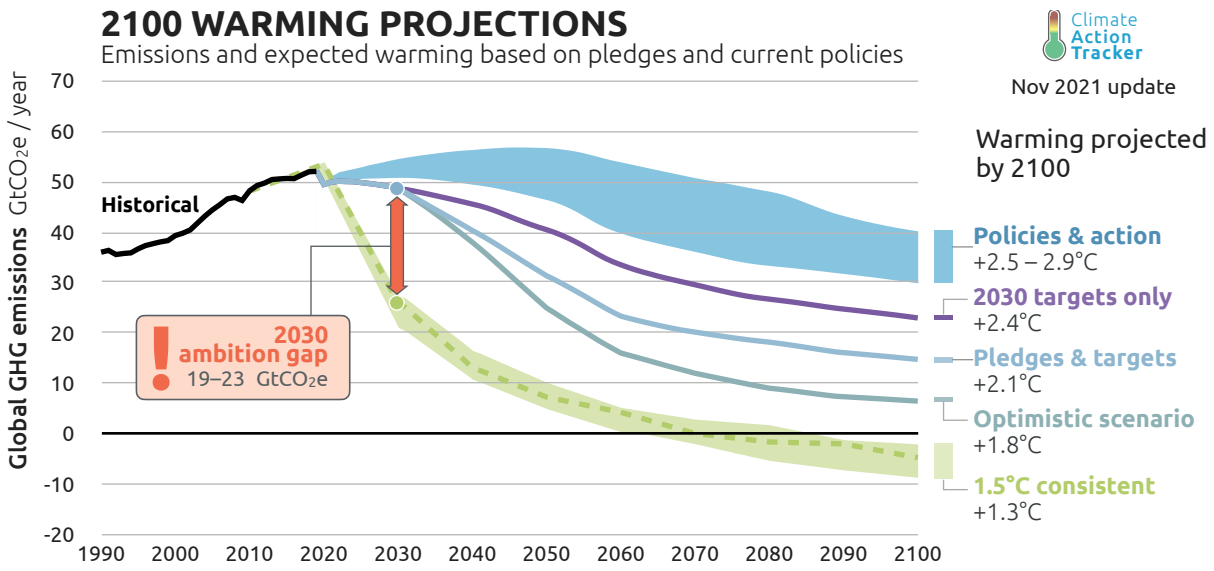


Figure 2 Global greenhouse gas emission pathways for CAT estimates of policies and action, 2030 targets only, 2030 and binding long-term targets and an optimistic pathway based on net zero targets of over 140 countries in comparison to a 1.5°C consistent pathway.

When all NDCs and binding[5] long-term pledges are considered (our "pledges and targets" scenario), end-of-century warming would be limited to 2.1°C. While this estimate is 0.3°C lower than our May 2021 assessment, the drop is primarily due to the official submissions of the long-term plans of US and China.

Expanding our scope to include all net zero targets that have been announced or are currently under discussion, including the most recent announcement from **India**, warming would peak at 1.9°C before falling to 1.8°C by the end of the century. While an estimate that comes under the 2°C level is an important milestone, it must be stressed that this is based on only a 50 / 50 chance that warming will indeed be limited to 1.8°C by 2100 and 1.9°C at its peak. While the level of warming in 2100, in probabilistic terms, is "likely" to be below 2.0°C, the same is not true of the peak level of warming in this century. But again, we reiterate that according to our analysis, only 6% of global emissions are covered by, in our analysis, an "acceptable" net zero target.

In recent weeks, many different organisations have published estimates of the impact of targets on temperature estimates. While at first glance, the headline figures may appear different, a closer examination of the underlying methods reveals that these are closely aligned and offer the same general message: 2030 targets are totally inadequate and put achieving 1.5°C at risk (see Annex 4 for further details).

5 We consider targets to be binding if they have been adopted in domestic legislation or submitted, with sufficient clarity, in long-term strategies to the UNFCCC. We exclude older submissions if we deem that the country has abandoned its target. See Annex I for details.

2 NDCs updates are not in line with the Paris Agreement

The majority of countries have submitted NDC updates, but emission cuts in 2030 remain woefully inadequate.

With the announced update from India, more than three-quarters of countries, representing near global emissions coverage (over 95%) and close to 90% of the population, have announced or submitted updates. Turkey is the only G20 country to not have submitted an update, having only ratified the Paris Agreement in October 2021.

While the number of NDC updates is high, the quality of the submissions varies greatly, with a great majority not raising ambition enough, and, in several cases, not raising ambition at all.

IMPROVEMENTS

Since our last update in May, some countries have submitted stronger targets, with a few going beyond their initial announcements.

- **SOUTH AFRICA** heeded the call of its Presidential Climate Commission and submitted a stronger NDC target in September 2021 than it had originally proposed earlier in the year. The bottom end of this range is knocking on the door of 1.5°C compatibility.
- **MOROCCO** strengthened its NDC targets in June 2021, its unconditional target is 1.5°C compatible, while its conditional target, for which it will need support to meet, is within striking distance of the 1.5°C limit.
- **UKRAINE** also submitted a stronger target, adopting the bottom end of the range it originally announced in December 2020. It still has some way to go to be 1.5°C compatible, but if the Ukraine fully implements all the policies it has planned, it could exceed its updated target.
- **ARGENTINA** submitted the slightly stronger it announced at Biden's Leaders' Summit in April 2021. With this strengthening, Argentina's domestic target is now compatible with a 2°C world, but it is still far off from 1.5°C compatible or doing its fair share.
- **NEW ZEALAND'S** new target appears to be continuing with its long history of creative accounting tricks that obscure its effective reductions, and it is still far from doing its fair share.
- **CANADA** and **JAPAN** have officially submitted the targets they announced at Biden's Leaders' Summit: while both domestic targets are getting closer, they still fall short of 1.5°C compatibility.
- **CHINA** officially submitted the stronger targets it had announced last year. While an improvement, these targets are still within the expected emissions level in 2030 under current policies, meaning that China can achieve these targets without further measures. China has yet to commit to a peaking year for carbon dioxide emissions before 2030, nor set absolute emission reduction targets, which leads to uncertainty around its emissions trajectory to 2030. It is also far off a 1.5°C compatible pathway
- **SOUTH KOREA** announced a stronger NDC target during the Glasgow World Leaders Summit. This announced domestic target has halved the distance to becoming 2°C compatible, but it is still far off from 1.5°C compatible or doing its fair share.

UNCERTAIN

For others, it has been harder to assess whether the targets are stronger, given the lack of details.

- **INDIA** announced updated NDC targets during the World Leaders Summit, but provided few details. Its new intensity target is unlikely to have any real-world effect, as it falls above India's likely 2030 emission level under current policies, while its 500GW non-fossil target will, at most, have a small impact on real-world emissions. Prime Minister Modi promised net zero by 2070, but did not mention any plans to phase out coal, despite having one of the highest coal capacities and pipelines in the world. Recent CAT analysis shows the early retirement of the existing capacity and a reduction of its pipeline could enable India to meet its fair share and save a quarter of a million premature deaths.
- **SAUDI ARABIA** has submitted an updated NDC with a seemingly stronger target, although it is difficult to assess this, as it has not communicated the baseline emissions upon which the reduction is based. The updated NDC retains its 'escape clause': the emissions reduction pledge is contingent on continued and significant oil and gas exports, without which Saudi Arabia reserves itself the right to revisit its target.

UNCHANGED

Unfortunately, it is quite clear that the laggards are still lagging.

- **AUSTRALIA** resubmitted its 2030 target unchanged. It claimed that this will be exceeded by up to 9%. The Paris Agreement requires countries to increase their ambition with each update: claiming that you will overachieve your target without actually committing to a stronger target does not cut it. Based on our assessment of current policies, the government may meet the lower bound of its 2030 target, but not overachieve it. Australia's new 2050 net zero target is also questionable (more on that in the net zero section below).
- **BRAZIL** continues to obfuscate with creative accounting tricks. While the headline reduction target has increased from 43% to 50%, changes in the baseline mean that this target is still less ambitious than the first NDC on an absolute basis. As of 4 November 2021, Brazil had also not submitted this update to the UNFCCC. **MEXICO** did a similar thing with its update last year.
- **INDONESIA** submitted an updated NDC in July 2021 but did not strengthen its 2030 target. It now joins the "submitted the same or a weaker target" club, along with **RUSSIA, SINGAPORE, SWITZERLAND, THAILAND** and **VIET NAM**, contrary to the Paris Agreement's requirement that each NDC must result in lower emissions than its predecessor.
- **TURKEY** finally ratified the Paris Agreement on 11 October 2021 at which time it officially submitted its 2015 INDC to the UNFCCC. This target is very weak and Turkey has been on track to overachieve it for some time. It needs to submit a much stronger updated target.
- **IRAN** has still not ratified the Paris Agreement, nor updated its 2030 target.
- **KAZAKHSTAN** has still not submitted an update target.

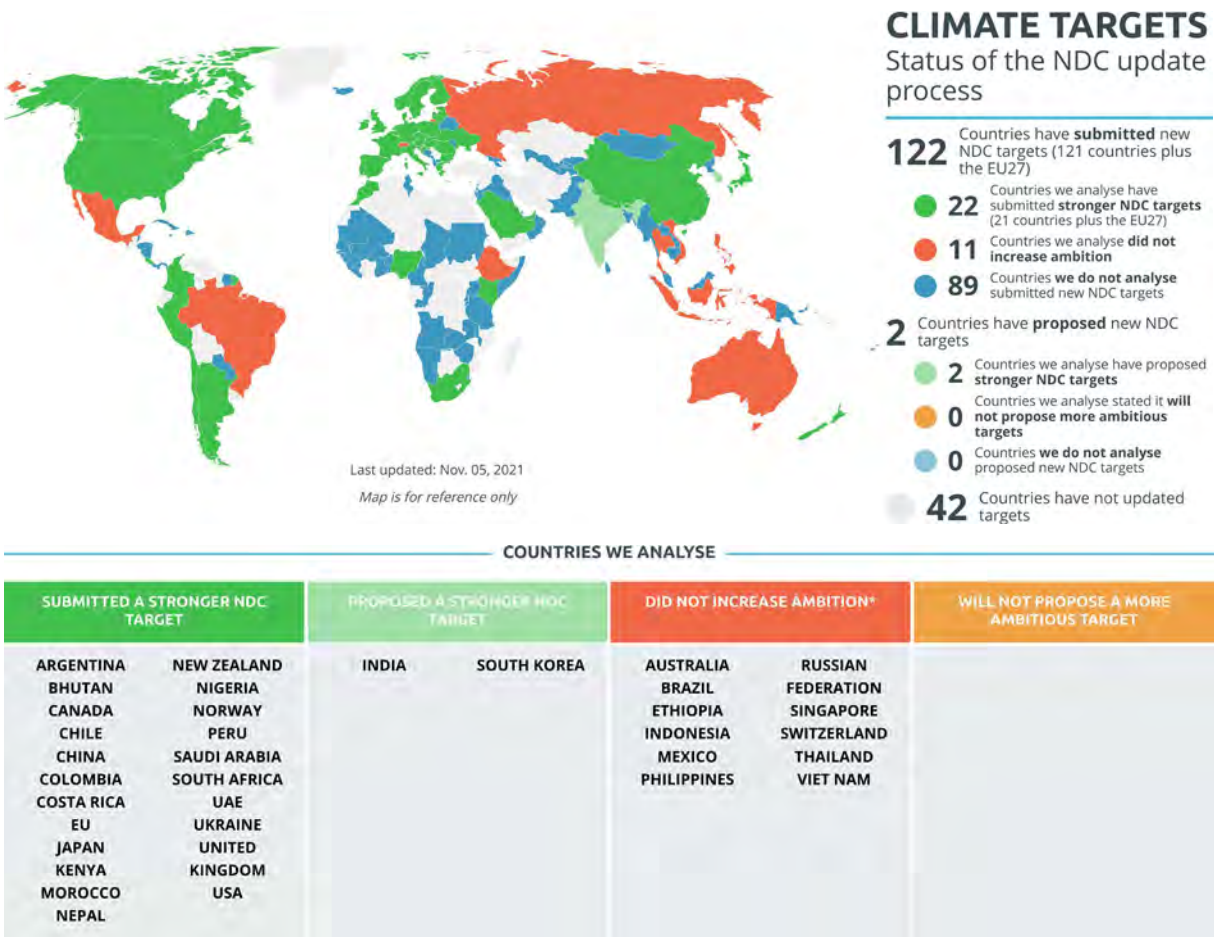


Figure 3 Status of NDC updates as of 5 November 2021. See our Climate Target Update Tracker page for further details.

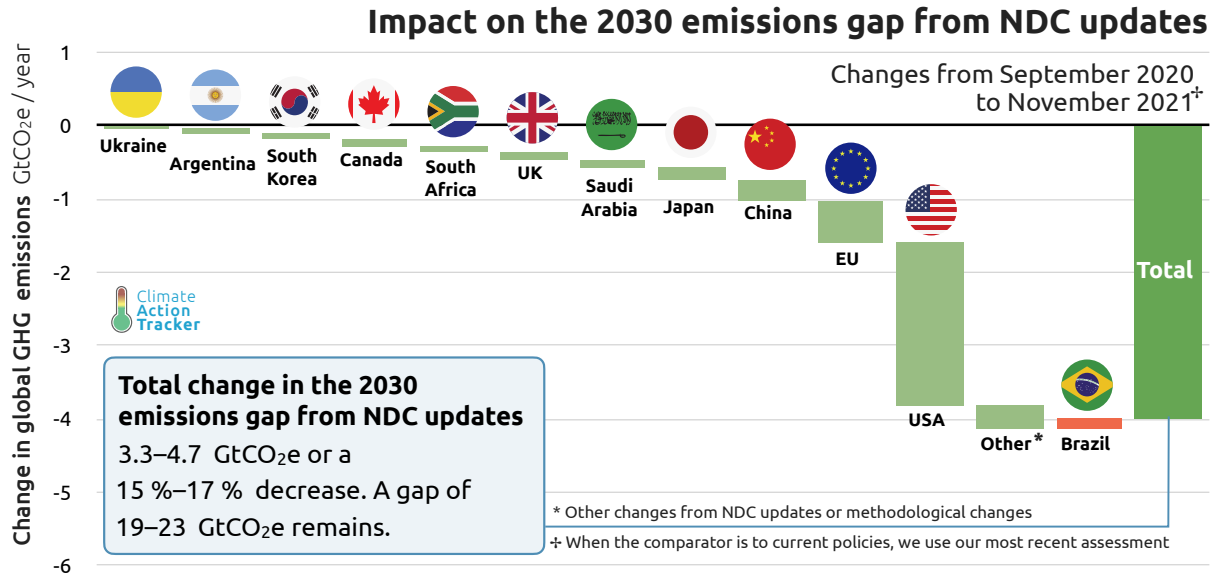


Figure 4 Impact of NDC updates since September 2020 on the reduction in the 2030 emissions gap.

Figure 4 shows the changes in contribution to the emissions gap since last September, while this has improved since our May 2021 update.[6] At the end of the day, the gap remains substantial.

6 While we are not able to track all countries, we have improved our methods in relation to emissions estimates for non-CAT countries. Part of the change is due to NDC updates and part is due to methodological improvements: we used the quantified NDC for over 100 countries based on the mitiQ tool provide by the Potsdam Institute for Climate Impact Research and updated the baseline of the remaining countries based on the newest PRIMAP baselines. These changes are also reflected in the waterfall graph.

3 Implementation gap is growing – and doing better is not enough

While our estimate of temperature warming based on real world action has fallen, the pace is still not fast enough to achieve the Paris Agreement temperature goal and countries are risking a lock-in in coal and gas infrastructure.

Coal

Kicking the coal habit should be on the top of everyone's policy agenda. Globally, we need to phase out coal-fired power generation by 2040, and by 2030 in developed countries, to keep the Paris temperature limit within reach. The COP26 presidency supports those targets through the Powering Past Coal Alliance, and has set accelerating the transition from coal to clean power as a key objective for COP26. Before and during Glasgow, multiple countries have strengthened or announced coal phase-out targets and other initiatives, including the first of its kind partnership to support the transition in a developing country away from coal, the Just Energy Transition Partnership of UK, EU, Germany, France and South Africa.

Phasing out coal has a number of benefits beyond climate protection. CAT analysis shows that faster coal plant retirements and reducing the new plant pipeline could avoid hundreds of thousands of premature deaths in the next decade in India and Indonesia alone. If India were to eliminate its coal pipeline and retire plants 18 years or older, it would reduce emissions enough to be making its fair share contribution to climate change. Electricity generation with existing coal-fired power plants is very often more expensive than building new renewable energy, calling into question the economic sensibility of new coal plants.

Despite the political momentum and clear benefits beyond climate change mitigation, there is still a huge amount of coal in the pipeline, for example in China and India. And too many countries still plan for coal to be a major contributor to electricity generation in 2030 (e.g. Japan 19%, South Korea 30%), although they have revised their energy sector planning. Some countries also continue to fund coal projects — public money spent on infrastructure at risk of becoming a stranded asset. China tops the list of countries financing coal projects internationally (but has announced it will stop doing so), followed by Japan, Czech Republic, Russia, and South Korea.

Natural gas

The increasing use of natural gas is not Paris Agreement compatible, yet we are seeing this pushed and promoted by the gas industry and supported by governments across the world. While, for example, Chile's progress to reduce coal-fired power generation is remarkable, it is not enough for 1.5°C. Chile's plans for retrofitting include the option of switching to natural gas. Gas reduces the emissions intensity compared to coal, but risks locking in higher emissions levels than required for 1.5°C, and increases dependency on energy imports. Gas for electricity generation, similarly to coal, needs to largely be phased out globally in the coming decades.

We are seeing similar developments in Southeast Asia, where heavily coal-dependent countries are now considering a switch from coal to gas, next to expanding renewables. Large infrastructure for natural gas is also under development in Europe (Nord Stream 2 for imports from Russia), Canada (expansions of pipelines for export), and USA (LNG exports), and multiple African countries are promoting the increased production and use of natural gas (e.g. Nigeria).

The recent gas price hikes in Europe illustrate the vulnerability of gas dependence. The answer to such a crisis is building up renewable energy and improving energy efficiency, actions that contribute to a sustainable pathway in the long term and are, to a large extent, independent of geopolitical developments - not the further expansion of gas infrastructure to improve the supply.

The CAT had already warned in 2017 about relying on gas in the transition towards 1.5°C pathways. Since then, research has become even clearer on the required decrease of the role of gas and the associated risks of investing in gas infrastructure, including the limitations of repurposing gas infrastructure for green gases later on.

If governments are serious about the Paris Agreement's temperature limit and their own net

zero goals, they need to realise what those long-term goals require in terms of short-term action, to guarantee the least disruptive pathway possible. Increasing ambition for 2030 follows naturally from such considerations.

Climate finance

To accelerate implementation globally, and ensure that all countries benefit from the transition to 1.5°C, **developed countries need to massively increase international climate finance**. Sufficient climate finance is critical to ensure that developing countries are able to meet their targets. None of the developed countries the CAT tracks have put forward sufficient climate finance (Figure 5). Recent analysis shows that the USD 100bn goal will only be met in 2023. While the goal is projected to be met around 2023, the anticipated level of USD 113-117bn in 2025 is still far below what would represent a fair contribution, but also what is needed. The Just Energy Transition Partnership for South Africa is a promising development, while details on the terms and quality of the financing are still outstanding.

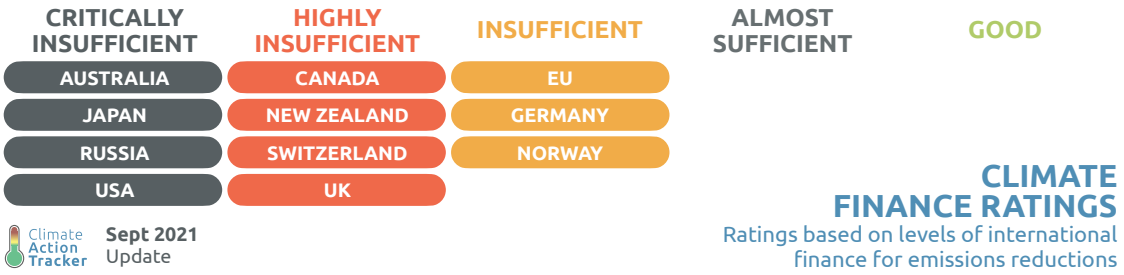


Figure 5 CAT climate finance ratings of developed countries.

Eliminating the provision of finance for fossil fuel developments internationally goes hand-in-hand with increasing climate finance, and stopping fossil fuel subsidies. The world already has sufficient oil and gas supply and no new field development is needed if we are serious about reaching net zero globally. Financing, or otherwise supporting such projects, in developing countries puts them at great risk for stranded assets, undermining efforts for sustainable development.

4 Sector and gas initiatives must go beyond existing national targets to be impactful

The Global Methane and Global Forest Finance Pledges made headlines in Glasgow, but their additional impact on the atmosphere is uncertain.

An increasing number of countries have joined the Global Methane Pledge to cut 30% of methane emissions by 2030 and the Global Forestry Finance Pledge.

Global methane emissions are projected to increase in the next decade by 4% under the current NDCs (7-12% under current policies). Any effort to reduce this gas emissions, in both the short and long term, will have a positive effect on the climate and contribute to slowing the global temperature increase.

One rapid assessment has estimated that **the Global Methane Pledge has the maximal potential to reduce the 2030 emissions gap** –the difference between current pledges and where we would need to be for 1.5°C in 2030—**by 3GtCO$_2$e (14% reduction)**. A different study attributed **a maximum warming reduction of -0.12°C** by end of the century. Both studies considered all countries in the world, not only those that have signed the Pledge, and considered all methane reductions as additional to existing activities.

The actual impact of the Global Methane Pledge is likely much lower. The pledge can only have a larger contribution to climate change mitigation if it is additional to the actions already committed by governments to meet NDCs and long-term strategies. However, this might not be the case for most countries. A prominent example is the US, which has already partially included the 30% methane reduction pledge by 2030 in its recently-submitted long-term strategy. The CAT temperature projections, discussed earlier in this briefing, do not consider additional emissions reductions from the Global Methane Pledge. We will only include them in future assessments, if they are shown to be additional to existing national climate pledges.

The same is likely the case for the Global Forest Finance Pledge, which was signed by most G20 countries, to provide finance to halt deforestation, promote forests restoration, and improve forest management. While stopping deforestation is important, governments should not solely rely on the forestry sector to capture emissions, but instead seek to decarbonise all sectors by implementing concrete measures. Currently, CO_2 emissions from land-use, land-use change and forestry make up roughly 5% (1 GtCO$_2$e) of the emission gap in 2030.

The Global Forest Finance Pledge will result in additional climate mitigation only if this finance is additional to the current levels of funding promised and does not cut other mitigation measures. Since the 100bn goal has not yet been met, the additionality of this initiative is questionable.

5 Net zero targets – inching closer to 1.5°C – but credibility is questionable

While NDCs, and their present level of implementation, lead to warming well above 2°C, the picture appears brighter when one considers all recently announced net zero targets, but their credibility is questionable.

Around 90% of global emissions now fall under net zero targets (Figure 6). **India** is the most recent major emitter to announce a net zero goal. Together with **China**, the **EU**, and **USA**, these four countries represent more than half of global greenhouse gas emissions. Even countries with a poor track record in fighting climate change, such as **Australia**, **Russia**, **Saudi Arabia**, **Turkey** and the **United Arab Emirates**, have felt obliged to also commit to net zero emissions. As of 2 November 2021, over 140 countries had announced or are considering net zero targets, covering 90% of global emissions (Figure 6), compared to the 130 countries, covering about 70% emissions, in May 2021.

Our 'optimistic scenario' now shows that if all governments were to fully implement their net zero targets, global temperature increase can be as low as 1.8°C, a 0.2°C improvement on our May 2021 estimate. While going below the 2°C level is an important milestone, it must be stressed that this estimate is based on only a 50 / 50 chance that warming will, indeed, be limited to 1.8°C. In probabilistic terms, warming is likely below 2.0°C. And, while words are good, one must judge governments by their actions.

Governments need to improve their net zero target design. In total, according to the CAT's "good practice" net zero analysis, the design of net zero targets covering a total of 73% of global emissions remains insufficient (Figure 7). Only four of the 40 countries covered by the CAT, responsible for 6% of global GHG emissions, have defined their net zero targets in an 'acceptable' way in terms of scope, architecture, and transparency. Another four countries, responsible for 17% of global emissions, fall into the 'average' category.

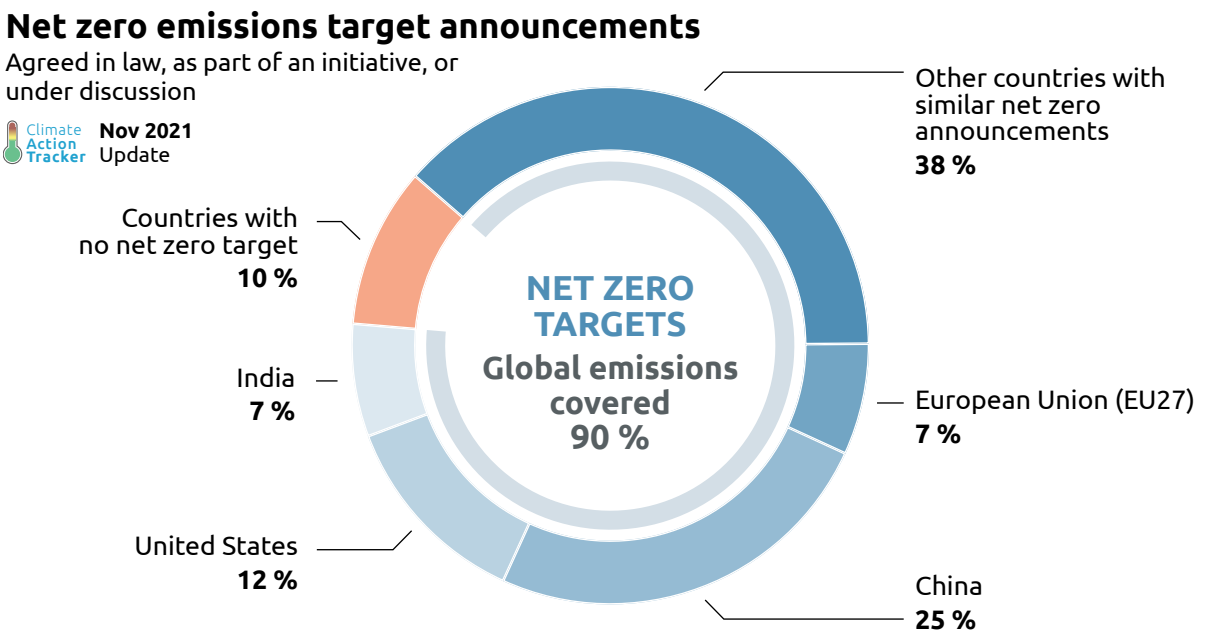


Figure 6 Share of GHG emissions covered by countries that have adopted or announced net zero emission targets (agreed in law, as part of an initiative, or under discussion). Compilation based on ECIU (2021) as of 2 November 2021 complemented by CAT analysis. Emissions data for 2017 taken from EDGAR emissions database (EDGAR, 2019).

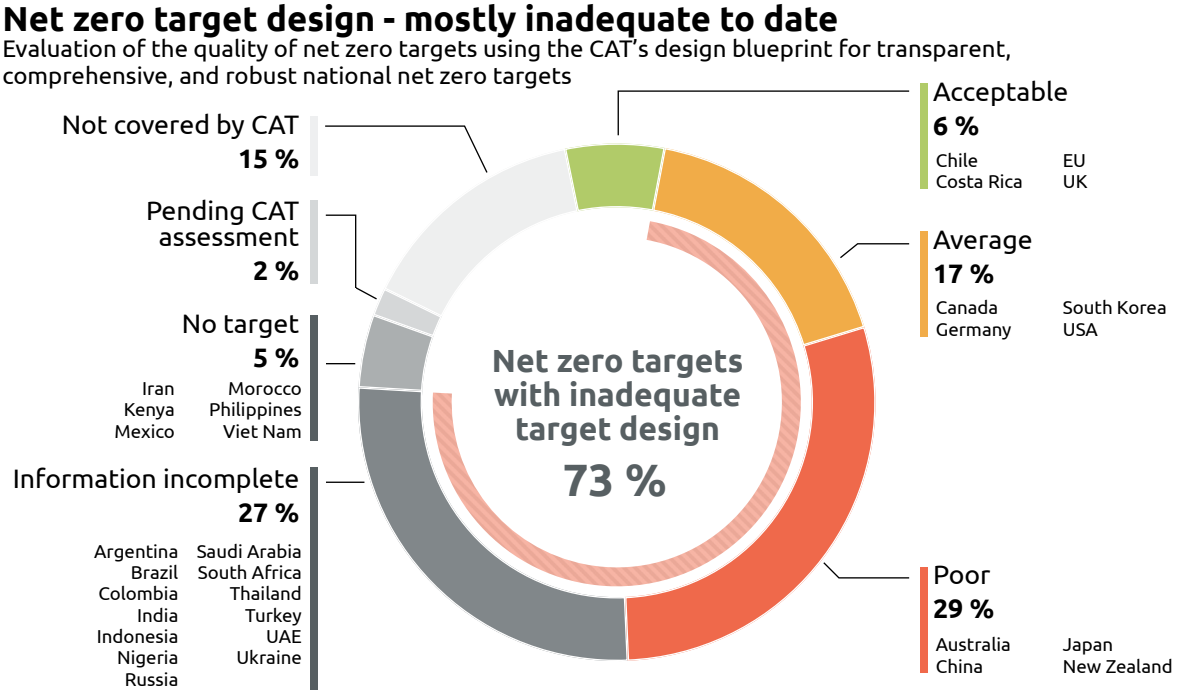


Figure 7 Share of global GHG emissions by Climate Action Tracker's headline evaluation for announced net zero targets as of November 2021. Emissions data for 2017 taken from EDGAR emissions database (EDGAR, 2019).

Australia, **Russia**, **Saudi Arabia**, **Turkey**, and the **United Arab Emirates** have put forward net zero targets that lack critical details on scope, target architecture, and transparency (Table 1). These announcements will only be credible if they are followed by robust legislations and detailed plans on how to achieve net zero, as well as stronger 2030 targets to put the countries on track to meet them. At their worst, these governments and others intend to use these vague and aspirational targets in the distant future to distract from inadequate short-term action.

Table 1: Overview of Climate Action Tracker's net zero target evaluations for Australia, Russia, Saudi Arabia, Turkey, and United Arab Emirates as of 2 November 2021

Rating the comprehensiveness of national net zero target design Country	Rating	Net zero target design elements 1 Target year	2 Emissions coverage	3 International aviation and shipping	4 Reductions or removals outside of own border	5 Legal status	6 Separate reduction & removal targets	7 Review process	8 Carbon dioxide removal	9 Comprehensive planning	10 Clarity on fairness of target
Australia	POOR	2050	✓	✗	✗	–	✗	–	✗	✗	✗
Turkey	INFORMATION INCOMPLETE	2053	✓	?	?	–	?	?	?	?	?
UAE	INFORMATION INCOMPLETE	2050	✗	?	?	–	?	?	?	?	?
Russia	INFORMATION INCOMPLETE	2060	✗	?	?	–	?	?	?	?	?
Saudi Arabia	INFORMATION INCOMPLETE	2060	✗	?	?	–	?	?	?	?	?

The **Indian** 2070 net zero target announcement caused a big stir during the World Leaders Summit in Glasgow. As with other recent net zero announcements, critical details on scope, target architecture, and transparency are lacking. While Prime Minister Modi referred to 'net zero' in his announcement at COP26, it is not clear whether that covers CO_2 or all GHGs.

Other countries are moving forward with elaborating on their net zero targets. Canada, Japan, South Korea and **Germany** legislated their net zero target in recent months, bringing the number of G20 countries with such target enshrined in law to seven.

Although Japan improved various aspects of its net zero targets in recent months, we still evaluate the target as 'poor', as it lacks clarity on key elements. Canada, Germany, and South Korea all have net zero targets that we evaluate as 'average' - these countries are on the right track, but still have substantial room for improvement. The **USA's** net zero target moved up from 'target information incomplete' to the 'average' category. The country submitted its LTS, with information on some key elements, in November 2021. China's target went from 'target information incomplete' to the 'poor' category, as its LTS lacks detail on most elements. Whereas we previously assumed China's target covered all GHGs, the LTS indicates it only covers CO_2 emissions. Finally, our evaluation of the **United Kingdom's** target moved from 'average' to 'acceptable' after the UK government published a detailed plan to achieve net zero. Only four countries covered by the CAT have net zero targets that fall into this category (see Table 2).

Table 2: Overview of Climate Action Tracker's net zero target evaluations for G20 member countries (excluding non-CAT countries France and Italy) and selected others as of November 2021.

CAT Net zero evaluation of comprehensiveness of target design		
Country	**Previous assessment** Status as of Sept 2021	**New assessment** Status as of Nov 2021
Chile	ACCEPTABLE	
Costa Rica	ACCEPTABLE	
EU	ACCEPTABLE	
UK	AVERAGE	ACCEPTABLE
Canada	AVERAGE	
Germany	AVERAGE	AVERAGE
South Korea	POOR	AVERAGE
USA	INFORMATION INCOMPLETE	AVERAGE
Australia	POOR	
China	INFORMATION INCOMPLETE	POOR
Japan	POOR	POOR
New Zealand	POOR	
Argentina	INFORMATION INCOMPLETE	
Brazil	INFORMATION INCOMPLETE	
Colombia	INFORMATION INCOMPLETE	
South Africa	INFORMATION INCOMPLETE	
Ukraine	INFORMATION INCOMPLETE	
India	INFORMATION INCOMPLETE	
Indonesia	INFORMATION INCOMPLETE	
Russia	INFORMATION INCOMPLETE	
Saudi Arabia	INFORMATION INCOMPLETE	
Turkey	INFORMATION INCOMPLETE	
UAE	INFORMATION INCOMPLETE	
Iran	NO TARGET	
Mexico[7]	NO TARGET	

A complete overview of our in-depth assessment can be found in Annex 2. These evaluations aim to provide a nuanced assessment of national net zero targets to understand their scope, architecture, and transparency. Without such scrutiny, there is a risk that poorly backed up net zero claims could render these targets meaningless.

7 We do not consider Mexico to have a net zero target, but do include the country in the Optimistic scenario as ECIU lists their net zero target as under discussion (see Annex 1 and 3 for details).

6 Warming outlook has improved since Paris

In 2015, ahead of the Paris Agreement, the CAT estimated current policies would lead to warming of 3.6°C, and the submitted targets (NDCs) would lead to 2.7˚C. Six years later, the warming from current policies has now come down to 2.7°C. If governments were to achieve all their submitted NDC pledges and long-term targets, temperature increase could be limited to 2.1°C. Adding all the net zero targets announced and discussed, this would even lead to 1.8°C. **The Paris Agreement ratcheting-up mechanism is working, but not fast enough.**

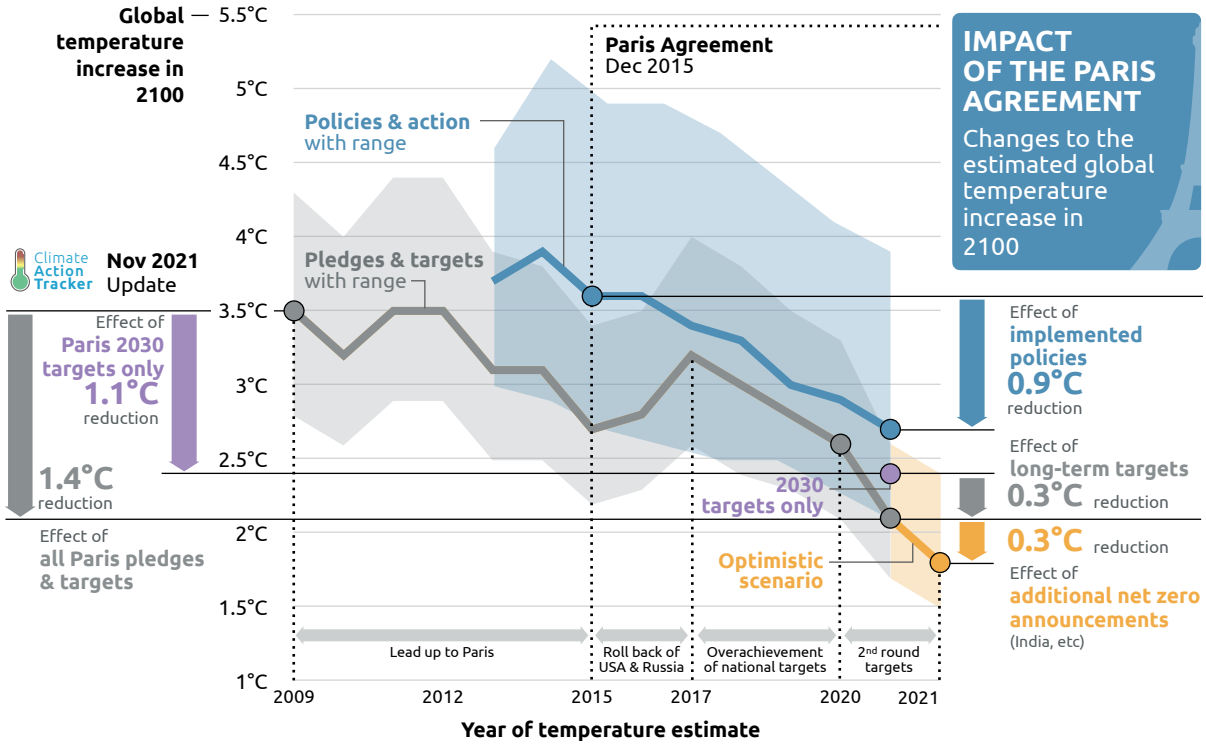


Figure 9 Impact of the Paris Agreement on the estimated global temperature increase in 2100. Figure shows the estimates of the Climate Action Tracker from 2009-2021 for "pledges and targets" and "current policies".[8] In this update, we have also added a temperature estimate for 2030 targets only.

8 The Climate Action Tracker is continuously updating and refining its methodology. As a result, the temperature estimates in this figure cannot solely be attributed to target improvements or real-world action; however, the figure does show the overall progression of our estimates.

7 Country snapshots



ARGENTINA submitted an updated and slightly more ambitious NDC in November 2021 based on the announcement in May 2021. Argentina continues to prioritise oil and gas exploitation in its energy strategy—in "Vaca Muerta", the world's second largest shale gas reserve—jeopardising the achievement of its climate objectives.



AUSTRALIA refused to strengthen its 2030 climate target, while claiming it could exceed it. Its continued strategy supporting fossil fuels (especially gas) over renewable energy is of major concern and makes its new net zero claim not credible. Australia has put forward a net zero target that lacks critical details on its scope, target architecture, and transparency.



BHUTAN submitted a second NDC in June 2021, which reiterated its goal to remain carbon neutral. However, increasing energy and industry emissions could put Bhutan in a difficult position in the long-term and risk breaking its carbon neutrality.



BRAZIL'S new announced 2030 target is only stronger on paper and, at best, only reverts some of the damage caused by the 2020 NDC update. Lack of clarity on the references used makes the target emissions level uncertain.



CANADA has updated its NDC, but needs to focus on implementing the policies to achieve it as it is currently far off-track. It continues to fund fossil fuel pipelines, exceeding the capacity need. Raising transport emissions are also a concern.



CHILE has increased the speed of its coal phase-out and approved a new energy efficiency law that could bring emissions under current policies downward. If all planned policies are implemented Chile could peak emissions two years before planned, in 2023. It has recently submitted a long-term strategy.



CHINA submitted only a mildly more ambitious NDC, which will make net zero CO_2 emissions by 2060 difficult to achieve. China is giving mixed signals about coal. While signals to "phase down" coal consumption are welcome, coal power increased by a net 29.8GW in 2020, 76% of the world's new coal plants.



COLOMBIA adopted a stronger target in its NDC update, but needs stronger action across the board. It must increase renewables and abandon coal, fracking plans – especially as coal mining investors are leaving the country. Deforestation is of great concern as LULUCF are 30% of its emissions.



COSTA RICA updated its NDC in December 2020, slightly increasing the ambition of its 2030 climate target and improving its target architecture. It outlined various sectoral measures and targets, and could improve further by specifying the sectoral breakdown.



ETHIOPIA submitted an NDC update in July 2021 committing to its first unconditional emissions target. It will achieve both targets if current policies are fully implemented.



The EUROPEAN UNION member states' policies are far from sufficient to meet the emissions reduction target of "at least 55%" below 1990. Some of its members are pushing for continued public funding of natural gas infrastructure – all while paying the price for the EU's high reliance on fossil fuel imports amidst the current energy crisis. The EU needs to step up ambition at home, and provide international finance to support decarbonisation abroad.



GERMANY'S updated target for 2030 and coal phase-out by 2038 is inconsistent with 1.5˚ C. It has a large and growing emissions gap in the transport sector. Renewables will not reach its 65% by 2030 target, which is, by itself, too low.



INDIA'S announced NDC will, at most, mildly improve emission reductions beyond current policies. Its 2070 net zero target is welcome, but it is difficult to evaluate due to a lack of clarity over its gas coverage. This target is incompatible with India's huge coal pipeline and this issue needs to be addressed. Its first COVID19 recovery package prioritised fossil fuels, but the second has some stimulus aimed at a green recovery.



INDONESIA'S coal pipeline is huge, while renewables face many regulatory hurdles. In 2020 alone, fossil fuel subsidies were a massive USD 7bn. Forests are still in decline, amid rollbacks of environmental regulation. Indonesia submitted an NDC in July 2021 but did not strengthen its 2030 target. In Glasgow, Indonesia joined the list of countries promising to phase out coal.



IRAN is the only country out of the 40 we assess that has yet to ratify the Paris Agreement. It is expected to overachieve its INDC due to an inflated baseline. This OPEC member's economy is dominated by fossil fuels despite having huge renewables potential.



JAPAN'S new 2030 target level is now close to being 1.5˚C-compatible. Government policies reduce emissions, but not enough to match the 46% emissions reduction target. Reducing coal to 19% share of power mix in 2030 is better, but it needs to be zero.



KAZAKHSTAN has yet to update its 2030 climate target. The failure to increase its mitigation ambition for 2030 does not comply with the Paris Agreement's requirement that each successive NDC should present a progression beyond the current one.



KENYA updated its NDC in December 2020, where it slightly increased its 2030 targets and provided an unconditional target.



MEXICO'S government continues to show a lack of commitment to climate change by refusing to update its climate target, rolling back regulation meant to foster investment in renewable energy, and favouring fossil fuels over renewables.



MOROCCO strengthened its unconditional and conditional 2030 emissions reductions targets in June 2021. It has one of the highest levels of renewable energy capacity in Africa, but it also continues to heavily rely on coal to meet its electricity needs.



NEPAL submitted its second NDC on December 2020, which, for the first time, included part of their energy-related targets as unconditional commitments. The submission also strengthened the conditional target's transparency, included more quantifiable targets and reference to a net zero target.



NEW ZEALAND is exempting methane from its 2050 target, with no policies to address 40% of its emissions (agriculture). Its emissions reduction plan must focus on high emitting sectors, not forests. It plans to meet a full two thirds of its new NDC by buying international credits.



NIGERIA has an ambitious 2030 renewable energy target, which it is not on track to achieve, due to slow implementation. Nigeria should reconsider policies to revive its coal sector and expand its gas market. These policies run the risk of stranded assets and are at odds with the Paris Agreements 1.5°C limit.



NORWAY was the world's ninth largest natural gas and eleventh largest oil producer in 2020—with no end in sight for continued exploration. Its 2020 NDC will cut emissions by at least 50% by 2030 and aims for a 55% emissions reduction below 1990 levels. If Norway were to drop the 50% target and move to the 55% target, consistent with the EU's update goal, its target would become 1.5°C compatible when compared to the minimum it needs to cut emissions within its own borders.



PERU'S updated NDC will result in 2030 emissions that are 6% lower than its predecessor. We estimate that Peru can reach this target with existing policies, and could therefore increase its climate targets. The updated NDC includes a goal to reach carbon neutrality by 2050.



THE PHILIPPINES increased its conditional target from 70% to 75% below BAU; and has proposed an unconditional target in its updated NDC for the first time. The unconditional target is well above emissions projections under current policies, and thus does not strengthen the country's own ambition. To achieve the conditional target, the Philippines would need international support for its planned policies as well as to adopt additional measures.



RUSSIA'S Energy Strategy focuses almost exclusively on promoting fossil fuels: extraction, consumption and exports. Its renewable target is negligible. It also intends to use unmanaged forests in its accounting, violating UN guidelines. This makes the new net zero pledge not credible.



SAUDI ARABIA'S updated 2030 target is contingent on a significant contribution of oil and gas exports to its economy, and it reserves itself the right to update its NDC target should exports decline as a result of other governments implementing the Paris Agreement. Despite numerous announcements and targets since 2013, renewables supply only 0.1% of electricity generation—far from the 50% target by 2030 in the NDC. There are still several uncertainties about the newly announced 2060 net zero target.



SINGAPORE updated its NDC in March 2020. While it improved the form of its target, moving from an emissions intensity target to an absolute cap on emissions and adopting the latest IPCC reporting guidelines, as well as gas coverage, the level at which Singapore will limit emissions remains unchanged.



SOUTH AFRICA'S submitted a stronger 2030 target in September 2021. The uncertainty around the successful implementation of the Integrated Resource Plan (IRP2019) remains high, given state-owned utility giant Eskom's unresolved financial and operational problems and government's poor past performance in managing the energy transition.



SOUTH KOREA is making slow progress in climate change mitigation and energy sector planning. It has cut coal, but is replacing it with gas, still a fossil fuel that must be phased out. The share of fossil fuels in power sector is still at 67%. South Korea's government appears to have backpedalled on its vow to stop funding international coal. At COP26, South Korea proposed a more ambitious NDC to reduce emissions by 40% by 2030 and has progressed on the development of its net-zero target, which is now enshrined in law.



SWITZERLAND rejected its amended CO_2 Act in a June 2021 referendum and did not submit a more ambitious target, a significant setback to progressing its climate action. Putting forward an alternative set of policies and regulations should now be a top priority.



THAILAND is shifting out of coal, but its huge push towards gas is a highly risky investment for the climate & stranded assets. We estimate that Thailand will not reach its weak 2030 target with current policies. In good news: Thailand has shown recent intent to get on track.



THE GAMBIA proposes more action in its second NDC but higher historical and baseline emissions means absolute emissions are higher, may impact CAT rating, full analysis to come.



TURKEY has ratified the Paris Agreement and set a 2053 net zero target, but details on how it will reach this target are lacking. It has not updated its very unambitious 2030 target and still has a large pipeline of planned coal power plants.



The **UNITED ARAB EMIRATES** was the first Gulf country to update its NDC in December 2020, setting the UAE's first economy-wide emissions reduction target for 2030. It has also recently announced a net zero target for 2050. The 2050 National Energy Strategy foresees expansion plans for coal and natural gas, which is inconsistent with global decarbonisation by 2050.



The **UNITED KINGDOM'S** Net Zero Strategy maps out several potential scenarios to achieve its 2050 target, but details on how it will achieve its 2030 and 2035 targets are still lacking.



UKRAINE submitted an updated NDC in July 2021, including a target of 65% reduction below 1990 levels by 2030 – a significant improvement from its previous target of at least 40% reduction below 1990 by 2030, and an announcement of climate neutrality no later than 2060.



The **UNITED STATES OF AMERICA'S** emissions will remain relatively high, reaching 16-18% below 2005 levels in 2030, far short of its 50-52% reduction target, without new policies. On November 5, the US passed one of two major bills before Congress, each with considerable steps forward on climate action. Together, both bills represent a major step forward for the US in bringing its 2030 target within reach. The US also submitted a long-term strategy at the beginning of COP26.



VIET NAM has the world's third largest coal pipeline, after China & India, & massive plans for gas. While it has supported some renewables, it has the potential to become a regional leader for solar energy & offshore wind.

Annex

A1 Scenario definition

What's included in the various temperature scenario?

Table 3: Overview of what is included for each country under the various Climate Action Tracker's temperature projections for 2100 (November 2021 update).

Country	2030 targets only*	Pledges & Targets		Optimistic scenario		Policies & action data from
		2030 NDC target*	Net Zero targets	NZT included?	Method	
Argentina	Updated NDC (Nov. 2021)	Updated NDC (Nov. 2021)	No	Yes	Conservative global estimate	July 2020
Australia	Current policies	Current policies	Yes (max)	Yes (min)	CAT estimate	Nov. 2021
Bhutan	Current policies	Current policies	No	Yes	Conservative global estimate	Nov. 2021
Brazil	Announced NDC (Nov. 2021)	Announced NDC (Nov. 2021)	No	Yes	CAT estimate	Nov. 2021
Canada	Updated NDC (July 2021)	Updated NDC (July 2021)	Yes (max)	Yes (min)	CAT estimate	Sept. 2021
Chile	Updated NDC (April 2020)	Updated NDC (April 2020)	Yes	Yes	CAT estimate	Nov. 2021
China	Updated NDC (Oct. 2021)	Updated NDC (Oct. 2021)	Yes (max)	Yes (min)	CAT estimate	Sept. 2021
Colombia	Updated NDC (Dec. 2020)	Updated NDC (Dec. 2020)	No	Yes	CAT estimate	Sept. 2021
Costa Rica	Updated NDC (Dec. 2020)	Updated NDC (Dec. 2020)	Yes (max)	Yes (min)	CAT estimate	July 2020
Ethiopia	Current policies	Current policies	No	Yes	Conservative global estimate	Sept. 2021
EU27	Updated NDC (Dec. 2020	Updated NDC (Dec. 2020)	Yes (max)	Yes (min)	CAT estimate	Sept. 2021
Germany	Covered in EU27					
India	Current policies	Current policies	No	Yes	CAT estimate	Sept. 2021
Indonesia	Current policies	Current policies	No	Yes	CAT estimate	Nov. 2021
Iran	Current policies	Current policies	No	No	--	Sept. 2021
Japan	NDC (Oct. 2021)	NDC (Oct. 2021)	Yes (max)	Yes (min)	CAT estimate	Sept. 2021
Kazakhstan	First NDC (Dec. 2016)	First NDC (Dec. 2016)	No	Yes	CAT estimate	Nov. 2021
Kenya	Current policies	Current policies	No	No	--	Nov. 2020
Mexico	Updated NDC (Dec. 2020)	Updated NDC (Dec. 2020)	No	Yes	Conservative global estimate	Sept. 2020
Morocco	Updated NDC (June 2021)	Updated NDC (June 2021)	No	No	--	July 2020
Nepal	Current policies	Current policies	No	Yes	Conservative global estimate	Nov. 2020

Country	2030 targets only*	Pledges & Targets		Optimistic scenario		Policies & action data from
		2030 NDC target*	Net Zero targets	NZT included?	Method	
New Zealand	Updated NDC (Nov. 2021)	Updated NDC (Nov. 2021)	Yes (max)	Yes (min)	CAT estimate	Sept. 2021
Nigeria	Updated NDC (July 2021)	Updated NDC (July 2021)	No	Yes	CAT estimate	Sept. 2021
Norway	Updated NDC (Feb. 2020)	Updated NDC (Feb. 2020)	Yes (max)	Yes (min)	CAT estimate	Sept. 2021
Peru	Current policies	Current policies	No	Yes	Conservative global estimate	Nov. 2020
Philippines	Current policies	Current policies	No	No	--	Nov. 2020
Russian Federation	Current policies	Current policies	No	Yes	CAT estimate	Oct. 2021
Saudi Arabia	Current policies	Current policies	No	Yes	CAT estimate	Sept. 2021
Singapore	Current policies	Current policies	Yes	Yes	CAT estimate	July 2020
South Africa	Updated NDC (Sept. 2021)	Updated NDC (Sept. 2021)	Yes	Yes	CAT estimate	Sept. 2021
South Korea	Announced NDC (Nov. 2021)	Announced NDC (Nov. 2021)	Yes	Yes	CAT estimate	Nov. 2021
Switzerland	Updated NDC (Dec. 2020)	Updated NDC (Dec. 2020)	Yes	Yes	CAT estimate	Sept. 2021
Thailand	Updated NDC (Oct. 2020)	Updated NDC (Oct. 2020)	No	Yes	Conservative global estimate	Sept. 2021
The Gambia**	First NDC (Nov. 2016)	First NDC (Nov. 2016)	No	Yes	Conservative global estimate	Nov. 2020
Turkey	Current policies	Current policies	No	Yes	CAT estimate	Oct. 2021
UAE	Updated NDC (Dec. 2020)	Updated NDC (Dec. 2020)	No	Yes	CAT estimate	Nov. 2020
UK	Updated NDC (Dec. 2020)	Updated NDC (Dec. 2020)	Yes	Yes	CAT estimate	Sept. 2021
Ukraine	Updated NDC (July 2021)	Updated NDC (July 2021)	No	Yes	CAT estimate	Nov. 2021
USA	Updated NDC (April 2021)	Updated NDC (April 2021)	Yes (max)	Yes (min)	CAT estimate	Sept. 2021
Viet Nam	Current policies	Current policies	No	No	--	Oct. 2021

* For weak targets, we take a country's estimated 2030 level under current policies, if that level is lower than the target.

** The Gambia submitted its second NDC in September 2021. We will incorporate its updated NDC in subsequent assessments.

CAT temperature estimates are done using the MAGICC climate model. More information on the model is available here.

A2 Detailed overview of net zero target assessments

Table 4: Overview of Climate Action Tracker's net zero target evaluations for G20 member countries (excluding France and Italy as both not separately analysed by the CAT) and selected other countries per key elements as of November 2021

Rating the comprehensiveness of national net zero target design		Net zero target design elements									
		1	2	3	4	5	6	7	8	9	10
Country	Rating	Target year	Emissions coverage	International aviation and shipping	Reductions or removals outside of own border	Legal status	Separate reduction & removal targets	Review process	Carbon dioxide removal	Comprehensive planning	Clarity on fairness of target
EU	ACCEPTABLE	2050	✓	−	✓	✓	✗	✓	✓	✓	✗
UK	ACCEPTABLE	2050	✓	✓	✗	✓	✗	✓	✓	✓	−
Chile	ACCEPTABLE	2050	✓	✗	✓	−	✓	−	✓	✓	✗
Costa Rica	ACCEPTABLE	2050	✓	✗	✓	−	✓	−	✓	✓	✗
Germany	AVERAGE	2045	✓	✗	✗	✓	✓	✓	✗	−	−
South Korea	AVERAGE	2050	✗	✗	✓	✓	✓	−	✓	−	✗
Canada	AVERAGE	2050	✓	✗	✓	✓	✗	✓	✗	−	✗
USA	AVERAGE	2050	✓	✗	✗	−	✗	−	✓	−	✗
Japan	POOR	2050	✓	✗	✗	✓	✗	✓	✗	−	✗
New Zealand	POOR	2050	✗	✗	✗	✓	✗	✓	✗	−	✗
Australia	POOR	2050	✓	✗	✗	−	✗	−	✗	✗	✗
China	POOR	2060	✗	✗	✗	−	✗	✗	✗	−	−

Rating the comprehensiveness of national net zero target design Country	Rating	Net zero target design elements 1 Target year	2 Emissions coverage	3 International aviation and shipping	4 Reductions or removals outside of own border	5 Legal status	6 Separate reduction & removal targets	7 Review process	8 Carbon dioxide removal	9 Comprehensive planning	10 Clarity on fairness of target
Ukraine	INFORMATION INCOMPLETE	2060	✓	?	?	–	?	?	?	?	?
Turkey	INFORMATION INCOMPLETE	2053	✓	?	?	–	?	?	?	?	?
South Africa	INFORMATION INCOMPLETE	2050	✗	?	?	–	?	?	?	?	?
Argentina	INFORMATION INCOMPLETE	2050	✗	?	?	–	?	?	?	?	?
Russia	INFORMATION INCOMPLETE	2060	✗	?	?	–	?	?	?	?	?
Saudi Arabia	INFORMATION INCOMPLETE	2060	✗	?	?	–	?	?	?	?	?
UAE	INFORMATION INCOMPLETE	2050	✗	?	?	–	?	?	?	?	?
Indonesia	INFORMATION INCOMPLETE	2060	?	?	?	–	?	?	?	?	?
Brazil	INFORMATION INCOMPLETE	2050	?	?	?	–	?	?	?	?	?
Colombia	INFORMATION INCOMPLETE	2050	?	?	?	–	?	?	?	?	?
India	INFORMATION INCOMPLETE	2070	?	?	?	–	?	?	?	?	?
Iran	NO TARGET	-	*Not applicable as no target existing*								
Mexico*	NO TARGET	-	*Not applicable as no target existing*								

* We do not consider Mexico to have a net zero target, but do include the country in the Optimistic scenario as ECIU lists their net zero target as under discussion

A3 Optimistic Temperature Estimate Assumptions

We had to make several assumptions to assess the impact of net zero targets on the global temperature increase by 2100. These relate to (1) the emissions covered by the various targets, (2) land-use, land-use change and forestry (LULUCF) emissions by 2050, (3) the trajectory of non-CO2 emissions and (4) the importance of 2030 targets.

Table 5 provides an overview of all net zero targets assessed for which the Climate Action Tracker has developed estimates. Table 5 lists all net zero targets included in the modelling runs for the CAT's temperature estimate in November 2020.

Table 5: List of net zero targets for which CAT has developed estimates

Country	Type of net zero target	Target year	Assumption on LULUCF	Assumptions on GHG emissions excluding LULUCF
Australia	Net zero GHGs	2050	N/A	We use the estimates for the scenarios excluding offsets contained in the government's long-term strategy, converted these values into AR4 GWP and assumed a linear decline between 2030 and 2050. The top end of the range is used in our standard pledges and targets pathway, the bottom end is used in the Optimistic pathway.
Brazil	Net zero GHGs	2050	We used an estimate from the Fórum Brasileiro de Mudança do Clima, a government advisory body, for 2050 LULUCF emissions.	We assumed a linear decline in total GHGs between 2030 and 2050 to balance LULUCF emissions in 2050.
Canada	Net zero GHGs	2050	The government has not provided any detail on how it intends to meet its 2050 target; therefore, we use the same LULUCF as for its NDC.	We assumed a linear decline in total GHGs between 2030 and 2050 to balance LULUCF emissions in 2050. The top end of the range is used in our standard pledges and targets pathway, the bottom end is used in the Optimistic pathway.
Chile	Net zero GHGs	2050	We used national projections for 2050 presented in the updated NDC and Climate Neutrality Plan of 2020 and assumed LULUCF emissions to be -65 $MtCO_2e$.	We used national projections for all GHG emission 2050 presented in the updated NDC and Climate Neutrality Plan of 2020 to balance LULUCF sinks in 2050.
China	Net zero CO_2	2060	We used a ten-year historical average based on GHG inventory data from 2005 to 2014. The average of LULUCF emissions in those years is –783 $MtCO_2e$, which we assumed as a value for 2050 and 2060. This estimate is consistent with the scenarios from Tsinghua University, which show agricultural and forestry sinks of 700-780 $MtCO_2e$ in 2050.	We apply a linear interpolation for economy-wide CO_2 emissions (excl. LULUCF) from 2030 emission levels expected under achievement of the NDC targets, to zero CO_2 emissions in 2060, expected under the carbon neutrality target. We assume that non-CO_2 gases, significant in China, will lag behind but still be phased out indirectly through carbon neutrality efforts. We apply linear interpolation between the 2030 economy-wide non-CO_2 emissions (excl. LULUCF) expected under achievement of NDCs to zero in 2080. For 2030 values, we use the average of the NDC non-fossil fuel and the NDC peaking pledge as the starting point. We assume LULUCF sinks will be in the order of 783 $MtCO_2e$ in mid-century and beyond, and expect it to be used to counterbalance hard-to-abate emissions. The top end of the range is used in our standard pledges and targets pathway, the bottom end is used in the optimistic pathway.

Country	Type of net zero target	Target year	Assumption on LULUCF	Assumptions on GHG emissions excluding LULUCF
Colombia	Net zero GHGs	2050	In the beginning of 2021, Colombia announced their target to reach "carbonon neutralidad" assumed to be net zero GHG emissions by 2050, for which the strategy is still in the works. Projections for LULUCF emissions in 2050 are taken here from the background modelling document used in the updated NDC. In even the most ambitious scenario, Colombia does not create a substantial land-based sink of emissions in 2050. We assume no contribution from LULUCF to the target.	We assume emissions are zero in 2050, with a linear decline from 2030 levels.
Costa Rica	Net zero GHGs	2050	We used national projections for 2050, as provided for in the 2018 Decarbonization Strategy submitted to the UNFCCC.	We used national projections for 2050, as provided for in the 2018 Decarbonization Strategy, to balance LULUCF sinks in 2050. We use the upper limited of the NDC in 2030 as the starting point. The top end of the range is used in our standard pledges and targets pathway, the bottom end is used in the Optimistic pathway.
European Union	Net zero GHGs	2050	*See assumptions for EU's for 2050 excluding LULUCF on the right.*	We used the EU's own projections for 2050 excluding LULUCF, from the 1.5LIFE and 1.5TECH scenarios, adjusted to the EU27. The top end of the range is used in our standard pledges and targets pathway, the bottom end is used in the Optimistic pathway.
India	Net zero GHGs	2070	The government has not provided any detail on how it intends to meet its 2070 target, nor the reliance on the land sector. In its first NDC, India committed to enhancing its sink by an additional 2.5 to 3bn tonnes by 2030. Assuming those figures represent a cumulative 15-year total (2016-2030), India's LULUCF sink would grow to around 500 $MtCO_2$ in 2030 (from a historic level of around 300$MtCO_2e$ in 2016). In the absence of any other estimate, we have used this figure for its sink in 2070.	We assume the target covers all gases and that there is a linear decline in total GHGs between 2030 and 2070 to balance LULUCF emissions in 2070.
Indonesia	Net zero GHGs	2060	The Indonesian government assumes a LULUCF sink of 299 $MtCO_2e$ in the LCCP scenario presented in the LTS submitted to the UNFCCC. We keep this value constant for 2060.	We assumed a linear decline in total GHGs between 2030 and 2060 to balance LULUCF emissions in 2060.
Japan	Net zero GHGs	2050	We extrapolated the 2009-2019 trend to 2030, followed by a constant sink to 2050, and took the average sink for the 2009-2019 period to create a range for LULUCF.	We applied a linear interpolation of all GHG emission between 2030 and 2050 to balance LULUCF sinks in 2050. The top end of the range is used in our standard pledges and targets pathway, the bottom end is used in the Optimistic pathway.

Country	Type of net zero target	Target year	Assumption on LULUCF	Assumptions on GHG emissions excluding LULUCF
Kazakhstan	Net zero GHGs	2060	As the government announced an extensive reforestation plan, we assumed that by 2060 LULUCF emissions will equal the lowest level between 1990 and 2020. We assumed that LULUCF emissions will linearly decrease between 2020 and 2060.	We assumed a linear decline in total GHGs between 2030 and 2060.
New Zealand	Net zero GHG, with the exception of CH_4 from agriculture and waste	2050	We used national projection for 2050, harmonised to historical data.	We calculate the methane reduction target separately and then assume a linear decline in emissions between 2030 and 2050, to balance LULUCF removals in 2050. The top end of the range is used in our standard pledges and targets pathway, the bottom end is used in the Optimistic pathway.
Nigeria	Net zero GHGs	Second half of the century*	We make no assumptions about LULUCF given the limited data available.	We quantified the 2050 target referenced in Nigeria's final NDC update of 50% below currently levels (which we took to be 2018). We did not explicitly calculation a net zero target during the second half of the century, but used our model's pathway extension from the 2050 value. **Note: Nigeria announced a 2060 net zero target during the World Leaders Summit. We will update our analysis for Nigeria to take this development into account in our next assessment.*
Norway	GHGs reduce by 90-95%, compared to 1990. We assumed that LULUCF emissions are included in this target.	2050	We used a projection from NIBIO, which gives a sink in 2050 of 20 $MtCO_2$.	We assume a linear decline in GHG emissions excluding LULUCF between 2030 and 2050, such that total emissions in 2050 including LULUCF are 90-95% below 1990 levels. The top end of the range is used in our standard pledges and targets pathway, the bottom end is used in the Optimistic pathway.
Russian Federation	Net zero CO_2	2060	Russia does not have 2060 LULUCF projections. We have used the most ambitious 2050 sink scenario in its draft long-term strategy.	We assumed that CO_2 emissions will decline at a linear rate between 2030 and 2060 to balance LULUCF removals in 2060. We assume that non-CO_2 emission follow a linear decline to zero by 2070 based on the 2030 value in Russia's 4th Biennial Update Report 'with measures' scenario.
Saudi Arabia	Net zero CO_2	2060	The Saudi government has announced to achieve a sink of 200 MtCO2 from 2030 onwards, which we assume to stay constant towards 2060.	We assumed that CO2 emissions will decline at a linear rate between 2030 and 2060 to balance LULUCF sinks in 2060. We assume that non-CO_2 emissions will decline at a linear rate between 2030 and 2080 in line with the IPCC SR1.5 pathways.
Singapore	Net zero GHGs	Second half of the century	We make no assumptions as LULUCF is negligible.	We use Singapore's 2050 target to peak emissions at 32$MtCO_2e$ in 2050 (converted from AR5 GWP values to AR4). We make no further assumptions about when the net zero target will be met later in the century.
South Africa	Net zero CO_2	2050	We used a ten-year historical average based on national inventory data from 2005-2015 resulting in -16 $MtCO_2e$.	We assumed that CO_2 emissions will decline at a linear rate between 2030 and 2050 to balance LULUCF sinks in 2050. We assume that non-CO_2 emissions will decline at a linear rate between 2030 and 2080 in line with the IPCC SR1.5 pathways.
South Korea	Net zero GHGs	2050	The government of South Korea projects a LULUCF sink of 25$MtCO_2e$ by 2050 in its 2050 Carbon Neutral Scenario report.	We assumed a linear decline in total GHGs between 2030 (announced NDC level) and 2050 to balance LULUCF emissions in 2050.

Country	Type of net zero target	Target year	Assumption on LULUCF	Assumptions on GHG emissions excluding LULUCF
Switzerland	Net zero GHGs	2050	We used the "with existing measures" projection for 2030 from the 4th Biennial Report and assumed the same value for 2050.	We assumed a linear decline in total GHGs between 2030 and 2050 to balance LULUCF emissions in 2050.
Turkey	Net zero GHGs	2053	We used the government projection for 2030 under the "with existing measures" scenario in the 4th Biennial Report as Turkey does not have a 2053 LULUCF projection.	We assumed a linear decline in total GHGs between 2030 and 2053 to balance LULUCF emissions in 2053.
Ukraine	Net zero GHGs	2060	We used the government's LULUCF projection for 2050, as described in the modelling report that informed Ukraine's updated NDC. As the report provides no data point for 2060, we assumed the LULUCF sink remains stable between 2050 and 2060, at -36 $MtCO_2e$.	We assumed that GHG emissions decrease linearly between 2030 and 2060. By 2060, emissions amount to 36 $MtCO_2e$, so Ukraine's net emissions are zero.
United Arab Emirates	Net zero CO_2	2050	We used a ten-year historical average based on national inventory data from 2004-2015 resulting in -11 $MtCO_2e$.	We assumed that CO_2 emissions will decline at a linear rate between 2030 and 2050 to balance LULUCF sinks in 2050. We assume that non-CO_2 emissions will decline at a linear rate between 2030 and 2080 in line with the IPCC SR1.5 pathways.
United Kingdom	Net zero GHGs	2050	We used the 2050 LULUCF projection from the 'balanced net zero pathway' scenario in the UK Centre for Ecology and Hydrology's Updated quantification of the impact of future land use scenarios to 2050 and beyond final report (-19 $MtCO_2e$).	We assumed that GHG emissions decrease linearly between 2030 and 2050 from the emissions level implied by the UK's 2030 target to balance the projected 2050 LULUCF sink.
United States	Net zero GHGs	2050	Our LULUCF assumptions are based on data extracted from the graphs in the US's long-term strategy. We use the LULUCF projection range for our assumptions on the sink by 2050.	We assumed that GHG emissions will decline at a linear rate between 2030 and 2050 to balance LULUCF removals in 2050. The top end of the range is used in our standard pledges and targets pathway, the bottom end is used in the Optimistic pathway

Table 6: List of all net zero targets included in the 'optimistic scenario' modelling runs for the global aggregation based on the ECIU (2021) complemented by CAT analysis as of 2 November 2021.

Country	Status	Year
Afghanistan	Target Under Discussion	2050
Andorra	In Policy Document	2050
Angola	Target Under Discussion	2050
Antigua and Barbuda	Target Under Discussion	2050
Argentina	Target Under Discussion	2050
Armenia	In Policy Document	2050
Australia	In Policy Document	2050
Austria*	In Policy Document	2040
Bahamas (the)	Target Under Discussion	2050
Bahrain	Target Under Discussion	2060
Bangladesh	Target Under Discussion	2050
Barbados	Target Under Discussion	2050

Country	Status	Year
Belgium*	Target Under Discussion	2050
Belize	Target Under Discussion	2050
Benin	Target Under Discussion	2050
Bhutan	Achieved	
Brazil	In Policy Document	2050
Bulgaria*	Target Under Discussion	2050
Burkina Faso	Target Under Discussion	2050
Burundi	Target Under Discussion	2050
Cabo Verde	Target Under Discussion	2050
Cambodia	Target Under Discussion	2050
Canada	In Law	2050
Central African Republic (the)	Target Under Discussion	2050
Chad	Target Under Discussion	2050
Chile	Proposed Legislation	2050
China	In Policy Document	2060
Colombia	Target Under Discussion	2050
Comoros (the)	Target Under Discussion	2050
Congo (the Democratic Republic of the)	Target Under Discussion	2050
Cook Islands (the)	Target Under Discussion	2050
Costa Rica	In Policy Document	2050
Croatia	Target Under Discussion	2050
Cyprus	Target Under Discussion	2050
Czechia	Target Under Discussion	2050
Denmark*	In Law	2050
Djibouti	Target Under Discussion	2050
Dominica	Target Under Discussion	2050
Dominican Republic (the)	Target Under Discussion	2050
Ecuador	Target Under Discussion	2050
Eritrea	Target Under Discussion	2050
Estonia*	Target Under Discussion	2050
Ethiopia	Target Under Discussion	2050
European Union	Proposed Legislation	2050
Fiji	Proposed Legislation	2050
Finland*	In Policy Document	2035
France*	In Law	2050
Gambia (the)	Target Under Discussion	2050
Germany*	In Policy Document	2050
Greece	Target Under Discussion	2050
Grenada	Target Under Discussion	2050
Guinea	Target Under Discussion	2050
Guinea-Bissau	Target Under Discussion	2050
Guyana	Target Under Discussion	2050
Haiti	Target Under Discussion	2050
Hungary*	In Law	2050
Iceland	In Policy Document	2040
India	Target Under Discussion	2070
Indonesia	In Policy Document	2060
Ireland*	In Policy Document	2050
Israel	Target Under Discussion	2050

Country	Status	Year
Italy*	Target Under Discussion	2050
Jamaica	Target Under Discussion	2050
Japan	In Law	2050
Kazakhstan	In Policy Document	2060
Kiribati	Target Under Discussion	2050
Korea (the Republic of)	In Law	2050
Lao People's Democratic Republic (the)	Target Under Discussion	2050
Latvia*	Target Under Discussion	2050
Lebanon	Target Under Discussion	2050
Lesotho	Target Under Discussion	2050
Liberia	Target Under Discussion	2050
Lithuania*	Target Under Discussion	2050
Luxembourg	Target Under Discussion	2050
Madagascar	Target Under Discussion	2050
Malawi	Target Under Discussion	2050
Malaysia	In Policy Document	2050
Maldives	Target Under Discussion	2050
Mali	Target Under Discussion	2050
Malta*	Target Under Discussion	2050
Marshall Islands (the)	In Policy Document	2050
Mauritania	Target Under Discussion	2050
Mauritius	Target Under Discussion	2050
Mexico	Target Under Discussion	2050
Micronesia (Federated States of)	Target Under Discussion	2050
Monaco	Target Under Discussion	2050
Mozambique	Target Under Discussion	2050
Myanmar	Target Under Discussion	2050
Namibia	Target Under Discussion	2050
Nauru	Target Under Discussion	2050
Nepal	In Policy Document	2045
Netherlands (the)	Target Under Discussion	2050
New Zealand	In Law	2050
Nicaragua	Target Under Discussion	2050
Niger (the)	Target Under Discussion	2050
Nigeria**	In Policy Document	second half of century
Niue	Target Under Discussion	2050
Norway	In Policy Document	2050
Panama	In Policy Document	2050
Pakistan	Target Under Discussion	2050
Palau	Target Under Discussion	2050
Papua New Guinea	Target Under Discussion	2050
Peru	Target Under Discussion	2050
Portugal*	In Policy Document	2050
Romania*	Target Under Discussion	2050
Russia	Target Under Discussion	2060
Rwanda	Target Under Discussion	2050
Saint Kitts and Nevis	Target Under Discussion	2050
Saint Lucia	Target Under Discussion	2050

Country	Status	Year
Saint Vincent and the Grenadines	Target Under Discussion	2050
Samoa	Target Under Discussion	2050
Sao Tome and Principe	Target Under Discussion	2050
Saudi Arabia	Target Under Discussion	2060
Senegal	Target Under Discussion	2050
Seychelles	Target Under Discussion	2050
Sierra Leone	Target Under Discussion	2050
Singapore	In Policy Document	2060
Slovakia*	Target Under Discussion	2050
Slovenia*	In Policy Document	2050
Solomon Islands	Target Under Discussion	2050
Somalia	Target Under Discussion	2050
South Africa	In Policy Document	2050
South Sudan	Target Under Discussion	2050
Spain*	Proposed Legislation	2050
Sri Lanka	In Policy Document	2050
Sudan (the)	Target Under Discussion	2050
Suriname	Achieved	
Sweden*	In Law	2045
Switzerland	In Policy Document	2050
Tanzania, United Republic of	Target Under Discussion	2050
Thailand	In Policy Document	2070
Timor-Leste	Target Under Discussion	2050
Togo	Target Under Discussion	2050
Tonga	Target Under Discussion	2050
Trinidad and Tobago	Target Under Discussion	2050
Turkey	Target Under Discussion	2053
Tuvalu	Target Under Discussion	2050
Uganda	Target Under Discussion	2050
Ukraine	In Policy Document	2060
United Arab Emirates	Target Under Discussion	2050
United Kingdom of Great Britain and Northern Ireland (the)	In Law	2050
United States of America (the)	In Policy Document	2050
Uruguay	Target Under Discussion	2030
Vanuatu	Target Under Discussion	2050
Yemen	Target Under Discussion	2050
Zambia	Target Under Discussion	2050

* Note: All Member States of the EU27 are included in the modelling runs through EU27, not individually.

** Nigeria announced a 2060 net zero target during the World Leaders Summit. We will update our analysis for Nigeria to take this development into account in our next assessment.

A4 Differences between Climate Action Tracker, UNFCCC Synthesis Report & UNEP Gap Report

Several studies, including the Climate Action Tracker, UNFCCC Synthesis Report (UNFCCC, 2021) & UNEP Emissions Gap Report (UNEP, 2021), illustrate the state of climate action in terms of end-of-century warming, the gigaton gap in emissions between where we are and a 1.5°C compatible level, or level of emissions reduction achieved. These reports are fully aligned after closer examination of the underlying methodological assumptions, even if at first glance estimates may appear to differ.

The studies are characterised as follows:

- The Climate Action Tracker provides a temperature estimate based on bottom-up, detailed and up-to-date policy and emission information of 39 countries plus the EU27 scaled to the global level.
- The UNEP Emissions Gap Report compares and synthesises eight studies using very different methodologies to derive global GHG emissions and estimate resulting temperature outcomes. CAT is one of the studies used in the UNEP emissions gap report to derive emissions.
- The UNFCCC Synthesis report is an independent analysis that only takes information reported by national governments under the Paris Agreement and compares the result to a global pathway in the literature.

The main messages hold over all three reports:

- The new round of NDCs decreases global greenhouse gas emissions expected for 2030, but narrows the gap to a 1.5°C compatible pathway only to a limited extent.
- Under current policies, temperature increase by 2100 is expected to be slightly below 3°C.
- With full implementation of NDCs, temperature increase by 2100 is expected to be lower than under current policies, i.e. between 2°C and 3°C. It is at the lower end of this range if not only the 2030 targets but also the submitted long-term targets are taken into account.
- With full implementation of all adopted and announced national net zero targets, temperature increase by 2100 could be around 2°C.

Table 7: Comparison of temperature estimates for 2100 (limit reached with 66% probability. CAT usually uses 50% probability)

	66% chance to be below…		
	CAT Nov 2021	UNEP Oct 2021	UNFCCC Oct 2021
Current Policies	2.9°C	2.8°C	N/A
Pledges	2.3°C	2.7°C	2.7°C
Net zero targets	2.0°C	2.2°C	N/A

In this section, we outline the differences in CAT methodology and that used by the UNFCCC Secretariat in its recent NDC Synthesis Report as well as the UNEP Emissions Gap Report.

Estimation of emissions in 2030 based on NDCs

One major difference is how the studies estimate the impact of NDCs on resulting 2030 emissions and an emissions gap in $GtCO_2e$. The Climate Action Tracker and UNEP Emissions Gap Report use more optimistic assumptions (including announcements and taking into account overachievement of NDCs) and therefore derive a slightly lower emissions gap in 2030 than the UNFCCC synthesis report.

Table 8: Methodological differences that affect the estimation of the 2030 emissions gap

	Climate Action Tracker	UNEP Emissions Gap Report	UNFCCC synthesis report
Including official submissions or announcements	Also includes announcements that are not yet submitted to UNFCCC (e.g.Republic of Korea) (Lower emissions)	Summarising studies, some of which some include announcements, others do not (Lower emissions)	Only officially submitted information (Higher emissions)
Overachievements of NDCs	Takes the current policy scenario for countries that overachieve their NDCs with current policies (Lowest emissions)	Takes the average current policy scenario from studies for countries that overachieve their NDCs with current policies (Lower emissions)	Assesses only the NDCs (Higher emissions)
Emissions in 2030 compatible with 1.5°C	26 $GtCO_2e$	25 $GtCO_2e$	29 $GtCO_2e$
Gap between unconditional NDCs and a 1.5°C compatible pathway	19-23 $GtCO_2e$ (November 2021 analysis)	22-28 $GtCO_2e$ (October 2021 analysis)	27 $GtCO_2e$ (October 2021 analysis)

The UNFCCC Synthesis Report released in October 2021 found that emissions under the current NDCs are set to be 16% higher than emissions levels in 2010. But this assumes that countries with very weak NDCs will grow their emissions to grow beyond what a business-as-usual trajectory based on current policies suggests. The Climate Action Tracker's analysis removes this 'hot air' and uses likely 2030 emission levels based on current policies, and finds that by 2030 emissions are set to rise by 1% from 2010 levels. This is still far short of the halving of emissions seen in 1.5°C compatible pathways, but at least suggests that emissions are flatlining, not continuing to rise.

Current policy estimates

The estimation of current policy projections for 2030 differs for the studies:

- The CAT includes the latest developments, which are usually trends that lead to decreasing emissions, including the faster uptake of renewables and the dip due to the COVID-19 pandemic in its estimate for 2030 emissions under current policies and action.
- UNEP compares and synthesises a set of studies. Not all studies used in the UNEP report include these latest developments. The CAT's estimate is the lowest of all the studies considered by UNEP.
- The UNFCCC synthesis report does not include a current policies projection.

This also has an effect on the estimate of pledges and targets, because several large countries are likely to overachieve their pledges (India, Russia), and in such cases the overachieving policies are assumed also in the "pledge" scenario in CAT results (see NDC estimates above).

Long term and net zero targets

Temperature increase by 2100 is significantly influenced by the emissions after 2030 and therefore by the inclusion of long term targets of countries. The methods of CAT and UNEP are compared in more detail in a paper in Nature Climate Change (Höhne et al., 2021).

Table 9: Long-term targets considered when estimating temperature increase

	Climate Action Tracker	UNEP Emissions Gap Report	UNFCCC synthesis report
NDC scenario	Includes 2050 targets submitted to the UNFCCC (lower temperature)	Does not include any 2050 targets (higher temperature)	Does not include any 2050 targets (higher temperature)
Net zero scenario	Includes announced and agreed net zero targets of over 140 countries, including CO_2 and non-CO_2.	Includes net zero targets of selected countries and CO_2 effect only	(Does not include a Net Zero scenario)

Climate system uncertainty

All studies have large uncertainty bands for the uncertainty of the climate system, and how it reacts to increased greenhouse gas concentrations. These bands are wider than the difference between the estimates of the individual studies.

The studies also differ in which value of the full band they report as the default:

- The CAT uses the "best guess" (median) estimate, i.e. temperature level at which there is a 50% chance that it is above and a 50% that it is below that level.
- UNEP uses a "likely below" estimate, i.e. there is a "likely" chance (66%) that the temperature is below this level.
- UNFCCC synthesis report also uses a "likely below" estimate, i.e. there is a "likely" chance (66%) that the temperature is below this level.

Comparison of temperature estimates

All three estimates can be translated in the same metric (see table below). Differences between estimates should be compared at the same probability level.

Table 10: Comparison of temperature estimates for 2100

	50% chance to be below…			66% chance to be below…		
	CAT Nov 2021	UNEP	UNFCCC	CAT Nov 2021	UNEP Oct 2021	UNFCCC Oct 2021
Current Policies	2.7°C	N/A	N/A	2.9°C	2.8°C	N/A
Pledges	2.1°C	N/A	N/A	2.3°C	2.7°C	2.7°C
Net zero targets	1.8°C	N/A	N/A	2.0°C	2.2°C	N/A

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Authors

Climate Analytics

Claire Stockwell
Andreas Geiges
Deborah Ramalope
Matthew Gidden
Bill Hare

NewClimate Institute

Maria José de Villafranca Casas
Mia Moisio
Frederic Hans
Silke Mooldijk
Niklas Höhne
Hanna Fekete

Editing and Design
Cindy Baxter
Carly Merrett
Foteini Spagopoulo
Matt Beer

The Consortium

The Climate Action Tracker (CAT) is an independent scientific analysis produced by two research organisations tracking climate action since 2009. We track progress towards the globally agreed aim of holding warming well below 2°C, and pursuing efforts to limit warming to 1.5°C.

climateactiontracker.org

Climate Analytics is a non-profit climate science and policy institute based in Berlin, Germany with offices in New York, USA, Lomé, Togo and Perth, Australia, which brings together interdisciplinary expertise in the scientific and policy aspects of climate change. Climate Analytics aims to synthesise and advance scientific knowledge in the area of climate, and by linking scientific and policy analysis provide state-of-the-art solutions to global and national climate change policy challenges.

Contact: Dr. h.c. Bill Hare, +61 468 372 179

climateanalytics.org

NewClimate Institute is a non-profit institute established in 2014. NewClimate Institute supports research and implementation of action against climate change around the globe, covering the topics international climate negotiations, tracking climate action, climate and development, climate finance and carbon market mechanisms. NewClimate Institute aims at connecting up-to-date research with the real world decision making processes.

Contact: Prof. Dr. Niklas Höhne, +49 173 715 2279

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DOCUMENT 10

Net Zero by 2050

A Roadmap for the Global Energy Sector



International Energy Agency

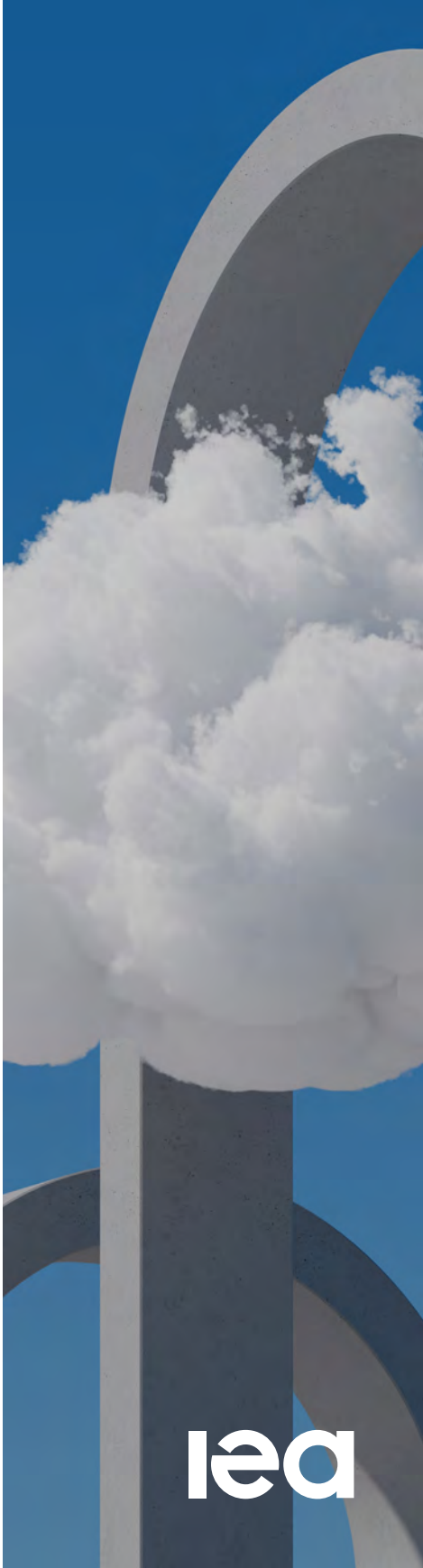
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A Roadmap for the Global Energy Sector

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We are approaching a decisive moment for international efforts to tackle the climate crisis – a great challenge of our times. The number of countries that have pledged to reach net-zero emissions by mid-century or soon after continues to grow, but so do global greenhouse gas emissions. This gap between rhetoric and action needs to close if we are to have a fighting chance of reaching net zero by 2050 and limiting the rise in global temperatures to 1.5 °C.

Doing so requires nothing short of a total transformation of the energy systems that underpin our economies. We are in a critical year at the start of a critical decade for these efforts. The 26th Conference of the Parties (COP26) of the United Nations Framework Convention on Climate Change in November is the focal point for strengthening global ambitions and action on climate by building on the foundations of the 2015 Paris Agreement. The International Energy Agency (IEA) has been working hard to support the UK government's COP26 Presidency to help make it the success the world needs. I was delighted to co-host the IEA-COP26 Net Zero Summit with COP26 President Alok Sharma in March, where top energy and climate leaders from more than 40 countries highlighted the global momentum behind clean energy transitions.

The discussions at that event fed into this special report, notably through the Seven Key Principles for Implementing Net Zero that the IEA presented at the Summit, which have been backed by 22 of our member governments to date. This report maps out how the global energy sector can reach net zero by 2050. I believe the report – *Net Zero by 2050: A roadmap for the global energy system* – is one of the most important and challenging undertakings in the IEA's history. The Roadmap is the culmination of the IEA's pioneering work on energy data modelling, combining for the first time the complex models of our two flagship series, the *World Energy Outlook* and *Energy Technology Perspectives*. It will guide the IEA's work and will be an integral part of both those series going forward.

Despite the current gap between rhetoric and reality on emissions, our Roadmap shows that there are still pathways to reach net zero by 2050. The one on which we focus is – in our analysis – the most technically feasible, cost-effective and socially acceptable. Even so, that pathway remains narrow and extremely challenging, requiring all stakeholders – governments, businesses, investors and citizens – to take action this year and every year after so that the goal does not slip out of reach.

This report sets out clear milestones – more than 400 in total, spanning all sectors and technologies – for what needs to happen, and when, to transform the global economy from one dominated by fossil fuels into one powered predominantly by renewable energy like solar and wind. Our pathway requires vast amounts of investment, innovation, skilful policy design and implementation, technology deployment, infrastructure building, international co-operation and efforts across many other areas.

Since the IEA's founding in 1974, one of its core missions has been to promote secure and affordable energy supplies to foster economic growth. This has remained a key concern of our Roadmap, drawing on special analysis carried out with the International Monetary Fund and the International Institute for Applied Systems Analysis. It shows that the enormous

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challenge of transforming our energy systems is also a huge opportunity for our economies, with the potential to create millions of new jobs and boost economic growth.

Another guiding principle of the Roadmap is that clean energy transitions must be fair and inclusive, leaving nobody behind. We have to ensure that developing economies receive the financing and technological know-how they need to continue building their energy systems to meet the needs of their expanding populations and economies in a sustainable way. It is a moral imperative to bring electricity to the hundreds of millions of people who currently are deprived of access to it, the majority in of them in Africa.

The transition to net zero is for and about people. It is paramount to remain aware that not every worker in the fossil fuel industry can ease into a clean energy job, so governments need to promote training and devote resources to facilitating new opportunities. Citizens must be active participants in the entire process, making them feel part of the transition and not simply subject to it. These themes are among those being explored by the Global Commission on People-Centred Clean Energy Transitions, which I convened at the start of 2021 to examine how to enable citizens to benefit from the opportunities and navigate the disruptions of the shift to a clean energy economy. Headed by Prime Minister Mette Frederiksen of Denmark and composed of government leaders, ministers and prominent thinkers, the Global Commission will make public its key recommendations ahead of COP26 in November.

The pathway laid out in our Roadmap is global in scope, but each country will need to design its own strategy, taking into account its specific circumstances. There is no one-size-fits-all approach to clean energy transitions. Plans need to reflect countries' differing stages of economic development: in our pathway, advanced economies reach net zero before developing economies do. As the world's leading energy authority, the IEA stands ready to provide governments with support and advice as they design and implement their own roadmaps, and to encourage the international co-operation across sectors that is so essential to reaching net zero by 2050.

This landmark report would not have been possible without the extraordinary dedication of the IEA colleagues who have worked so tirelessly and rigorously on it. I would like to thank the entire team under the outstanding leadership of my colleagues Laura Cozzi and Timur Gül.

The world has a huge challenge ahead of it to move net zero by 2050 from a narrow possibility to a practical reality. Global carbon dioxide emissions are already rebounding sharply as economies recover from last year's pandemic-induced shock. It is past time for governments to act, and act decisively to accelerate the clean energy transformation.

As this report shows, we at the IEA are fully committed to leading those efforts.

Dr Fatih Birol
Executive Director
International Energy Agency

This study, a cross-agency effort, was prepared by the World Energy Outlook team and the Energy Technology Perspectives team. The study was designed and directed by **Laura Cozzi**, Chief Energy Modeller and Head of Division for Energy Demand Outlook, and **Timur Gül**, Head of Division for Energy Technology Policy.

The lead authors and co-ordinators were: **Stéphanie Bouckaert**, **Araceli Fernandez Pales**, **Christophe McGlade**, **Uwe Remme** and **Brent Wanner**. **Laszlo Varro**, Chief Economist, **Davide D'Ambrosio** and **Thomas Spencer** were also part of the core team.

The other main authors were: **Thibaut Abergel** (buildings), **Yasmine Arsalane** (economic outlook, electricity), **Praveen Bains** (biofuels), **Jose Miguel Bermudez Menendez** (hydrogen), **Elizabeth Connelly** (transport), **Daniel Crow** (behaviour), **Amrita Dasgupta** (innovation), **Chiara Delmastro** (buildings), **Timothy Goodson** (buildings, bioenergy), **Alexandre Gouy** (industry), **Paul Hugues** (industry), **Lilly Lee** (transport), **Peter Levi** (industry), **Hana Mandova** (industry), **Ariane Millot** (buildings), **Paweł Olejarnik** (fossil fuel supply), **Leonardo Paoli** (innovation, transport), **Faidon Papadimoulis** (data management), **Sebastian Papapanagiotou** (electricity networks), **Francesco Pavan** (hydrogen), **Apostolos Petropoulos** (transport), **Ryszard Pośpiech** (data management), **Leonie Staas** (behaviour, industry), **Jacopo Tattini** (transport), **Jacob Teter** (transport), **Gianluca Tonolo** (energy access), **Tiffany Vass** (industry) and **Daniel Wetzel** (jobs).

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Rosanna Fusco	Eni
Li Gao	Ministry of Ecology and Environment of the People's Republic of China

François Gautier	Permanent Delegation of France to the OECD
Oliver Geden	German Institute for International and Security Affairs
Dolf Gielen	International Renewable Energy Agency (IRENA)
Francesca Gostinelli	Enel
Jae H. Jung	Ministry of Foreign Affairs, Republic of Korea
Michael Hackethal	Ministry for Economic Affairs and Industry, Germany
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Jacob Herbers	US Department of Energy
Takashi Hongo	Mitsui & Co. Global Strategic Studies Institute, Japan
Christina Hood	Compass Climate, New Zealand
Michael Kelly	World LPG Association
Sir David King	Cambridge University
Ken Koyama	The Institute of Energy Economics, Japan
Fabien Kreuzer	DG Energy, European Commission
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Claude Lorea	Global Cement and Concrete Association
Ritu Mathur	The Energy and Resources Institute (TERI)
Vincent Minier	Schneider Electric
Steve Nadel	American Council for an Energy-Efficient Economy
Stefan Nowak	Technology Collaboration Programme on Photovoltaic Power Systems (PVPS TCP)
Brian Ó Gallachóir	MaREI, SFI Research Centre for Energy, Climate and Marine, University College Cork
Henri Paillère	International Atomic Energy Agency (IAEA)
Yongduk Pak	Korea Energy Economics Institute (KEEI)
Alessandra Pastorelli	Permanent Delegation of Italy to the OECD
Jonathan Pershing	US State Department
Glen Peters	Centre for International Climate and Environmental Research (CICERO)
Stephanie Pfeifer	Institutional Investors Group on Climate Change (IIGCC)
Cédric Philibert	Independent consultant
Lynn Price	Lawrence Berkeley National Laboratory, United States
Andrew Purvis	World Steel
Julia Reinaud	Breakthrough Energy
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Ignacio Santelices	Sustainable Energy Agency, Chile
Andreas Schäfer	University College London
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Simon Sharpe	Cabinet Office, United Kingdom
Adnan Shihab Eldin	Formerly Kuwait Foundation for the Advancement of Sciences
Toshiyuki Shirai	Ministry of Economy, Trade and Industry, Japan
Adam Sieminski	KAPSARC
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Tom van Ierland	DG for Climate Action, European Commission
David Victor	University of California, San Diego
Amanda Wilson	Natural Resources Canada
Harald Winkler	University of Cape Town
Markus Wolf	Electric Power Research Institute (EPRI), United States
Markus Wråke	Swedish Energy Research Centre
William Zimmern	BP

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Comments and questions are welcome and should be addressed to:

Laura Cozzi and Timur Gül

Directorate of Sustainability, Technology and Outlooks
International Energy Agency
9, rue de la Fédération
75739 Paris Cedex 15
France

E-mail: IEANZE2050@iea.org

Web: www.iea.org

Foreword **3**
Acknowledgements **5**
Executive summary **13**

1 *Announced net zero pledges and the energy sector* *29*

1.1 Introduction 30
1.2 Emissions reduction targets and net zero pledges 31
1.2.1 Nationally Determined Contributions 31
1.2.2 Net-zero emissions pledges 32
1.3 Outlook for emissions and energy in the STEPS 36
1.3.1 CO_2 emissions 36
1.3.2 Total energy supply, total final consumption and electricity generation 37
1.3.3 Emissions from existing assets 39
1.4 Announced Pledges Case 40
1.4.1 CO_2 emissions 41
1.4.2 Total energy supply 43
1.4.3 Total final consumption 44
1.4.4 Electricity generation 45

2 *A global pathway to net-zero CO_2 emissions in 2050* *47*

2.1 Introduction 48
2.2 Scenario design 48
2.2.1 Population and GDP 50
2.2.2 Energy and CO_2 prices 51
2.3 CO_2 emissions 53
2.4 Total energy supply and total final consumption 56
2.4.1 Total energy supply 56
2.4.2 Total final consumption 60
2.5 Key pillars of decarbonisation 64
2.5.1 Energy efficiency 65
2.5.2 Behavioural change 67
2.5.3 Electrification 70

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2.5.4 Renewables ... 73
2.5.5 Hydrogen and hydrogen-based fuels ... 75
2.5.6 Bioenergy ... 77
2.5.7 Carbon capture, utilisation and storage ... 79
2.6 Investment ... 81
2.7 Key uncertainties ... 83
2.7.1 Behavioural change ... 84
2.7.2 Bioenergy and land-use change ... 90
2.7.3 CCUS applied to emissions from fossil fuels ... 94

3 *Sectoral pathways to net-zero emissions by 2050* *99*

3.1 Introduction ... 100
3.2 Fossil fuel supply ... 100
3.2.1 Energy trends in the Net-Zero Emissions Scenario ... 100
3.2.2 Investment in oil and gas ... 103
3.2.3 Emissions from fossil fuel production ... 104
3.3 Low-emissions fuel supply ... 105
3.3.1 Energy trends in the Net-Zero Emissions Scenario ... 105
3.3.2 Biofuels ... 106
3.3.3 Hydrogen and hydrogen-based fuels ... 108
3.3.4 Key milestones and decision points ... 111
3.4 Electricity sector ... 113
3.4.1 Energy and emissions trends in the Net-Zero Emissions Scenario ... 113
3.4.2 Key milestones and decision points ... 117
3.5 Industry ... 121
3.5.1 Energy and emission trends in the Net-Zero Emissions Scenario ... 121
3.5.2 Key milestones and decision points ... 129
3.6 Transport ... 131
3.6.1 Energy and emission trends in the Net-Zero Emissions Scenario ... 131
3.6.2 Key milestones and decision points ... 138
3.7 Buildings ... 141
3.7.1 Energy and emission trends in the Net-Zero Emissions Scenario ... 141
3.7.2 Key milestones and decision points ... 147

4 *Wider implications of achieving net-zero emissions* 151

4.1 Introduction ... 152
4.2 Economy ... 153
4.2.1 Investment and financing ... 153
4.2.2 Economic activity ... 155
4.2.3 Employment ... 157
4.3 Energy industry ... 160
4.3.1 Oil and gas ... 160
4.3.2 Coal ... 162
4.3.3 Electricity ... 163
4.3.4 Energy-consuming industries ... 165
4.4 Citizens ... 167
4.4.1 Energy-related Sustainable Development Goals ... 167
4.4.2 Affordability ... 170
4.4.3 Behavioural changes ... 173
4.5 Governments ... 175
4.5.1 Energy security ... 175
4.5.2 Infrastructure ... 180
4.5.3 Tax revenues from retail energy sales ... 183
4.5.4 Innovation ... 184
4.5.5 International co-operation ... 187

Annexes 191

Annex A. Tables for scenario projections ... 193
Annex B. Technology costs ... 201
Annex C. Definitions ... 203
Annex D. References ... 217

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The energy sector is the source of around three-quarters of greenhouse gas emissions today and holds the key to averting the worst effects of climate change, perhaps the greatest challenge humankind has faced. Reducing global carbon dioxide (CO_2) emissions to net zero by 2050 is consistent with efforts to limit the long-term increase in average global temperatures to 1.5 °C. This calls for nothing less than a complete transformation of how we produce, transport and consume energy. The growing political consensus on reaching net zero is cause for considerable optimism about the progress the world can make, but the changes required to reach net-zero emissions globally by 2050 are poorly understood. A huge amount of work is needed to turn today's impressive ambitions into reality, especially given the range of different situations among countries and their differing capacities to make the necessary changes. This special IEA report sets out a pathway for achieving this goal, resulting in a clean and resilient energy system that would bring major benefits for human prosperity and well-being.

The global pathway to net-zero emissions by 2050 detailed in this report requires all governments to significantly strengthen and then successfully implement their energy and climate policies. Commitments made to date fall far short of what is required by that pathway. The number of countries that have pledged to achieve net-zero emissions has grown rapidly over the last year and now covers around 70% of global emissions of CO_2. This is a huge step forward. However, most pledges are not yet underpinned by near-term policies and measures. Moreover, even if successfully fulfilled, the pledges to date would still leave around 22 billion tonnes of CO_2 emissions worldwide in 2050. The continuation of that trend would be consistent with a temperature rise in 2100 of around 2.1 °C. Global emissions fell in 2020 because of the Covid-19 crisis but are already rebounding strongly as economies recover. Further delay in acting to reverse that trend will put net zero by 2050 out of reach.

In this Summary for Policy Makers, we outline the essential conditions for the global energy sector to reach net-zero CO_2 emissions by 2050. The pathway described in depth in this report achieves this objective with no offsets from outside the energy sector, and with low reliance on negative emissions technologies. It is designed to maximise technical feasibility, cost-effectiveness and social acceptance while ensuring continued economic growth and secure energy supplies. We highlight the priority actions that are needed today to ensure the opportunity of net zero by 2050 – narrow but still achievable – is not lost. The report provides a global view, but countries do not start in the same place or finish at the same time: advanced economies have to reach net zero before emerging markets and developing economies, and assist others in getting there. We also recognise that the route mapped out here is a path, not necessarily the path, and so we examine some key uncertainties, notably concerning the roles played by bioenergy, carbon capture and behavioural changes. Getting to net zero will involve countless decisions by people across the world, but our primary aim is to inform the decisions made by policy makers, who have the greatest scope to move the world closer to its climate goals.

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Net zero by 2050 hinges on an unprecedented clean technology push to 2030

The path to net-zero emissions is narrow: staying on it requires immediate and massive deployment of all available clean and efficient energy technologies. In the net-zero emissions pathway presented in this report, the world economy in 2030 is some 40% larger than today but uses 7% less energy. A major worldwide push to increase energy efficiency is an essential part of these efforts, resulting in the annual rate of energy intensity improvements averaging 4% to 2030 – about three-times the average rate achieved over the last two decades. Emissions reductions from the energy sector are not limited to CO_2: in our pathway, methane emissions from fossil fuel supply fall by 75% over the next ten years as a result of a global, concerted effort to deploy all available abatement measures and technologies.

Ever-cheaper renewable energy technologies give electricity the edge in the race to zero. Our pathway calls for scaling up solar and wind rapidly this decade, reaching annual additions of 630 gigawatts (GW) of solar photovoltaics (PV) and 390 GW of wind by 2030, four-times the record levels set in 2020. For solar PV, this is equivalent to installing the world's current largest solar park roughly every day. Hydropower and nuclear, the two largest sources of low-carbon electricity today, provide an essential foundation for transitions. As the electricity sector becomes cleaner, electrification emerges as a crucial economy-wide tool for reducing emissions. Electric vehicles (EVs) go from around 5% of global car sales to more than 60% by 2030.

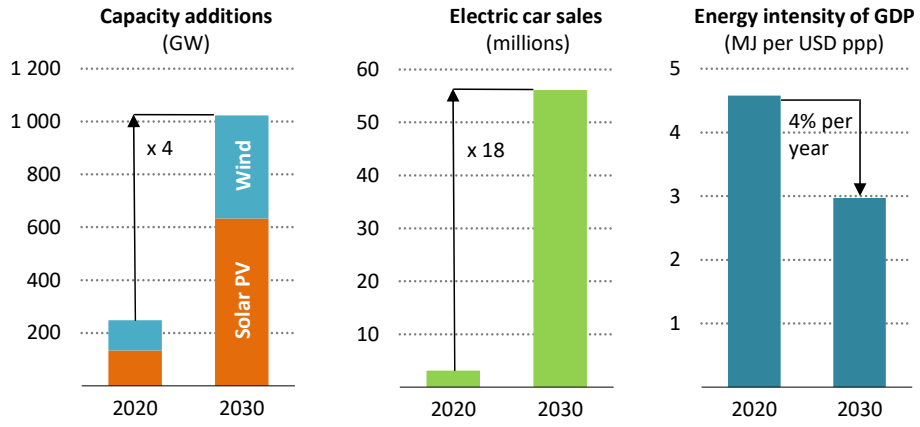
P R I O R I T Y A C T I O N

Make the 2020s the decade of massive clean energy expansion

All the technologies needed to achieve the necessary deep cuts in global emissions by 2030 already exist, and the policies that can drive their deployment are already proven.

As the world continues to grapple with the impacts of the Covid-19 pandemic, it is essential that the resulting wave of investment and spending to support economic recovery is aligned with the net zero pathway. Policies should be strengthened to speed the deployment of clean and efficient energy technologies. Mandates and standards are vital to drive consumer spending and industry investment into the most efficient technologies. Targets and competitive auctions can enable wind and solar to accelerate the electricity sector transition. Fossil fuel subsidy phase-outs, carbon pricing and other market reforms can ensure appropriate price signals. Policies should limit or provide disincentives for the use of certain fuels and technologies, such as unabated coal-fired power stations, gas boilers and conventional internal combustion engine vehicles. Governments must lead the planning and incentivising of the massive infrastructure investment, including in smart transmission and distribution grids.

Key clean technologies ramp up by 2030 in the net zero pathway



Note: MJ = megajoules; GDP = gross domestic product in purchasing power parity.

Net zero by 2050 requires huge leaps in clean energy innovation

Reaching net zero by 2050 requires further rapid deployment of available technologies as well as widespread use of technologies that are not on the market yet. Major innovation efforts must occur over this decade in order to bring these new technologies to market in time. Most of the global reductions in CO_2 emissions through 2030 in our pathway come from technologies readily available today. But in 2050, almost half the reductions come from technologies that are currently at the demonstration or prototype phase. In heavy industry and long-distance transport, the share of emissions reductions from technologies that are still under development today is even higher.

The biggest innovation opportunities concern advanced batteries, hydrogen electrolysers, and direct air capture and storage. Together, these three technology areas make vital contributions the reductions in CO_2 emissions between 2030 and 2050 in our pathway. Innovation over the next ten years – not only through research and development (R&D) and demonstration but also through deployment – needs to be accompanied by the large-scale construction of the infrastructure the technologies will need. This includes new pipelines to transport captured CO_2 emissions and systems to move hydrogen around and between ports and industrial zones.

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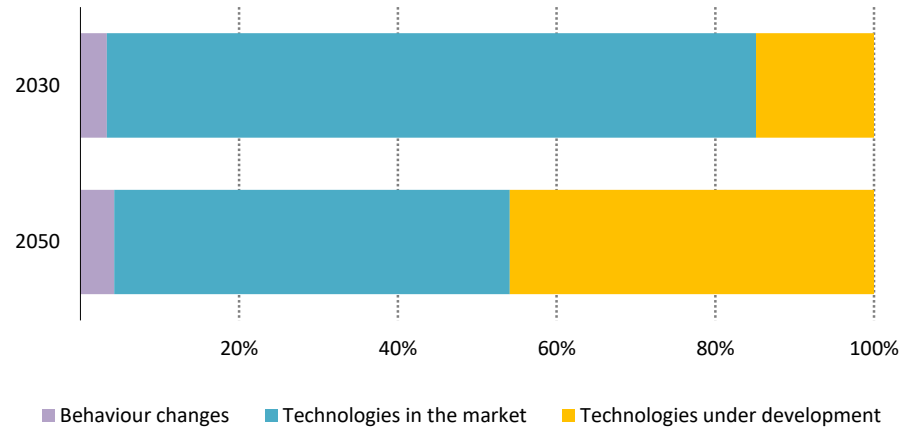
PRIORITY ACTION

Prepare for the next phase of the transition by boosting innovation

Clean energy innovation must accelerate rapidly, with governments putting R&D, demonstration and deployment at the core of energy and climate policy.

Government R&D spending needs to be increased and reprioritised. Critical areas such as electrification, hydrogen, bioenergy and carbon capture, utilisation and storage (CCUS) today receive only around one-third of the level of public R&D funding of the more established low-carbon electricity generation and energy efficiency technologies. Support is also needed to accelerate the roll-out of demonstration projects, to leverage private investment in R&D, and to boost overall deployment levels to help reduce costs. Around USD 90 billion of public money needs to be mobilised globally as soon as possible to complete a portfolio of demonstration projects before 2030. Currently, only roughly USD 25 billion is budgeted for that period. Developing and deploying these technologies would create major new industries, as well as commercial and employment opportunities.

Annual CO_2 emissions savings in the net zero pathway, relative to 2020



The transition to net zero is for and about people

A transition of the scale and speed described by the net zero pathway cannot be achieved without sustained support and participation from citizens. The changes will affect multiple aspects of people's lives – from transport, heating and cooking to urban planning and jobs. We estimate that around 55% of the cumulative emissions reductions in the pathway are linked to consumer choices such as purchasing an EV, retrofitting a house with energy-efficient technologies or installing a heat pump. Behavioural changes, particularly in advanced economies – such as replacing car trips with walking, cycling or public transport, or foregoing a long-haul flight – also provide around 4% of the cumulative emissions reductions.

Providing electricity to around 785 million people that have no access and clean cooking solutions to 2.6 billion people that lack those options is an integral part of our pathway. Emissions reductions have to go hand-in-hand with efforts to ensure energy access for all by 2030. This costs around USD 40 billion a year, equal to around 1% of average annual energy sector investment, while also bringing major co-benefits from reduced indoor air pollution.

Some of the changes brought by the clean energy transformation may be challenging to implement, so decisions must be transparent, just and cost-effective. Governments need to ensure that clean energy transitions are people-centred and inclusive. Household energy expenditure as a share of disposable income – including purchases of efficient appliances and fuel bills – rises modestly in emerging market and developing economies in our net zero pathway as more people gain access to energy and demand for modern energy services increases rapidly. Ensuring the affordability of energy for households demands close attention: policy tools that can direct support to the poorest include tax credits, loans and targeted subsidies.

PRIORITY ACTION

Clean energy jobs will grow strongly but must be spread widely

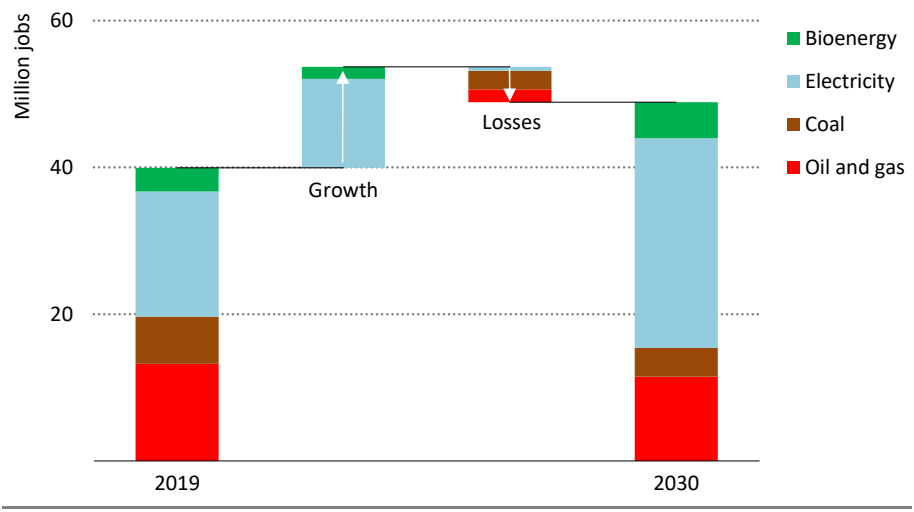
Energy transitions have to take account of the social and economic impacts on individuals and communities, and treat people as active participants.

The transition to net zero brings substantial new opportunities for employment, with 14 million jobs created by 2030 in our pathway thanks to new activities and investment in clean energy. Spending on more efficient appliances, electric and fuel cell vehicles, and building retrofits and energy-efficient construction would require a further 16 million workers. But these opportunities are often in different locations, skill sets and sectors than the jobs that will be lost as fossil fuels decline. In our pathway, around 5 million jobs are lost. Most of those jobs are located close to fossil fuel resources, and many are well paid, meaning structural changes can cause shocks for communities with impacts that persist over time. This requires careful policy attention to address the employment

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losses. It will be vital to minimise hardships associated with these disruptions, such as by retraining workers, locating new clean energy facilities in heavily affected areas wherever possible, and providing regional aid.

Global employment in energy supply in the net zero pathway, 2019-2030



An energy sector dominated by renewables

In the net zero pathway, global energy demand in 2050 is around 8% smaller than today, but it serves an economy more than twice as big and a population with 2 billion more people. More efficient use of energy, resource efficiency and behavioural changes combine to offset increases in demand for energy services as the world economy grows and access to energy is extended to all.

Instead of fossil fuels, the energy sector is based largely on renewable energy. Two-thirds of total energy supply in 2050 is from wind, solar, bioenergy, geothermal and hydro energy. Solar becomes the largest source, accounting for one-fifth of energy supplies. Solar PV capacity increases 20-fold between now and 2050, and wind power 11-fold.

Net zero means a huge decline in the use of fossil fuels. They fall from almost four-fifths of total energy supply today to slightly over one-fifth by 2050. Fossil fuels that remain in 2050 are used in goods where the carbon is embodied in the product such as plastics, in facilities fitted with CCUS, and in sectors where low-emissions technology options are scarce.

Electricity accounts for almost 50% of total energy consumption in 2050. It plays a key role across all sectors – from transport and buildings to industry – and is essential to produce low-emissions fuels such as hydrogen. To achieve this, total electricity generation increases over

two-and-a-half-times between today and 2050. At the same time, no additional new final investment decisions should be taken for new unabated coal plants, the least efficient coal plants are phased out by 2030, and the remaining coal plants still in use by 2040 are retrofitted. By 2050, almost 90% of electricity generation comes from renewable sources, with wind and solar PV together accounting for nearly 70%. Most of the remainder comes from nuclear.

Emissions from industry, transport and buildings take longer to reduce. Cutting industry emissions by 95% by 2050 involves major efforts to build new infrastructure. After rapid innovation progress through R&D, demonstration and initial deployment between now and 2030 to bring new clean technologies to market, the world then has to put them into action. Every month from 2030 onwards, ten heavy industrial plants are equipped with CCUS, three new hydrogen-based industrial plants are built, and 2 GW of electrolyser capacity are added at industrial sites. Policies that end sales of new internal combustion engine cars by 2035 and boost electrification underpin the massive reduction in transport emissions. In 2050, cars on the road worldwide run on electricity or fuel cells. Low-emissions fuels are essential where energy needs cannot easily or economically be met by electricity. For example, aviation relies largely on biofuels and synthetic fuels, and ammonia is vital for shipping. In buildings, bans on new fossil fuel boilers need to start being introduced globally in 2025, driving up sales of electric heat pumps. Most old buildings and all new ones comply with zero-carbon-ready building energy codes.[1]

PRIORITY ACTION

Set near-term milestones to get on track for long-term targets

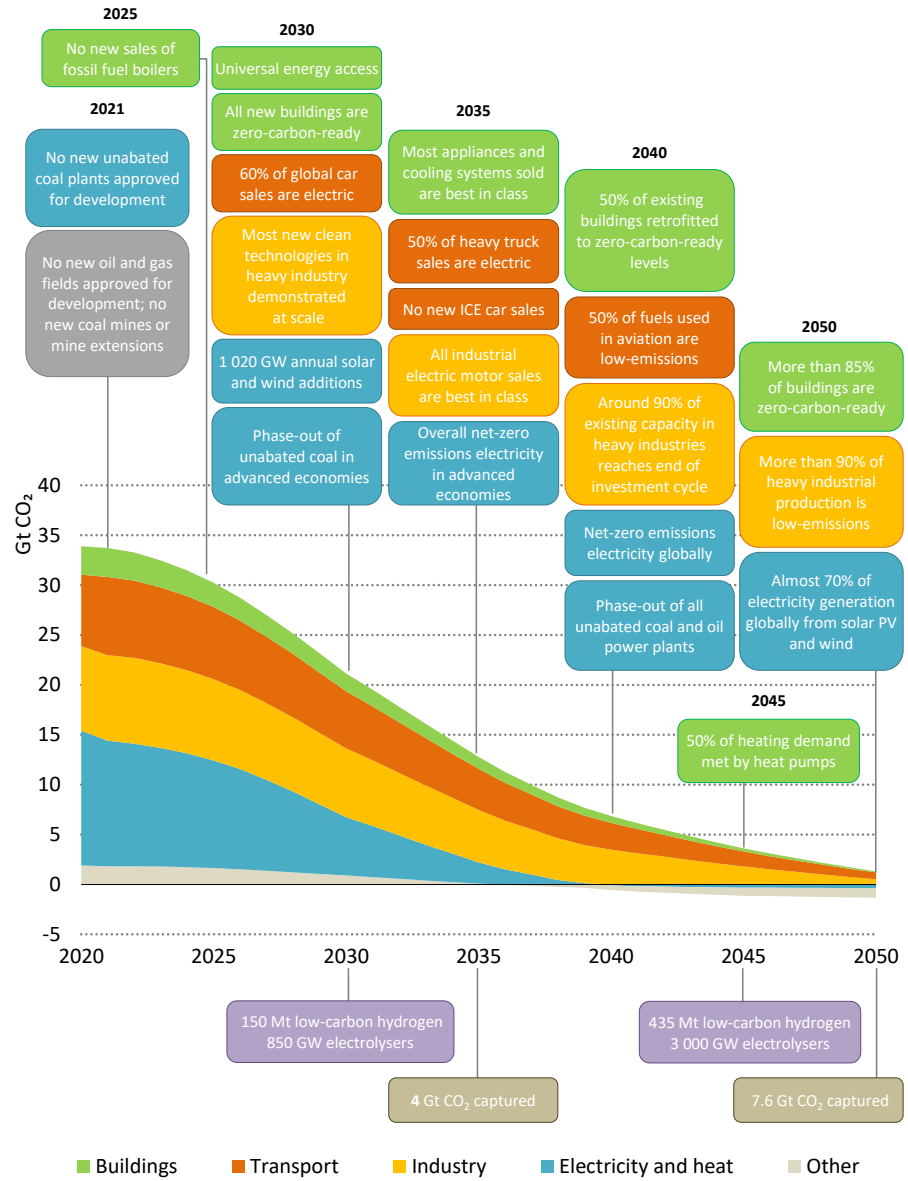
Governments need to provide credible step-by-step plans to reach their net zero goals, building confidence among investors, industry, citizens and other countries.

Governments must put in place long-term policy frameworks to allow all branches of government and stakeholders to plan for change and facilitate an orderly transition. Long-term national low-emissions strategies, called for by the Paris Agreement, can set out a vision for national transitions, as this report has done on a global level. These long-term objectives need to be linked to measurable short-term targets and policies. Our pathway details more than 400 sectoral and technology milestones to guide the global journey to net zero by 2050.

[1] A zero-carbon-ready building is highly energy efficient and either uses renewable energy directly or uses an energy supply that will be fully decarbonised by 2050, such as electricity or district heat.

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Key milestones in the pathway to net zero



There is no need for investment in new fossil fuel supply in our net zero pathway

Beyond projects already committed as of 2021, there are no new oil and gas fields approved for development in our pathway, and no new coal mines or mine extensions are required. The unwavering policy focus on climate change in the net zero pathway results in a sharp decline in fossil fuel demand, meaning that the focus for oil and gas producers switches entirely to output – and emissions reductions – from the operation of existing assets. Unabated coal demand declines by 98% to just less than 1% of total energy use in 2050. Gas demand declines by 55% to 1 750 billion cubic metres and oil declines by 75% to 24 million barrels per day (mb/d), from around 90 mb/d in 2020.

Clean electricity generation, network infrastructure and end-use sectors are key areas for increased investment. Enabling infrastructure and technologies are vital for transforming the energy system. Annual investment in transmission and distribution grids expands from USD 260 billion today to USD 820 billion in 2030. The number of public charging points for EVs rises from around 1 million today to 40 million in 2030, requiring annual investment of almost USD 90 billion in 2030. Annual battery production for EVs leaps from 160 gigawatt-hours (GWh) today to 6 600 GWh in 2030 – the equivalent of adding almost 20 gigafactories[2] each year for the next ten years. And the required roll-out of hydrogen and CCUS after 2030 means laying the groundwork now: annual investment in CO_2 pipelines and hydrogen-enabling infrastructure increases from USD 1 billion today to around USD 40 billion in 2030.

PRIORITY ACTION

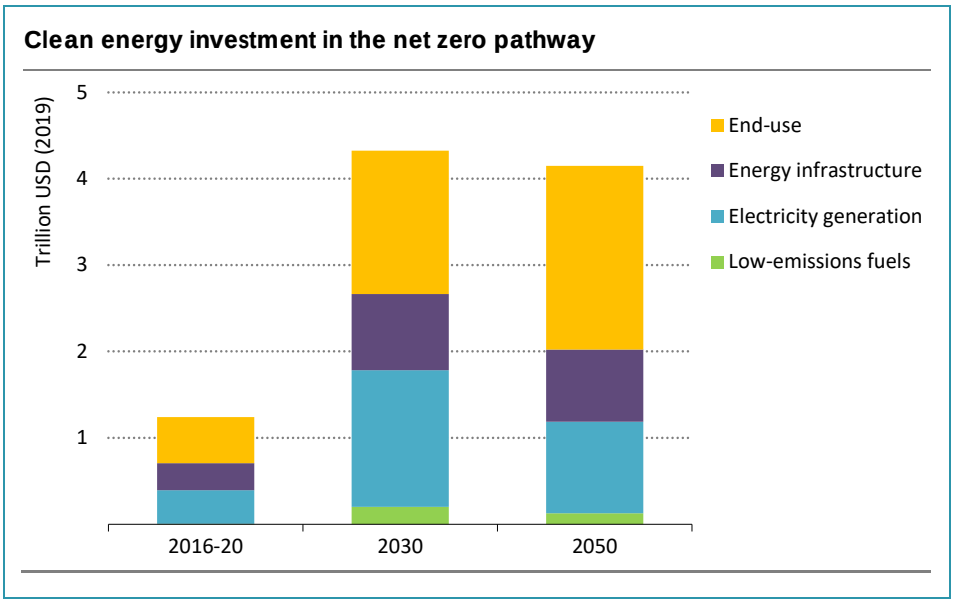
Drive a historic surge in clean energy investment

Policies need to be designed to send market signals that unlock new business models and mobilise private spending, especially in emerging economies.

Accelerated delivery of international public finance will be critical to energy transitions, especially in developing economies, but ultimately the private sector will need to finance most of the extra investment required. Mobilising the capital for large-scale infrastructure calls for closer co-operation between developers, investors, public financial institutions and governments. Reducing risks for investors will be essential to ensure successful and affordable clean energy transitions. Many emerging market and developing economies, which rely mainly on public funding for new energy projects and industrial facilities, will need to reform their policy and regulatory frameworks to attract more private finance. International flows of long-term capital to these economies will be needed to support the development of both existing and emerging clean energy technologies.

[2] Battery gigafactory capacity assumption = 35 gigawatt-hours per year.

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An unparalleled clean energy investment boom lifts global economic growth

Total annual energy investment surges to USD 5 trillion by 2030, adding an extra 0.4 percentage point a year to annual global GDP growth, based on our joint analysis with the International Monetary Fund. This unparalleled increase – with investment in clean energy and energy infrastructure more than tripling already by 2030 – brings significant economic benefits as the world emerges from the Covid-19 crisis. The jump in private and government spending creates millions of jobs in clean energy, including energy efficiency, as well as in the engineering, manufacturing and construction industries. All of this puts global GDP 4% higher in 2030 than it would be based on current trends.

Governments have a key role in enabling investment-led growth and ensuring that the benefits are shared by all. There are large differences in macroeconomic impacts between regions. But government investment and public policies are essential to attract large amounts of private capital and to help offset the declines in fossil fuel income that many countries will experience. The major innovation efforts needed to bring new clean energy technologies to market could boost productivity and create entirely new industries, providing opportunities to locate them in areas that see job losses in incumbent industries. Improvements in air quality provide major health benefits, with 2 million fewer premature deaths globally from air pollution in 2030 than today in our net zero pathway. Achieving universal energy access by 2030 would provide a major boost to well-being and productivity in developing economies.

New energy security concerns emerge, and old ones remain

The contraction of oil and natural gas production will have far-reaching implications for all the countries and companies that produce these fuels. No new oil and natural gas fields are needed in our pathway, and oil and natural gas supplies become increasingly concentrated in a small number of low-cost producers. For oil, the OPEC share of a much-reduced global oil supply increases from around 37% in recent years to 52% in 2050, a level higher than at any point in the history of oil markets. Yet annual per capita income from oil and natural gas in producer economies falls by about 75%, from USD 1 800 in recent years to USD 450 by the 2030s, which could have knock-on societal effects. Structural reforms and new sources of revenue are needed, even though these are unlikely to compensate fully for the drop in oil and gas income. While traditional supply activities decline, the expertise of the oil and natural gas industry fits well with technologies such as hydrogen, CCUS and offshore wind that are needed to tackle emissions in sectors where reductions are likely to be most challenging.

The energy transition requires substantial quantities of critical minerals, and their supply emerges as a significant growth area. The total market size of critical minerals like copper, cobalt, manganese and various rare earth metals grows almost sevenfold between 2020 and 2030 in the net zero pathway. Revenues from those minerals are larger than revenues from coal well before 2030. This creates substantial new opportunities for mining companies. It also creates new energy security concerns, including price volatility and additional costs for transitions, if supply cannot keep up with burgeoning demand.

The rapid electrification of all sectors makes electricity even more central to energy security around the world than it is today. Electricity system flexibility – needed to balance wind and solar with evolving demand patterns – quadruples by 2050 even as retirements of fossil fuel capacity reduce conventional sources of flexibility. The transition calls for major increases in all sources of flexibility: batteries, demand response and low-carbon flexible power plants, supported by smarter and more digital electricity networks. The resilience of electricity systems to cyberattacks and other emerging threats needs to be enhanced.

PRIORITY ACTION

Address emerging energy security risks now

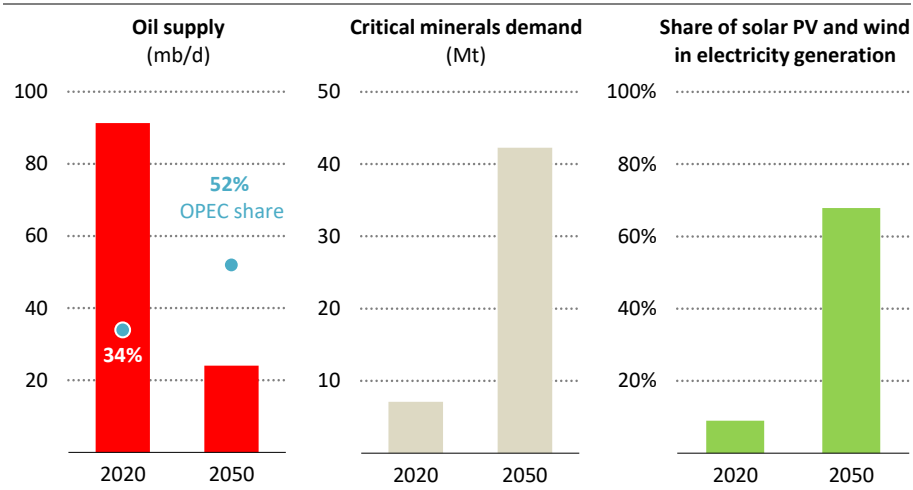
Ensuring uninterrupted and reliable supplies of energy and critical energy-related commodities at affordable prices will only rise in importance on the way to net zero.

The focus of energy security will evolve as reliance on renewable electricity grows and the role of oil and gas diminishes. Potential vulnerabilities from the increasing importance of electricity include the variability of supply and cybersecurity risks. Governments need to create markets for investment in batteries, digital solutions and electricity grids that reward flexibility and enable adequate and reliable supplies of electricity. The growing dependence on critical minerals required for key clean energy technologies calls for new international mechanisms to ensure both the timely

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availability of supplies and sustainable production. At the same time, traditional energy security concerns will not disappear, as oil production will become more concentrated.

Global energy security indicators in the net zero pathway



Note: mb/d = million barrels per day; Mt = million tonnes.

International co-operation is pivotal for achieving net-zero emissions by 2050

Making net-zero emissions a reality hinges on a singular, unwavering focus from all governments – working together with one another, and with businesses, investors and citizens. All stakeholders need to play their part. The wide-ranging measures adopted by governments at all levels in the net zero pathway help to frame, influence and incentivise the purchase by consumers and investment by businesses. This includes how energy companies invest in new ways of producing and supplying energy services, how businesses invest in equipment, and how consumers cool and heat their homes, power their devices and travel.

Underpinning all these changes are policy decisions made by governments. Devising cost-effective national and regional net zero roadmaps demands co-operation among all parts of government that breaks down silos and integrates energy into every country's policy making on finance, labour, taxation, transport and industry. Energy or environment ministries alone cannot carry out the policy actions needed to reach net zero by 2050.

Changes in energy consumption result in a significant decline in fossil fuel tax revenues. In many countries today, taxes on diesel, gasoline and other fossil fuel consumption are an important source of public revenues, providing as much as 10% in some cases. In the net zero pathway, tax revenue from oil and gas retail sales falls by about 40% between 2020 and 2030. Managing this decline will require long-term fiscal planning and budget reforms.

The net zero pathway relies on unprecedented international co-operation among governments, especially on innovation and investment. The IEA stands ready to support governments in preparing national and regional net zero roadmaps, to provide guidance and assistance in implementing them, and to promote international co-operation to accelerate the energy transition worldwide.

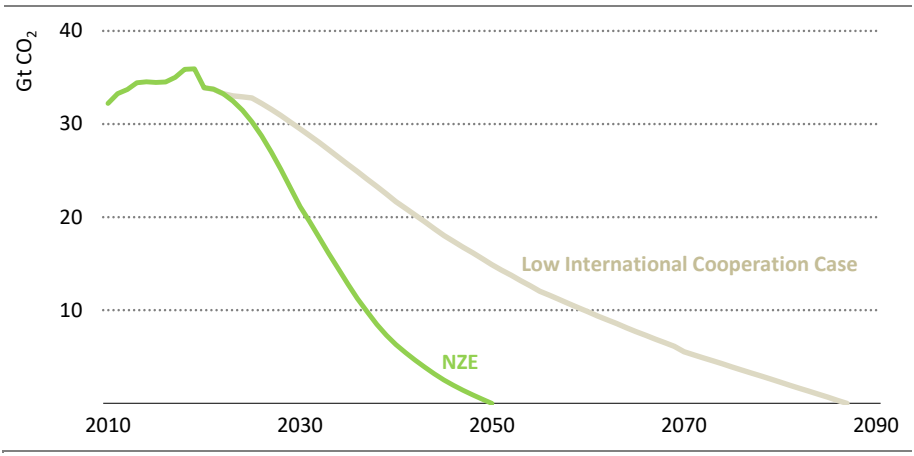
PRIORITY ACTION

Take international co-operation to new heights

This is not simply a matter of all governments seeking to bring their national emissions to net zero – it means tackling global challenges through co-ordinated actions.

Governments must work together in an effective and mutually beneficial manner to implement coherent measures that cross borders. This includes carefully managing domestic job creation and local commercial advantages with the collective global need for clean energy technology deployment. Accelerating innovation, developing international standards and co-ordinating to scale up clean technologies needs to be done in a way that links national markets. Co-operation must recognise differences in the stages of development of different countries and the varying situations of different parts of society. For many rich countries, achieving net-zero emissions will be more difficult and costly without international co-operation. For many developing countries, the pathway to net zero without international assistance is not clear. Technical and financial support is needed to ensure deployment of key technologies and infrastructure. Without greater international co-operation, global CO_2 emissions will not fall to net zero by 2050.

Global energy-related CO_2 emissions in the net zero pathway and Low International Co-operation Case

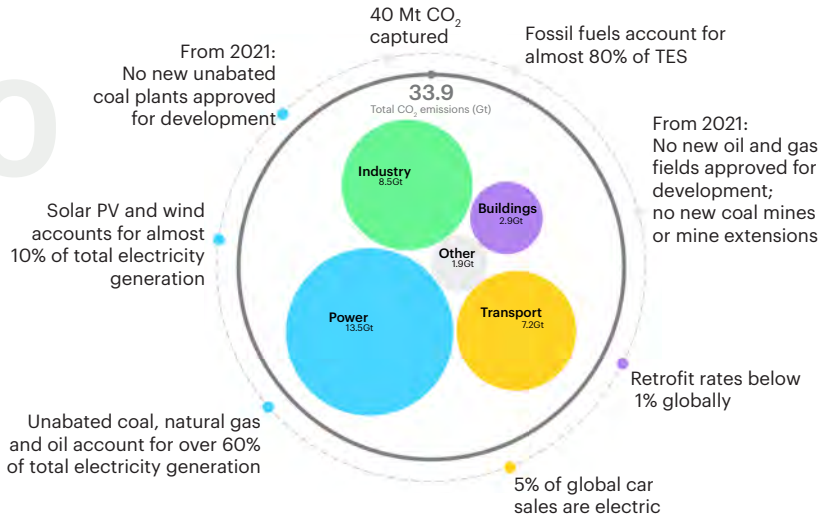


Note: Gt = gigatonnes.

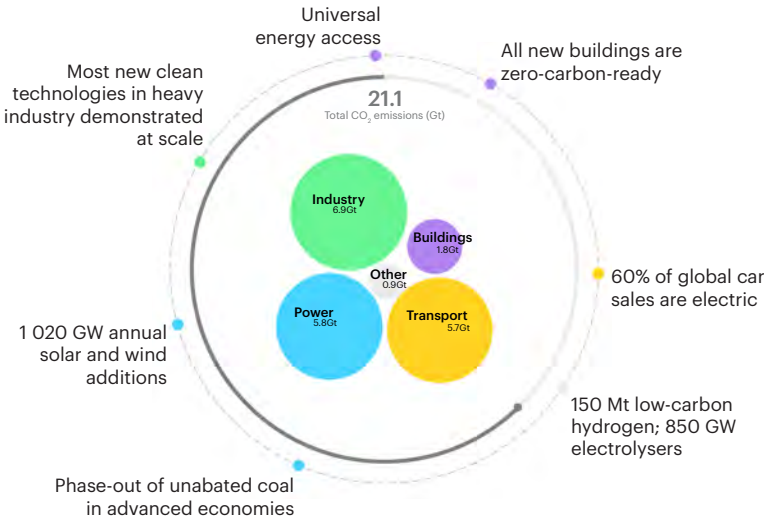
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Net Zero Emissions by 2050 Interactive iea.li/nzeroadmap

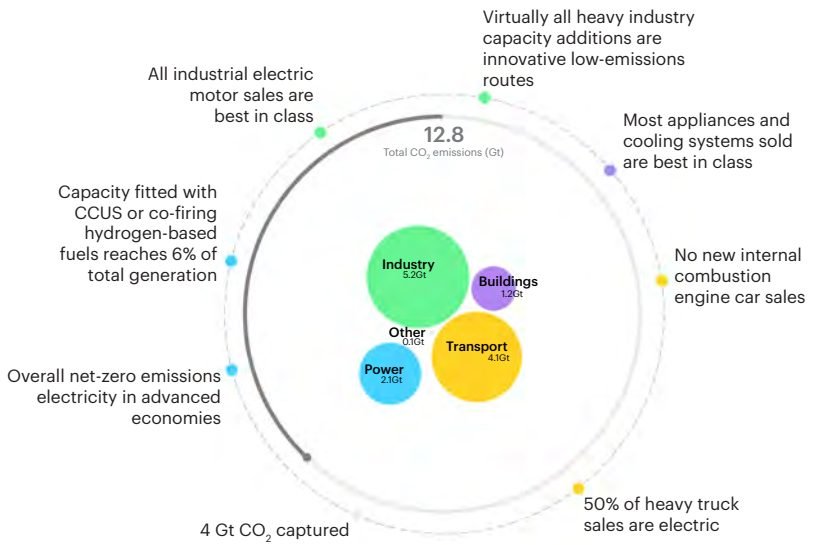
2020

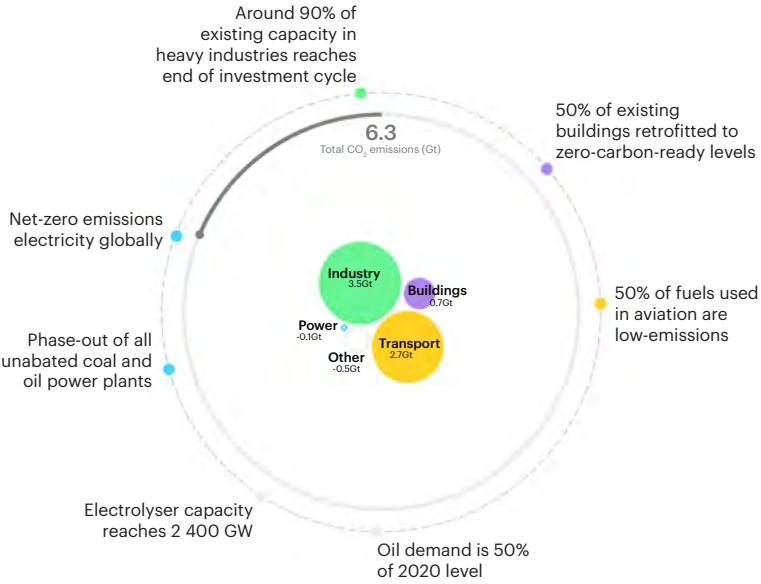


2030

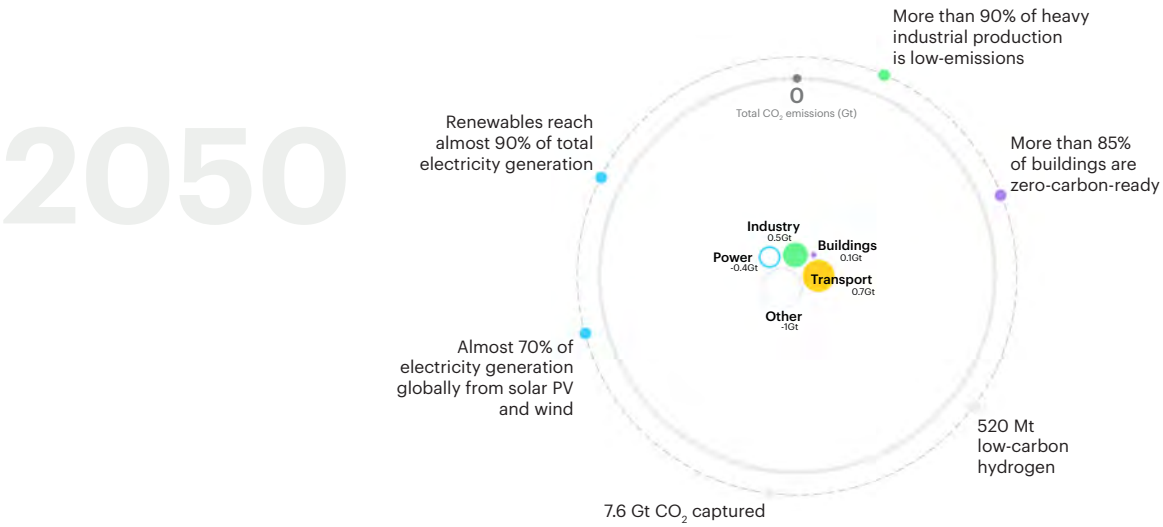


2035





2040



2050

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Net Zero Emissions by 2050 Interactive iea.li/nzeroadmap

Announced net zero pledges and the energy sector

SUMMARY

- There has been a rapid increase over the last year in the number of governments pledging to reduce greenhouse gas emissions to net zero. Net zero pledges to date cover around 70% of global GDP and CO_2 emissions. However, fewer than a quarter of announced net zero pledges are fixed in domestic legislation and few are yet underpinned by specific measures or policies to deliver them in full and on time.
- The Stated Policies Scenario (STEPS) takes account only of specific policies that are in place or have been announced by governments. Annual energy-related and industrial process CO_2 emissions rise from 34 Gt in 2020 to 36 Gt in 2030 and remain around this level until 2050. If emissions continue on this trajectory, with similar changes in non-energy-related GHG emissions, this would lead to a temperature rise of around 2.7 °C by 2100 (with a 50% probability). Renewables provide almost 55% of global electricity generation in 2050 (up from 29% in 2020), but clean energy transitions lag in other sectors. Global coal use falls by 15% between 2020 and 2050; oil use in 2050 is 15% higher than in 2020; and natural gas use is almost 50% higher.
- The Announced Pledges Case (APC) assumes that all announced national net zero pledges are achieved in full and on time, whether or not they are currently underpinned by specific policies. Global energy-related and industrial process CO_2 emissions fall to 30 Gt in 2030 and 22 Gt in 2050. Extending this trajectory, with similar action on non-energy-related GHG emissions, would lead to a temperature rise in 2100 of around 2.1 °C (with a 50% probability). Global electricity generation nearly doubles to exceed 50 000 TWh in 2050. The share of renewables in electricity generation rises to nearly 70% in 2050. Oil demand does not return to its 2019 peak and falls about 10% from 2020 to 80 mb/d in 2050. Coal use drops by 50% to 2 600 Mtce in 2050, while natural gas use expands by 10% to 4 350 bcm in 2025 and remains about that level to 2050.
- Efficiency, electrification and the replacement of coal by low-emissions sources in electricity generation play a central role in achieving net zero goals in the APC, especially over the period to 2030. The relative contributions of nuclear, hydrogen, bioenergy and CCUS vary across countries, depending on their circumstances.
- The divergence in trends between the APC and the STEPS shows the difference that current net zero pledges could make, while underlining at the same time the need for concrete policies and short-term plans that are consistent with long-term net zero pledges. However, the APC also starkly highlights that existing net zero pledges, even if delivered in full, fall well short of what is necessary to reach global net-zero emissions by 2050.

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1.1 Introduction

November 2021 will see the most important UN Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP 26) since the Paris Agreement was signed in 2015. As COP 26 approaches, an increasing number of countries have announced long-term goals to achieve net-zero greenhouse gas (GHG) emissions over the coming decades. On 31 March 2021, the International Energy Agency (IEA) hosted a Net Zero Summit to take stock of the growing list of commitments from countries and companies to reach the goals of the Paris Agreement, and to focus on the actions necessary to start turning those net zero goals into reality.

Achieving those goals will be demanding. The Covid-19 pandemic delivered a major shock to the world economy, resulting in an unprecedented 5.8% decline in CO_2 emissions in 2020. However, our monthly data show that global energy-related CO_2 emissions started to climb again in December 2020, and we estimate that they will rebound to around 33 gigatonnes of carbon dioxide (Gt CO_2) in 2021, only 1.2% below the level in 2019 (IEA, 2021). Sustainable economic recovery packages offered a unique opportunity to make 2019 the definitive peak in global emissions, but the evidence so far points to a rebound in emissions in parallel with renewed economic growth, at least in the near term (IEA, 2020a).

Recent IEA analyses examined the technologies and policies needed for countries and regions to achieve net-zero emissions energy systems. The *World Energy Outlook 2020* examined what would be needed over the period to 2030 to put the world on a path towards net-zero emissions by 2050 in the context of the pandemic-related economic recovery (IEA, 2020b). The Faster Innovation Case in *Energy Technology Perspectives 2020* explored whether net-zero emissions could be achieved globally by 2050 through accelerated energy technology development and deployment alone: it showed that, relative to baseline trends, almost half of the emissions savings needed in 2050 to reach net-zero emissions rely on technologies that are not yet commercially available (IEA, 2020c).

This special report, prepared at the request of the UK President of the COP 26, incorporates the insights and lessons learned from both reports to create a comprehensive and detailed pathway, or roadmap, to achieve net-zero energy-related and industrial process CO_2 emissions globally by 2050. It assesses the costs of achieving this goal, the likely impacts on employment and the economy, and the wider implications for the world. It also highlights the key milestones for technologies, infrastructure, investment and policy that are needed along the road to 2050.

This report is set out in four chapters:

- **Chapter 1** explores the outlook for global CO_2 emissions and energy supply and use based on existing policies and pledges. It sets out projections of global energy use and emissions based on the **Stated Policies Scenario (STEPS)**, which includes only the firm policies that are in place or have been announced by countries, including Nationally

Determined Contributions. It also examines the **Announced Pledges Case (APC)**, a variant of the STEPS that assumes that all of the net zero targets announced by countries around the world to date are met in full.

- **Chapter 2** presents the **Net-Zero Emissions by 2050 Scenario (NZE)**, which describes how energy demand and the energy mix will need to evolve if the world is to achieve net-zero emissions by 2050. It also assesses the corresponding investment needs and explores key uncertainties surrounding technology and consumer behaviour.
- **Chapter 3** examines the implications of the NZE for various sectors, covering fossil fuel supply, the supply of low-emissions fuels (such as hydrogen, ammonia, biofuels, synthetic fuels and biomethane) and the electricity, transport, industry and buildings sectors. It highlights the key changes required to achieve net-zero emissions in the NZE and the major milestones that are needed along the way.
- **Chapter 4** explores the implications of the NZE for the economy, the energy industry, citizens and governments.

1.2 Emissions reduction targets and net zero pledges

1.2.1 Nationally Determined Contributions

Under the Paris Agreement, Parties [1] are required to submit Nationally Determined Contributions (NDCs) to the UNFCCC and to implement policies with the aim of achieving their stated objectives. The process is dynamic; it requires Parties to update their NDCs every five years in a progressive manner to reflect the highest possible ambition. The first round of NDCs, submitted by 191 countries, covers more than 90% of global energy-related and industrial process CO_2 emissions. [2] The first NDCs included some targets that were unconditional and others that were conditional on international support for finance, technology and other means of implementation.

As of 23 April 2021, 80 countries have submitted new or updated NDCs to the UNFCCC, covering just over 40% of global CO_2 emissions (Figure 1.1).[3] Many of the updated NDCs include more stringent targets than in the initial round of NDCs, or targets for a larger number of sectors or for a broader coverage of GHGs. In addition, 27 countries and the European Union have communicated long-term low GHG emissions development strategies to the UNFCCC, as requested by the Paris Agreement. Some of these strategies incorporate a net zero pledge.

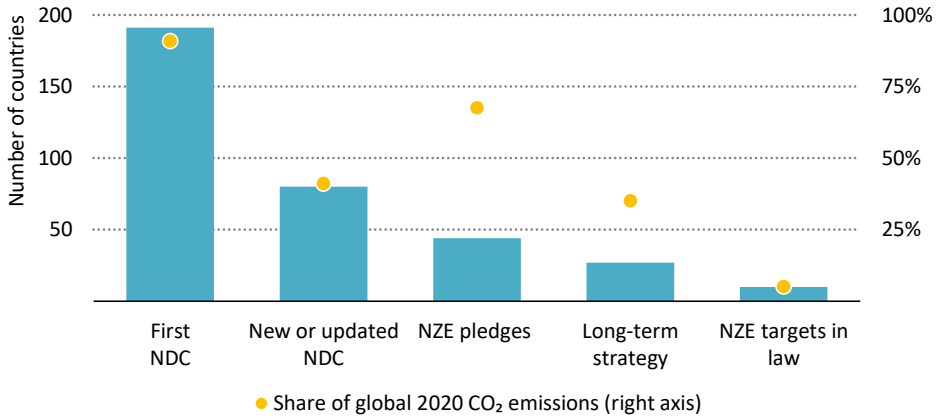
[1] Parties refers to the 197 members of the UNFCCC which includes all United Nations member states, United Nations General Assembly Observer State of Palestine, UN non-member states Niue and the Cook Islands and the European Union.

[2] Unless otherwise stated, CO_2 emissions in this report refer to energy-related and industrial process CO_2 emissions.

[3] Several countries have indicated that they intend to submit new or updated NDCs later in 2021 or in 2022.

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Figure 1.1 ▷ Number of countries with NDCs, long-term strategies and net zero pledges, and their shares of 2020 global CO_2 emissions



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Around 40% of countries that have ratified the Paris Agreement have updated their NDCs, but net zero pledges cover around 70% of global CO_2 emissions

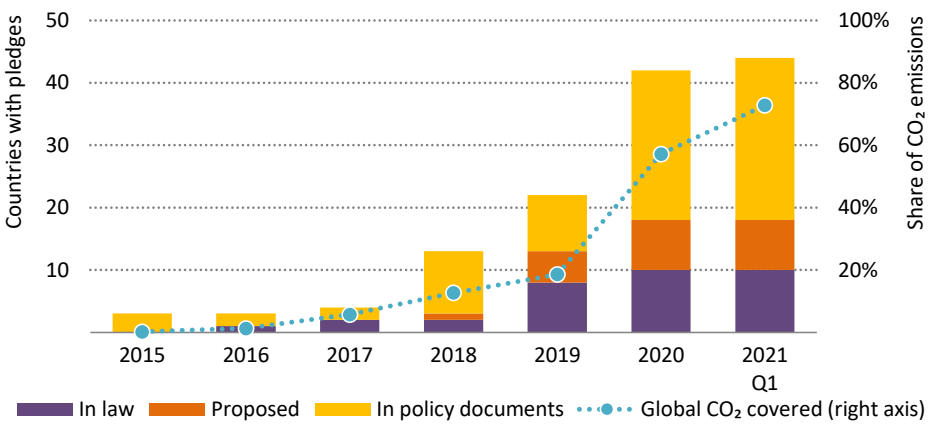
1.2.2 Net-zero emissions pledges

There has been a rapid increase in the number of governments making pledges to reduce GHG emissions to net zero (Figure 1.2). In the Paris Agreement, countries agreed to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second-half of the century". The Intergovernmental Panel on Climate Change (IPCC) *Special Report on Global Warming of 1.5 °C* highlighted the importance of reaching net-zero CO_2 emissions globally by mid-century or sooner to avoid the worst impacts of climate change (IPCC, 2018).

Net-zero emissions pledges have been announced by national governments, subnational jurisdictions, coalitions[4] and a large number of corporate entities (see Spotlight). As of 23 April 2021, 44 countries and the European Union have pledged to meet a net-zero emissions target: in total they account for around 70% of global CO_2 emissions and GDP (Figure 1.3). Of these, ten countries have made meeting their net zero target a legal obligation, eight are proposing to make it a legal obligation, and the remainder have made their pledges in official policy documents.

[4] Examples include: the UN-led Climate Ambition Alliance in which signatories signal they are working towards achieving net-zero emissions by 2050; and the Carbon Neutrality Coalition launched at the UN Climate Summit in 2017, in which signatories commit to develop long-term low GHG emissions strategies in line with limiting temperature rises to 1.5 °C.

Figure 1.2 ▷ Number of national net zero pledges and share of global CO_2 emissions covered

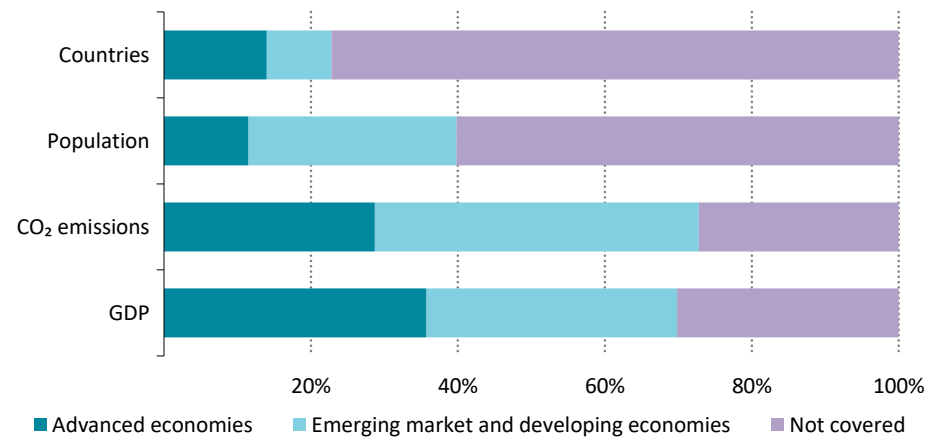


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There has been a significant acceleration in net-zero emissions pledges announced by governments, with an increasing number enshrined in law

Notes: In law = a net zero pledge has been approved by parliament and is legally binding. Proposed = a net zero pledge has been proposed to parliament to be voted into law. In policy document = a net zero pledge has been proposed but does not have legally binding status.

Figure 1.3 ▷ Coverage of announced national net zero pledges



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Countries accounting for around 70% of global CO_2 emissions and GDP have set net zero pledges in law, or proposed legislation or in an official policy document

Note: GDP = gross domestic product at purchasing power parity.

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In contrast to some of the shorter term commitments contained within NDCs, few net zero pledges are supported by detailed policies and firm routes to implementation. Net-zero emissions pledges also vary considerably in their timescale and scope. Some key differences include:

- **GHG coverage.** Most pledges cover all GHG emissions, but some include exemptions or different rules for certain types of emissions. For example, New Zealand's net zero pledge covers all GHGs except biogenic methane, which has a separate reduction target.
- **Sectoral boundaries**. Some pledges exclude emissions from specific sectors or activities. For example, the Netherlands aims to achieve net-zero GHG emissions only in its electricity sector (as part of an overall aim to reduce total GHG emissions by 95%), and some countries, including France, Portugal and Sweden, exclude international aviation and shipping.
- **Use of carbon dioxide removal (CDR)**. Pledges take varying approaches to account for CDR within a country's sovereign territory. CDR options include natural CO_2 sinks, such as forests and soils, as well as technological solutions, such as direct air capture or bioenergy with carbon capture and storage. For example, Uruguay has stated that natural CO_2 sinks will be used to help it reach net-zero emissions, while Switzerland plans to use CDR technologies to balance a part of its residual emissions in 2050.
- **Use of international mitigation transfers**. Some pledges allow GHG mitigation that occurs outside a country's borders to be counted towards the net zero target, such as through the transfer of carbon credits, while others do not. For example, Norway allows the potential use of international transfers, while France explicitly rules them out. Some countries, such as Sweden, allow such transfers but specify an upper limit to their use.
- **Timeframe**. The majority of pledges, covering 35% of global CO_2 emissions in 2020, target net-zero emissions by 2050, but Finland aims to reach that goal by 2035, Austria and Iceland by 2040 and Sweden by 2045. Among others, the People's Republic of China (hereafter China) and Ukraine have set a target date after 2050.

S P O T L I G H T

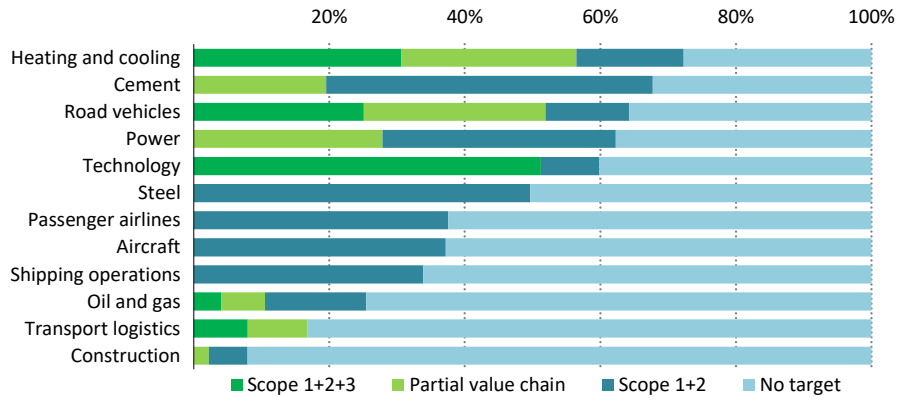
How are businesses responding to the need to reach net-zero emissions?

There has been a rapid rise in net-zero emissions announcements from companies in recent years: as of February 2021, around 110 companies that consume large amounts of energy directly or produce energy-consuming goods have announced net-zero emissions goals or targets.

Around 60-70% of global production of heating and cooling equipment, road vehicles, electricity and cement is from companies that have announced net-zero emissions targets (Figure 1.4). Nearly 60% of gross revenue in the technology sector is also generated by companies with net-zero emission targets. In other sectors, net zero

pledges cover 30-40% of air and shipping operations, 15% of transport logistics and 10% of construction. All these shares are likely to keep growing as more companies make pledges.

Figure 1.4 ▷ Sectoral activity of large energy-related companies with announced pledges to reach net-zero emissions by 2050



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Some sectors are more advanced in terms of the extent of net zero targets by companies active in the sector

Notes: Scope 1 = direct emissions from energy and other sources owned or controlled. Scope 2 = indirect emissions from the production of electricity and heat, and fuels purchased and used. Scope 3 = indirect emissions from sources not owned or directly controlled but related to their activities (such as employee travel, extraction, transport and production of purchased materials and fuels, and end-use of fuels, products and services). Partial value chain includes Scope 1 and 2 emissions and Scope 3 emissions in specific geographic locations or sections of a company's value chain.

Source: IEA analysis based on company reports from the largest 10-25 companies within each sector.

Company pledges may not be readily comparable. Most companies account for emissions and set net zero pledges based on the GHG Protocol (WRI, WBCSD, 2004), but the coverage and timeframe of these pledges varies widely. Some cover only their own emissions, for example by shifting to the use of zero-emissions electricity in offices and production facilities, and by eliminating the use of oil in transport or industrial operations, e.g. FedEx, ArcelorMittal and Maersk. Others also cover wider emissions from certain parts of their values chains, e.g. Renault in Europe, or all indirect emissions related to their activities, e.g. Daikin, Toyota, Shell, Eni and Heidelberg. Around 60% of pledges aim to achieve net-zero emissions by 2050, but several companies have set an earlier deadline of 2030 or 2040.

Around 40% of companies that have announced net zero pledges have yet to set out how they aim to achieve them. For those with detailed plans, the main options include direct emissions reductions, use of CO_2 removal technologies, such as afforestation, bioenergy

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with carbon capture, utilisation and storage (CCUS), or direct air capture with CO_2 storage, and purchasing emissions (credits generated through emissions reductions that occur elsewhere). The use of offsets could be a cost-effective mechanism to eliminate emissions from parts of value chains where emissions reductions are most challenging, provided that schemes to generate emissions credits result in permanent, additional and verified emissions reductions. However, there is likely to be a limited supply of emissions credits consistent with net-zero emissions globally and the use of such credits could divert investment from options that enable direct emissions reductions.

1.3 Outlook for emissions and energy in the STEPS

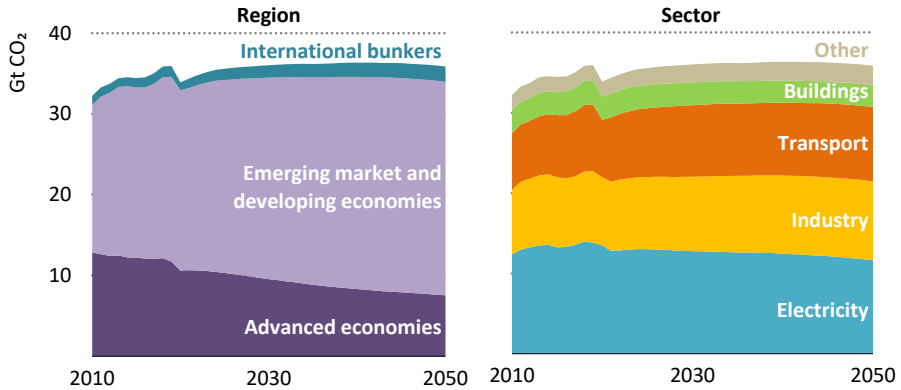
The IEA Stated Policies Scenario (STEPS) illustrates the consequences of existing and stated policies for the energy sector. It draws on the latest information regarding national energy and climate plans and the policies that underpin them. It takes account of all policies that are backed by robust implementing legislation or regulatory measures, including the NDCs that countries have put forward under the Paris Agreement up to September 2020 and the energy components of announced economic stimulus and recovery packages. So far, few net-zero emissions pledges have been backed up by detailed policies, implementation plans or interim targets: most net zero pledges therefore are not included in the STEPS.

1.3.1 CO_2 emissions

Global CO_2 emissions in the STEPS bring about only a marginal overall improvement in recent trends. Switching to renewables leads to an early peak in emissions in the electricity sector, but reductions across all sectors fall far short of what is required for net-zero emissions in 2050. Annual CO_2 emissions rebound quickly from the dip caused by the Covid-19 pandemic in 2020: they increase from 34 Gt in 2020 to 36 Gt in 2030 and then remain around this level until 2050 (Figure 1.5). If emissions trends were to continue along the same trajectory after 2050, and with commensurate changes in other sources of GHG emissions, the global average surface temperature rise would be around 2.7 °C in 2100 (with a 50% probability).

There is strong divergence between the outlook for emissions in advanced economies on one hand and the emerging market and developing economies on the other. In advanced economies, despite a small rebound in the early 2020s, CO_2 emissions decline by about a third between 2020 and 2050, thanks to the impact of policies and technological progress in reducing energy demand and switching to cleaner fuels. In emerging market and developing economies, energy demand continues to grow strongly because of increased population, brisk economic growth, urbanisation and the expansion of infrastructure: these effects outweigh improvements in energy efficiency and the deployment of clean technologies, causing CO_2 emissions to grow by almost 20% by the mid-2040s, before declining marginally to 2050.

Figure 1.5 ▷ Energy-related and industrial process CO_2 emissions by region and sector in the STEPS



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Global CO_2 emissions rebound quickly after 2020 and then plateau, with declines in advanced economies offset by increases elsewhere

Note: Other = agriculture and own use in the energy sector.

1.3.2 Total energy supply, total final consumption and electricity generation

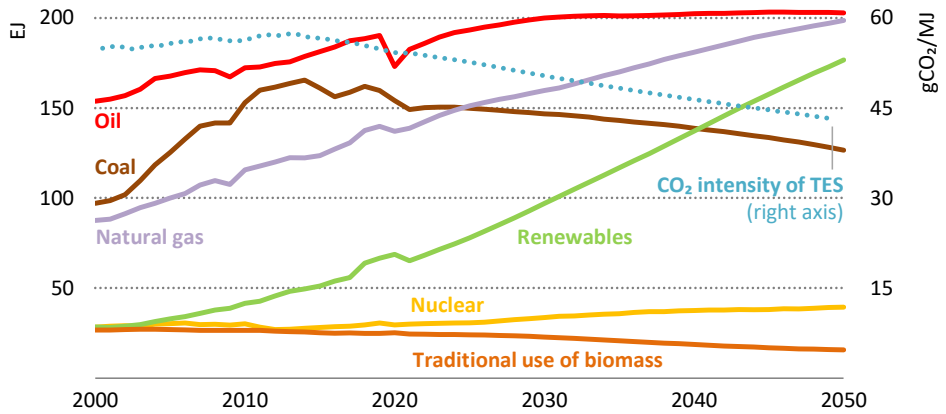
The projected trends in CO_2 emissions in the STEPS result from changes in the amount of energy used and the mix of fuels and technologies. Total energy supply (TES)[5] worldwide rises by just over 30% between 2020 and 2050 in the STEPS (Figure 1.6). Without a projected annual average reduction of 2.2% in energy intensity, i.e. energy use per unit of GDP, TES in 2050 would be around 85% higher. In advanced economies, energy use falls by around 5% to 2050, despite a 75% increase in economic activity over the period. In emerging market and developing economies, energy use increases by 50% to 2050, reflecting a tripling of economic output between 2020 and 2050. Despite the increase in GDP and energy use in emerging market and developing economies, 750 million people still have no access to electricity in 2050, more than 95% of them in sub-Saharan Africa, and 1.5 billion people continue to rely on the traditional use of bioenergy for cooking.

The global fuel mix changes significantly between 2020 and 2050. Coal use, which peaked in 2014, falls by around 15%. Having fallen sharply in 2020 due to the pandemic, oil demand rebounds quickly, returning to the 2019 level of 98 million barrels per day (mb/d) by 2023 and reaching a plateau of around 104 mb/d shortly after 2030. Natural gas demand increases from 3 900 billion cubic metres (bcm) in 2020 to 4 600 bcm in 2030 and 5 700 bcm in 2050. Nuclear energy grows by 15% between 2020 and 2030, mainly reflecting expansions in China.

[5] Total primary energy supply (or total primary energy demand) has been renamed total energy supply in accordance with the International Recommendations for Energy Statistics (IEA, 2020d).

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Figure 1.6 ▷ Total energy supply and CO_2 emissions intensity in the STEPS



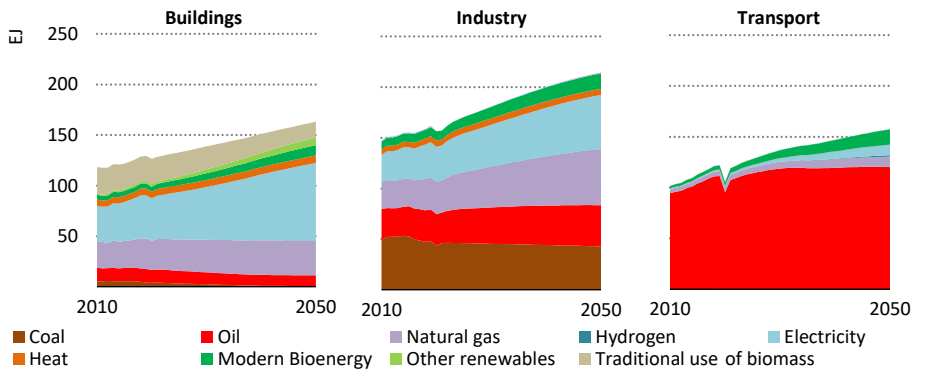
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Coal use declines, oil plateaus and renewables and natural gas grow substantially to 2050

Note: EJ = exajoule; MJ = megajoule; TES = total energy supply.

Total final consumption increases in all sectors in the STEPS, led by electricity and natural gas (Figure 1.7). All the growth is in emerging market and developing economies. The biggest change in energy use is in the electricity sector (Figure 1.8). Global electricity demand increases by 80% between 2020 and 2050, around double the overall rate of growth in final energy consumption. More than 85% of the growth in global electricity demand comes from emerging market and developing economies. Coal continues to play an important role in electricity generation in those economies to 2050, despite strong growth in renewables: in advanced economies, the use of coal for electricity generation drops sharply.

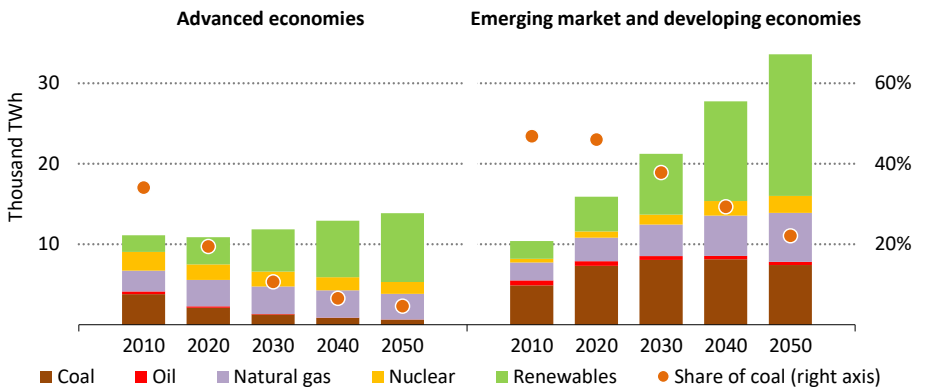
Figure 1.7 ▷ Total final consumption by sector and fuel in the STEPS



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Final energy consumption grows on average by 1% per year between 2020 and 2050, with electricity and natural gas meeting most of the increase

Figure 1.8 ▷ Electricity generation by fuel and share of coal in the STEPS



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Emerging market and developing economies drive most of the increase in global electricity demand, met mainly by renewables and gas, though coal remains important

1.3.3 Emissions from existing assets

The energy sector contains a large number of long-lived and capital-intensive assets. Urban infrastructure, pipelines, refineries, coal-fired power plants, heavy industrial facilities, buildings and large hydro power plants can have technical and economic lifetimes of well over 50 years. If today's energy infrastructure was to be operated until the end of the typical lifetime in a manner similar to the past, we estimate that this would lead to cumulative energy-related and industrial process CO_2 emissions between 2020 and 2050 of just under 650 Gt CO_2. This is around 30% more than the remaining total CO_2 budget consistent with limiting global warming to 1.5 °C with a 50% probability (see Chapter 2).

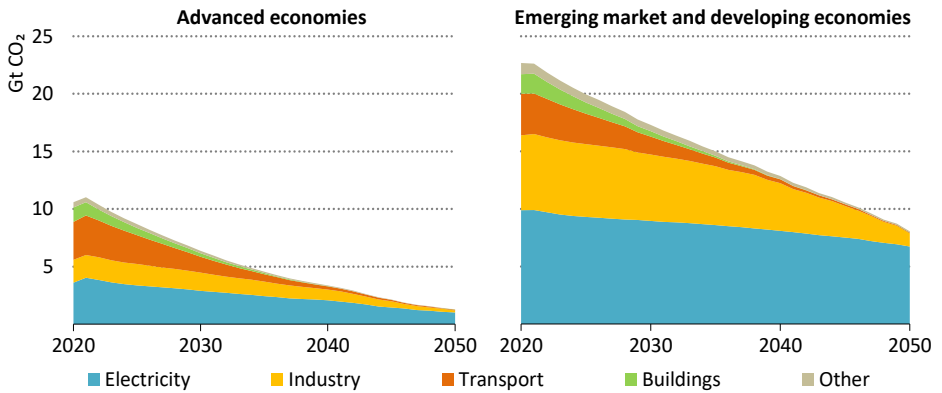
The electricity sector accounts for more than 50% of the total emissions that would come from existing assets; 40% of total emissions would come from coal-fired power plants alone. Industry is the next largest sector, with steel, cement, chemicals and other industry accounting for around 30% total emissions from existing assets. The long lifetime of production facilities in these sub-sectors (typically 30-40 years for a blast furnace or cement kiln) and the relatively young age of the global capital stock explain their large contribution. Transport accounts for just over 10% of emissions from existing assets and the buildings sector accounts for just under 5%. The lifetime of vehicles and equipment in the transport and buildings sectors is generally much shorter than is the case in electricity and industry – passenger cars, for example, are generally assumed to have a lifetime of around 17 years – but associated infrastructure networks such as roads, electricity networks and gas grids have very long lifetimes.

There are some large regional differences in emissions levels from existing assets (Figure 1.9). Advanced economies tend to have much older capital stocks than emerging market and developing economies, particularly in the electricity sector, and existing assets will reach the end of their lifetimes earlier. For example, the average age of coal-fired power

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plants in China is 13 years and 16 years in the rest of Asia, compared to around 35 years in Europe and 40 years in the United States (IEA, 2020e).

Figure 1.9 ▷ Emissions from existing infrastructure by sector and region



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Emerging market and developing economies account for three-quarters of cumulative emissions from existing infrastructure through to 2050

1.4 Announced Pledges Case

The Announced Pledges Case (APC) assumes that all national net-zero emissions pledges are realised in full and on time. It therefore goes beyond the policy commitments incorporated in the STEPS. The aim of the APC is to see how far full implementation of the national net-zero emissions pledges would take the world towards reaching net-zero emissions, and to examine the scale of the transformation of the energy sector that such a path would require.

The way these pledges are assumed to be implemented in the APC has important implications for the energy system. A net zero pledge for all GHG emissions does not necessarily mean that CO_2 emissions from the energy sector need to reach net zero. For example, a country's net zero plans may envisage some remaining energy-related emissions are offset by the absorption of emissions from forestry or land use, or by negative emissions arising from the use of bioenergy or direct capture of CO_2 from the air (DAC) with CCUS.[6] It is not possible to know exactly how net zero pledges will be implemented, but the design of the APC, particularly with respect to the details of the energy system pathway, has been informed by the pathways that a number of national bodies have developed to support net zero pledges (Box 1.1). Policies in countries that have not yet made a net zero pledge are assumed to be the same as in the STEPS. Non policy assumptions, including population and economic growth, are the same as in the STEPS.

[6] For example, in recent economy-wide net zero mitigation pathways for the European Union, around 140-210 million tonnes CO_2 of emissions from the energy sector remain in 2050, which are offset by CDR from managed land-use sinks, and bioenergy and DAC with CCUS (European Commission, 2018).

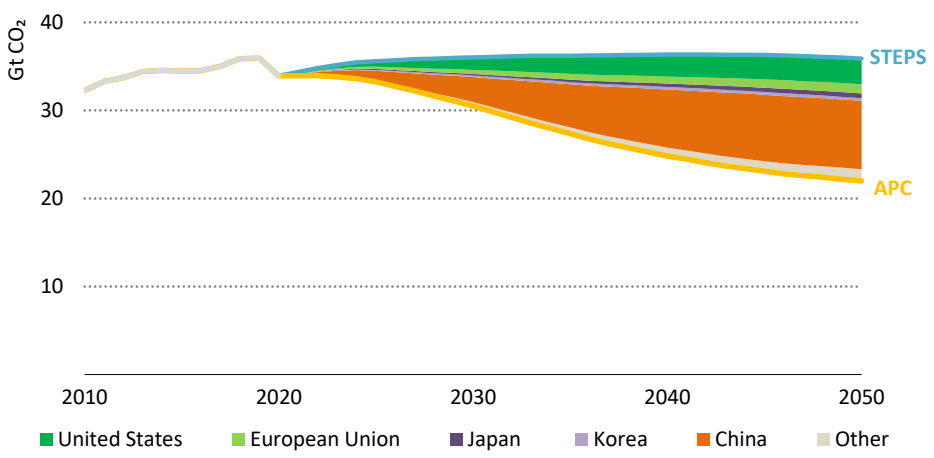
Box 1.1 ▷ Consultations with national bodies on achieving national net-zero emissions goals

To help inform its work on net zero pathways, the IEA engaged in extensive consultations with experts in academia and national bodies that have developed pathways to support net zero pledges made by governments. This includes groups that have developed net-zero emissions pathways for several countries including China, European Union, Japan, United Kingdom and United States, as well as the IPCC. These pathways were not used directly as input for the APC, but the discussions informed our modelling of national preferences and constraints within each jurisdiction and to benchmark the overall level of energy-related CO_2 emissions reductions that are commensurate with economy-wide net zero goals.

1.4.1 CO_2 emissions

In the APC, there is a small rebound in emissions to 2023, although this is much smaller than the increase that immediately followed the financial crisis in 2008-09. Emissions never reach the previous peak of 36 Gt CO_2. Global CO_2 emissions fall around 10% to 30 Gt in 2030 and to 22 Gt in 2050. This is around 35% below the level in 2020 and 14 Gt CO_2 lower than in the STEPS (Figure 1.10). If emissions continue this trend after 2050, and with a similar level of changes in non-energy-related GHG emissions, the global average surface temperature rise in 2100 would be around 2.1 °C (with a 50% probability).

Figure 1.10 ▷ Global energy-related and industrial process CO_2 emissions by scenario and reductions by region, 2010-2050



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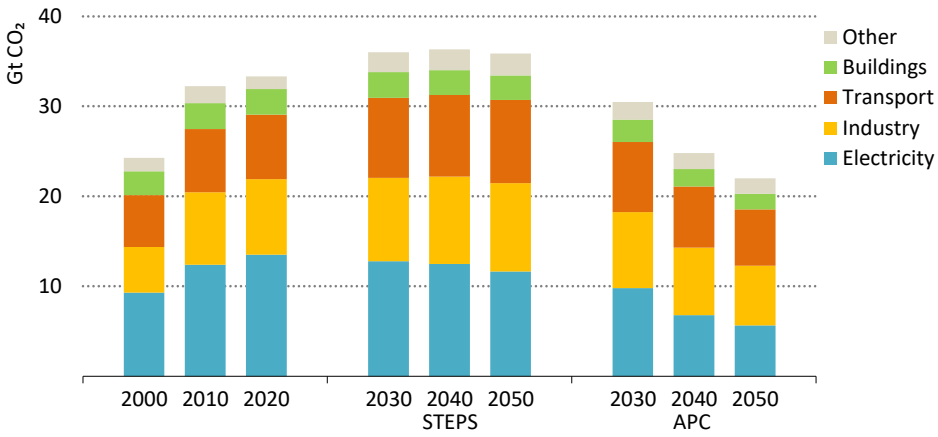
Achieving existing net zero pledges would reduce emissions globally to 22 Gt CO_2 in 2050, a major reduction compared with current policies but still far from net-zero emissions

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The net zero pledges that have been made to date therefore make a major difference to the current trajectory for CO_2 emissions. Equally, however, existing net zero pledges fall well short of what is necessary to reach net-zero emissions globally by 2050. This highlights the importance of concrete policies and plans to deliver in full long-term net zero pledges. It also underlines the value of other countries making (and delivering on) net zero pledges: the more countries that do so, and the more ambitious those pledges are, the more the gap will narrow with what is needed to reach net-zero emissions by 2050.

The largest drop in CO_2 emissions is in the APC is in the electricity sector with global emissions falling by nearly 60% between 2020 and 2050. This occurs despite a near-doubling of electricity demand as energy end-uses are increasingly electrified, notably in transport and buildings (Figure 1.11). This compares with a fall in emissions of less than 15% in the STEPS.

Figure 1.11 ▷ Global CO_2 emissions by sector in the STEPS and APC



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Announced net zero pledges would cut emissions in 2050 by 60% in the electricity sector, 40% in buildings, 25% in industry and just over 10% in transport

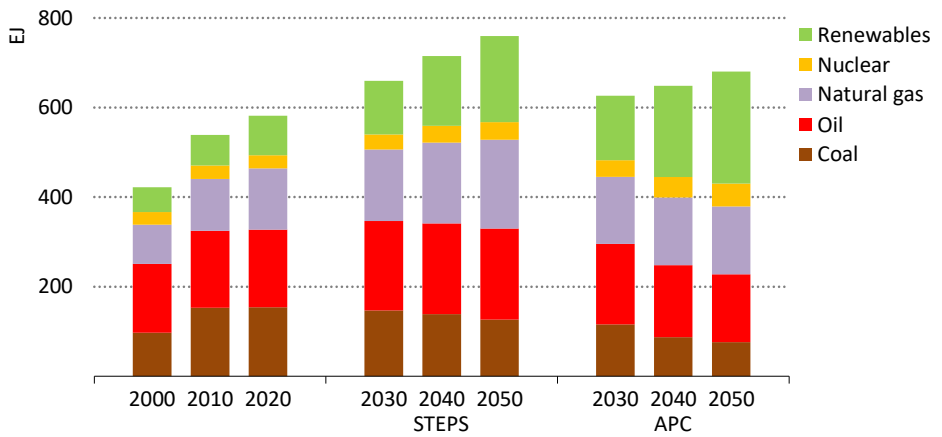
The transport and industry sectors see a less marked fall in CO_2 emissions to 2050 in the APC, with increases in energy demand in regions without net zero pledges partially offsetting emissions reduction efforts in other regions. Emissions from the buildings sector decline by around 40% between 2020 and 2050, compared with around 5% in the STEPS: fossil fuel use in buildings is mostly to provide heating, and countries that have made pledges account for a relatively high proportion of global heating demand.

Even in regions with net zero pledges, there are some residual emissions in 2050, mainly in industry and transport. This reflects the scarcity of commercially available options to eliminate all emissions from heavy-duty trucks, aviation, shipping and heavy industry.

1.4.2 Total energy supply

Global total energy supply increases by more than 15% between 2020 and 2050 in the APC, compared with a third in the STEPS (Figure 1.12). Energy intensity falls on average by around 2.6% per year to 2050 compared with 2.2% in the STEPS. There is a substantial increase in energy demand in emerging market and developing economies, where economic and population growth is fastest and where there are fewer net zero pledges, which outweighs the reductions in energy demand in the countries with net zero pledges.

Figure 1.12 ▷ Total energy supply by source in STEPS and APC



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Announced net zero pledges lift renewables in the APC from 12% of total energy supply in 2020 to 35% in 2050, mainly at the expense of coal and oil

The global increase in energy supply in the APC is led by renewables, which increase their share in the energy mix from 12% in 2020 to 35% by 2050 (compared with 25% in 2050 in the STEPS). Solar photovoltaics (PV) and wind in the electricity sector together contribute about 50% of the growth in renewables supply, and bioenergy contributes around 30%. Bioenergy use doubles in industry, triples in electricity generation and grows by a factor of four in transport: it plays an important role in reducing emissions from heat supply and removing CO_2 from the atmosphere when it is combined with CCUS. Nuclear maintains its share of the energy mix, its output rising by a quarter to 2030 (compared with a 15% increase in the STEPS), driven by lifetime extensions at existing plants and new reactors in some countries.

Global coal use falls significantly more rapidly in the APC than in the STEPS. It drops from 5 250 million tonnes of coal equivalent (Mtce) in 2020 to 4 000 Mtce in 2030 and 2 600 Mtce in 2050 (compared with 4 300 Mtce in the STEPS in 2050). Most of this decline is due to reduced coal-fired electricity generation in countries with net zero pledges as plants are repurposed, retrofitted or retired. In advanced economies, unabated coal-fired power plants

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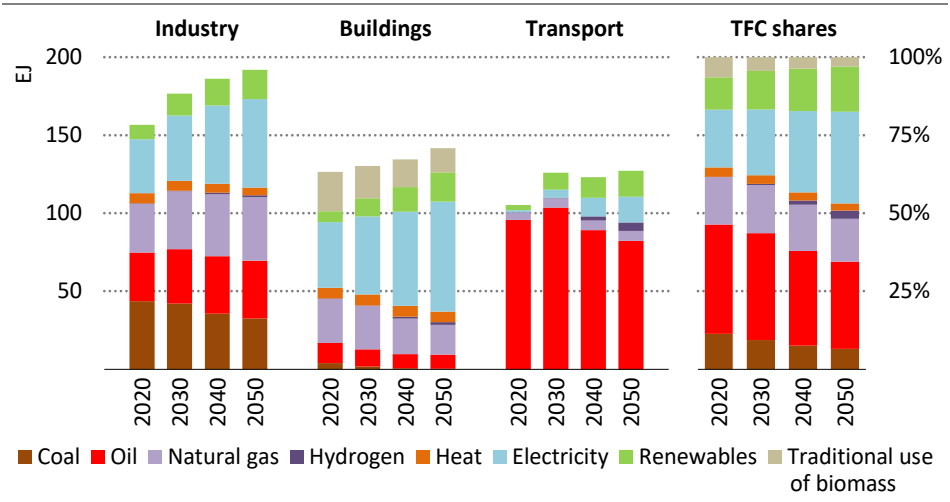
are generally phased out over the next 10-15 years. China's coal consumption for electricity declines by 85% between 2020 and 2050 on its path towards carbon neutrality in 2060. These declines more than offset continued growth for coal in countries without net zero pledges. Globally, coal use in industry falls by 25% between 2020 and 2050, compared with a 5% decline in the STEPS.

Oil demand recovers slightly in the early 2020s but never again reaches its historic peak in 2019. It declines to 90 mb/d in the early 2030s and to 80 mb/d in 2050, around 25 mb/d lower than in the STEPS, thanks to a strong push to electrify transport and shifts to biofuels and hydrogen, especially in regions with pledges. Natural gas demand increases from about 3 900 bcm in 2020 to around 4 350 bcm in 2025, but is then broadly flat to 2050 (it continues to grow to around 5 700 bcm in the STEPS).

1.4.3 Total final consumption

Global energy use continues to grow in all major end-use sectors in the APC, albeit substantially more slowly than in the STEPS (Figure 1.13). Total final consumption (TFC) increases by around 20% in 2020-50, compared with a 35% increase globally in the STEPS. Measures to improve energy efficiency play a major role in the APC in reducing demand growth in countries with net zero pledges. Without those efficiency gains, electricity demand growth would make it much harder for renewables to displace fossil fuels in electricity generation. The biggest reduction in energy demand relative to the STEPS is in transport, thanks to an accelerated shift to electric vehicles (EVs), which are around three-times as energy efficient as conventional internal combustion engine vehicles.

Figure 1.13 ▷ Total final consumption in the APC



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Announced net zero pledges lead to a shift away from fossil fuels globally to electricity, renewables and hydrogen. Electricity's share rises from 20% to 30% in 2050

The fuel mix in final energy use shifts substantially in the APC. By 2050, electricity is the largest single fuel used in all sectors except transport, where oil remains dominant. The persistence of oil in transport stems partly from the extent of its continued use in countries without net zero pledges, and partly from the difficulty of electrifying substantial parts of the transport sector, notably trucking and aviation. Electricity does make inroads into transport, however, and rapid growth in the uptake of EVs puts oil use into decline after 2030, with EVs accounting for around 35% of global passenger car sales by 2030 and nearly 50% in 2050 in the APC (versus around 25% in the STEPS in 2050). Electrification in the buildings sector is also much faster in the APC than in the STEPS.

The direct use of renewables expands in all end-use sectors globally through to 2050. Modern bioenergy accounts for the bulk of this growth, predominantly through the blending of biomethane into natural gas networks and liquid biofuels in transport. This occurs mainly in regions with net zero pledges. Hydrogen and hydrogen-based fuels play a larger role in the APC than in the STEPS, reaching almost 15 exajoules (EJ) in 2050, though they still account for only 3% of total final consumption worldwide in 2050. Transport accounts for more than two-thirds of all hydrogen consumption in 2050. In parallel, on-site hydrogen production in the industry and refining sectors gradually shifts towards low-carbon technologies.

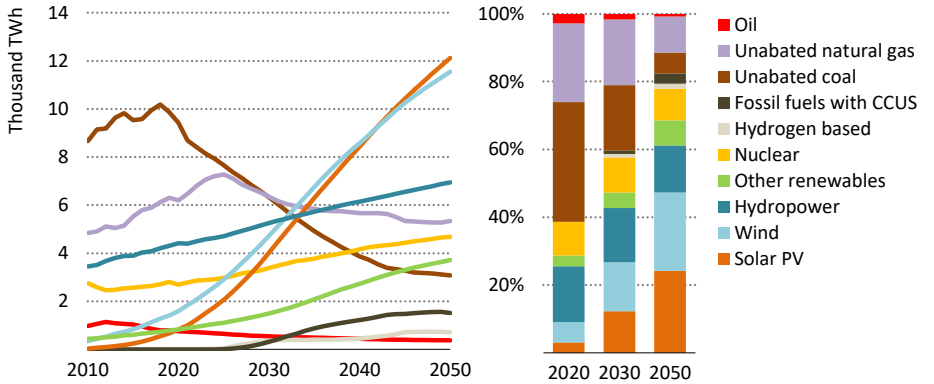
1.4.4 Electricity generation

Global electricity generation nearly doubles during the next three decades in the APC, rising from about 26 800 terawatt-hours (TWh) in 2020 to over 50 000 TWh in 2050, some 4 000 TWh higher than in the STEPS. Low-emissions energy sources provide all the increase. The share of renewables in electricity generation rises from 29% in 2020 to nearly 70% in 2050, compared with about 55% in the STEPS, as solar PV and wind race ahead of all other sources of generation (Figure 1.14). By 2050, solar PV and wind together account for almost half of electricity supply. Hydropower also continues to expand, emerging as the third-largest energy source in the electricity mix by 2050. Nuclear power increases steadily too, maintaining its global market share of about 10%, led by increases in China. Natural gas use in electricity increases slightly to the mid-2020s before starting to fall back, while coal's share of electricity generation falls from around 35% in 2020 to below 10% in 2050. At that point, 20% of the remaining coal-fired output comes from plants equipped with CCUS.

Hydrogen and ammonia start to emerge as fuel inputs to electricity generation by around 2030, used largely in combination with natural gas in gas turbines and with coal in coal-fired power plants. This extends the life of existing assets, contributes to electricity system adequacy and reduces the overall costs of transforming the electricity sectors in many countries. Total battery capacity also rises substantially, reaching 1 600 gigawatts (GW) in 2050, 70% more than in the STEPS.

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Figure 1.14 ▷ Global electricity generation by source in the APC



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Renewables reach new heights in the APC, rising from just under 30% of electricity supply in 2020 to nearly 70% in 2050, while coal-fired generation steadily declines

Note: Other renewables = geothermal, solar thermal and marine.

A global pathway to net-zero CO_2 emissions in 2050

SUMMARY

- The Net-Zero Emissions by 2050 Scenario (NZE) shows what is needed for the global energy sector to achieve net-zero CO_2 emissions by 2050. Alongside corresponding reductions in GHG emissions from outside the energy sector, this is consistent with limiting the global temperature rise to 1.5 °C without a temperature overshoot (with a 50% probability). Achieving this would require all governments to increase ambitions from current Nationally Determined Contributions and net zero pledges.
- In the NZE, global energy-related and industrial process CO_2 emissions fall by nearly 40% between 2020 and 2030 and to net zero in 2050. Universal access to sustainable energy is achieved by 2030. There is a 75% reduction in methane emissions from fossil fuel use by 2030. These changes take place while the global economy more than doubles through to 2050 and the global population increases by 2 billion.
- Total energy supply falls by 7% between 2020 and 2030 in the NZE and remains at around this level to 2050. Solar PV and wind become the leading sources of electricity globally before 2030 and together they provide nearly 70% of global generation in 2050. The traditional use of bioenergy is phased out by 2030.
- Coal demand declines by 90% to less than 600 Mtce in 2050, oil declines by 75% to 24 mb/d, and natural gas declines by 55% to 1 750 bcm. The fossil fuels that remain in 2050 are used in the production of non-energy goods where the carbon is embodied in the product (like plastics), in plants with carbon capture, utilisation and storage (CCUS), and in sectors where low-emissions technology options are scarce.
- Energy efficiency, wind and solar provide around half of emissions savings to 2030 in the NZE. They continue to deliver emissions reductions beyond 2030, but the period to 2050 sees increasing electrification, hydrogen use and CCUS deployment, for which not all technologies are available on the market today, and these provide more than half of emissions savings between 2030 and 2050. In 2050, there is 1.9 Gt of CO_2 removal in the NZE and 520 million tonnes of low-carbon hydrogen demand. Behavioural changes by citizens and businesses avoid 1.7 Gt CO_2 emissions in 2030, curb energy demand growth, and facilitate clean energy transitions.
- Annual energy sector investment, which averaged USD 2.3 trillion globally in recent years, jumps to USD 5 trillion by 2030 in the NZE. As a share of global GDP, average annual energy investment to 2050 in the NZE is around 1% higher than in recent years.
- The NZE taps into all opportunities to decarbonise the energy sector, across all fuels and all technologies. But the path to 2050 has many uncertainties. If behavioural changes were to be more limited than envisaged in the NZE, or sustainable bioenergy less available, then the energy transition would be more expensive. A failure to develop CCUS for fossil fuels could delay or prevent the development of CCUS for process emissions from cement production and carbon removal technologies, making it much harder to achieve net-zero emissions by 2050.

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2.1 Introduction

Achieving a global energy transition that is compatible with the world's climate goals is unquestionably a formidable task. As highlighted in Chapter 1, current pledges by governments to reduce emissions to net zero collectively cover around 70% of today's global economic activity and global CO_2 emissions. The Announced Pledges Case shows that, if all those pledges were met in full, it would narrow the gap between where we are heading and where we need to be to achieve net-zero emissions by 2050 worldwide. But it also shows that the gap would remain large. Meeting all existing net zero pledges in full would still leave 22 gigatonnes (Gt) of energy-related and industrial process CO_2 emissions globally in 2050, consistent with a temperature rise in 2100 of around 2.1 °C (with a 50% probability).

In this chapter, we examine the energy sector transformation which is embodied in our Net-Zero Emissions by 2050 Scenario. First, it provides an overview of the key assumptions and market dynamics underlying the projections, including projected fossil fuel and CO_2 prices. It discusses trends in global CO_2 emissions, energy use and investment, including the key roles played by efficiency measures, behavioural change, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy, and carbon capture, utilisation and storage (CCUS). Further, it discusses some of the key uncertainties surrounding the global pathway towards net-zero emissions related to behavioural change, the availability of sustainable bioenergy, and the deployment of CCUS for fossil fuels. The transformation of specific energy sectors is assessed and discussed in detail in Chapter 3.

2.2 Scenario design

The Net-Zero Emissions by 2050 Scenario (NZE) is designed to show what is needed across the main sectors by various actors, and by when, for the world to achieve net-zero energy-related and industrial process CO_2 emissions by 2050.[1] It also aims to minimise methane emissions from the energy sector. In recent years, the energy sector was responsible for around three-quarters of global greenhouse gas (GHG) emissions. Achieving net-zero energy-related and industrial process CO_2 emissions by 2050 in the NZE does not rely on action in areas other than the energy sector, but limiting climate change does require such action. We therefore additionally examine the reductions in CO_2 emissions from land use that would be commensurate with the transformation of the energy sector in the NZE, working in co-operation with the International Institute for Applied Systems Analysis (IIASA). In parallel with action on reducing all other sources of GHG emissions, achieving net-zero CO_2 emissions from the energy sector by 2050 is consistent with around a 50% chance of limiting the long-term average global temperature rise to 1.5 °C without a temperature overshoot (IPCC, 2018).

[1] Unless otherwise stated, carbon dioxide (CO_2) emissions in this chapter refer to energy-related and industrial process CO_2 emissions. Net-zero CO_2 emissions refers to zero CO_2 emissions to the atmosphere, or with any residual CO_2 emissions offset by CO_2 removal from direct air capture or bioenergy with carbon capture and storage.

The NZE aims to ensure that energy-related and industrial process CO_2 emissions to 2030 are in line with reductions in 1.5 °C scenarios with no or low or limited temperature overshoot assessed in the IPCC in its Special Report on Global Warming of 1.5 °C.[2] In addition, the NZE incorporates concrete action on the energy-related United Nations Sustainable Development Goals related to achieving universal energy access by 2030 and delivering a major reduction in air pollution. The projections in the NZE were generated by a hybrid model that combines components of the IEA's World Energy Model (WEM), which is used to produce the projections in the annual *World Energy Outlook,* and the Energy Technology Perspectives (ETP) model.

Box 2.1 ▻ International Energy Agency modelling approach for the NZE

A new, hybrid modelling approach was adopted to develop the NZE and combines the relative strengths of the WEM and the ETP model. The WEM is a large-scale simulation model designed to replicate how competitive energy markets function and to examine the implications of policies on a detailed sector-by-sector and region-by-region basis. The ETP model is a large-scale partial-optimisation model with detailed technology descriptions of more than 800 individual technologies across the energy conversion, industry, transport and buildings sectors.

This is the first time this modelling approach has been implemented. The combination of the two models allows for a unique set of insights on energy markets, investment, technologies, and the level and detail of policies that would be needed to bring about the energy sector transformation in the NZE.

Results from the WEM and ETP model have been coupled with the Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model developed by IIASA (Amann et al., 2011). The GAINS model is used to evaluate air pollutant emissions and resultant health impacts linked to air pollution. For the first time, IEA model results have also been coupled with the IIASA's Global Biosphere Management Model (GLOBIOM) to provide data on land use and net emissions impacts of bioenergy demand.

The impacts of changes in investment and spending on global GDP in the NZE have been estimated by the International Monetary Fund (IMF) using the Global Integrated Monetary and Fiscal (GIMF) model. GIMF is a multi-country dynamic stochastic general equilibrium model used by the IMF for policy and risk analysis (Laxton et al., 2010; Anderson et al., 2013). It has been used to produce the IMF's World Economic Outlook scenario analyses since 2008.

There are many possible paths to achieve net-zero CO_2 emissions globally by 2050 and many uncertainties that could affect any of them; the NZE is therefore *a* path, not *the* path to net-zero emissions. Much depends, for example, on the pace of innovation in new and emerging

[2] The IPCC classifies scenarios as "no or limited temperature overshoot", if temperatures exceed 1.5 °C by less than 0.1 °C but return to less than 1.5 °C in 2100, and as "higher overshoot", if temperatures exceed 1.5 °C by 0.1-0.4 °C but return to less than 1.5 °C in 2100.

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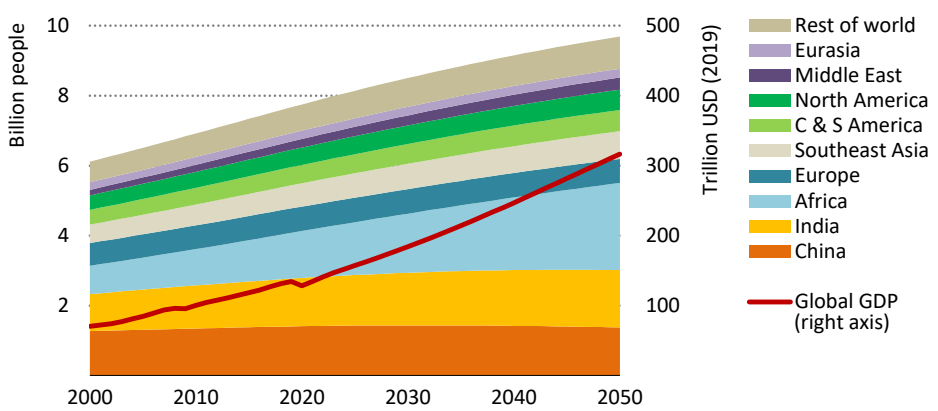
technologies, the extent to which citizens are able or willing to change behaviour, the availability of sustainable bioenergy and the extent and effectiveness of international collaboration. We investigate some of the key alternatives and uncertainties here and in Chapter 3. The Net-Zero Emissions by 2050 Scenario is built on the following principles.

- The uptake of all the available technologies and emissions reduction options is dictated by costs, technology maturity, policy preferences, and market and country conditions.
- All countries co-operate towards achieving net-zero emissions worldwide. This involves all countries participating in efforts to meet the net zero goal, working together in an effective and mutually beneficial way, and recognising the different stages of economic development of countries and regions, and the importance of ensuring a just transition.
- An orderly transition across the energy sector. This includes ensuring the security of fuel and electricity supplies at all times, minimising stranded assets where possible and aiming to avoid volatility in energy markets.

2.2.1 Population and GDP

The energy sector transformation in the NZE occurs against the backdrop of large increases in the world's population and economy (Figure 2.1). In 2020, there were around 7.8 billion people in the world; this is projected to increase by around 750 million by 2030 and by nearly 2 billion people by 2050 in line with the median variant of the United Nations projections (UNDESA, 2019). Nearly all of the population increase is in emerging market and developing economies: the population of Africa alone increases by more than 1.1 billion between 2020 and 2050.

Figure 2.1 ▷ World population by region and global GDP in the NZE



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By 2050, the world's population expands to 9.7 billion people and the global economy is more than twice as large as in 2020

Notes: GDP = gross domestic product in purchasing power parity; C & S America = Central and South America.

Sources: IEA analysis based on UNDESA (2019); Oxford Economics (2020); IMF (2020a, 2020b).

The world's economy is assumed to recover rapidly from the impact of the Covid-19 pandemic. Its size returns to pre-crisis levels in 2021. From 2022, the GDP growth trend is close to the pre-pandemic rate of around 3% per year on average, in line with assessments from the IMF. The response to the pandemic leads to a large increase in government debt, but resumed growth, along with low interest rates in many countries, make this manageable in the long term. By 2030, the world's economy is around 45% larger than in 2020, and by 2050 it is more than twice as large.

2.2.2 Energy and CO_2 prices

Projections of future energy prices are inevitably subject to a high degree of uncertainty. In IEA scenarios, they are designed to maintain an equilibrium between supply and demand. The rapid drop in oil and natural gas demand in the NZE means that no fossil fuel exploration is required and no new oil and natural gas fields are required beyond those that have already been approved for development. No new coal mines or mine extensions are required either. Prices are increasingly set by the operating costs of the marginal project required to meet demand, and this results in significantly lower fossil fuel prices than in recent years. The oil price drops to around USD 35/barrel by 2030 and then drifts down slowly towards USD 25/barrel in 2050.

Table 2.1 ▷ Fossil fuel prices in the NZE

Real terms (USD 2019)	2010	2020	2030	2040	2050
IEA crude oil (USD/barrel)	91	37	35	28	24
Natural gas (USD/MBtu)					
United States	5.1	2.1	1.9	2.0	2.0
European Union	8.7	2.0	3.8	3.8	3.5
China	7.8	5.7	5.2	4.8	4.6
Japan	12.9	5.7	4.4	4.2	4.1
Steam coal (USD/tonne)					
United States	60	45	24	24	22
European Union	108	56	51	48	43
Japan	125	75	57	53	49
Coastal China	135	81	60	54	50

Notes: MBtu = million British thermal units. The IEA crude oil prices are a weighted average import price among IEA member countries. Natural gas prices are weighted averages expressed on a gross calorific-value basis. US natural gas prices reflect the wholesale price prevailing on the domestic market. The European Union and China gas prices reflect a balance of pipeline and liquefied natural gas (LNG) imports, while Japan gas prices solely reflect LNG imports. LNG prices used are those at the customs border, prior to regasification. Steam coal prices are weighted averages adjusted to 6 000 kilocalories per kilogramme. US steam coal prices reflect mine-mouth price plus transport and handling cost. Coastal China steam coal price reflects a balance of imports and domestic sales, while the European Union and Japanese steam coal prices are solely for imports.

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In line with the principle of orderly transitions governing the NZE, the trajectory for oil markets and prices avoids excessive volatility. What happens depends to a large degree on the strategies adopted by resource-rich governments and their national oil companies. In the NZE it is assumed that, despite having lower cost resources at their disposal, they restrict investment in new fields. This limits the need for the shutting in and closure of higher cost production. The market share of major resource-rich countries nevertheless still rises in the NZE due to the large size and slow decline rates of their existing fields.

Producer economies could pursue alternative approaches. Faced with rapidly falling oil and gas demand, they could, for example, opt to increase production so as to capture an even larger share of the market. In this event, the combination of falling demand and increased availability of low cost oil would undoubtedly lead to even lower – and probably much more volatile – prices. In practice, the options open to particular producer countries would depend on their resilience to lower oil prices and on the extent to which export markets have developed for low-emissions fuels that could be produced from their natural resources.

Anticipating and mitigating feedbacks from the supply side is a central element of the discussion about orderly energy transitions. A drop in prices usually results in some rebound in demand, and policies and regulations would be essential to avoid this leading to any increase in the unabated use of fossil fuels, which would undermine wider emissions reduction efforts.

As the energy sector transforms, more fuels are traded globally, such as hydrogen-based fuels and biofuels. The prices of these commodities are assumed to be set by the marginal cost of domestic production or imports within each region.

A broad range of energy policies and accompanying measures are introduced across all regions to reduce emissions in the NZE. This includes: renewable fuel mandates; efficiency standards; market reforms; research, development and deployment; and the elimination of inefficient fossil fuel subsidies. Direct emissions reduction regulations are also needed in some cases. In the transport sector, for example, regulations are implemented to reduce sales of internal combustion engine vehicles and increase the use of liquid biofuels and synthetic fuels in aviation and shipping, as well as measures to ensure that low oil prices do not lead to an increase in consumption.

CO_2 prices are introduced across all regions in the NZE (Table 2.2). They are assumed to be introduced in the immediate future across all advanced economies for the electricity generation, industry and energy production sectors, and to rise on average to USD 130 per tonne (tCO_2) by 2030 and to USD 250/tCO_2 by 2050. In a number of other major economies – including China, Brazil, Russia and South Africa – CO_2 prices in these sectors are assumed to rise to around USD 200/tCO_2 in 2050. CO_2 prices are introduced in all other emerging market and developing economies, although it is assumed that they pursue more direct policies to adapt and transform their energy systems and so the level of CO_2 prices is lower than elsewhere.

Table 2.2 ▷ CO_2 prices for electricity, industry and energy production in the NZE

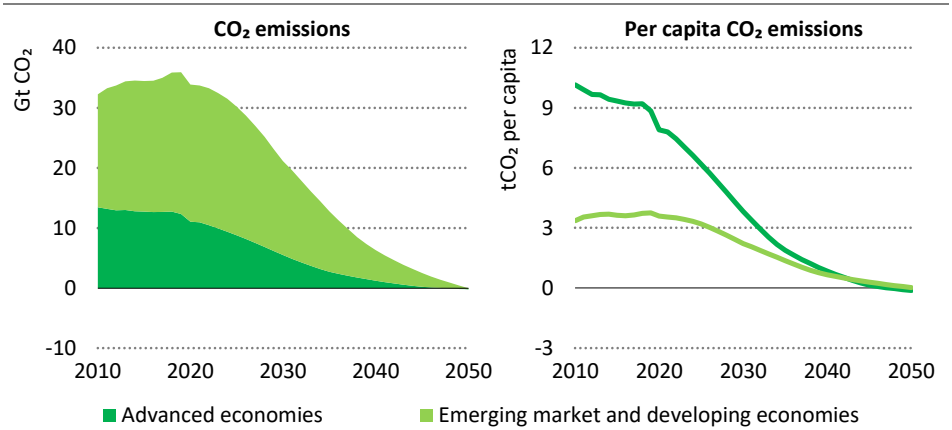
USD (2019) per tonne of CO_2	2025	2030	2040	2050
Advanced economies	75	130	205	250
Selected emerging market and developing economies*	45	90	160	200
Other emerging market and developing economies	3	15	35	55

* Includes China, Russia, Brazil and South Africa.

2.3 CO_2 emissions

Global energy-related and industrial process CO_2 emissions in the NZE fall to around 21 Gt CO_2 in 2030 and to net-zero in 2050 (Figure 2.2).[3] CO_2 emissions in advanced economies as a whole fall to net zero by around 2045 and these countries collectively remove around 0.2 Gt CO_2 from the atmosphere in 2050. Emissions in several individual emerging market and developing economies also fall to net zero well before 2050, but in aggregate there are around 0.2 Gt CO_2 of remaining emissions in this group of countries in 2050. These are offset by CO_2 removal in advanced economies to provide net-zero CO_2 emissions at the global level.

Figure 2.2 ▷ Global net CO_2 emissions in the NZE



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CO_2 emissions fall to net zero in advanced economies around 2045 and globally by 2050. Per capita emissions globally are similar by the early-2040s.

Note: Includes CO_2 emissions from international aviation and shipping.

[3] In the period to 2030, CO_2 emissions in the NZE fall at a broadly similar rate to the P2 illustrative pathway in the IPCC SR 1.5 (IPCC, 2018). The P2 scenario is described as "a scenario with … shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS [bioenergy with carbon capture and storage]". After 2030, emissions in the NZE fall at a much faster pace than in the P2 scenario, which has 5.6 Gt CO_2 of residual energy sector and industrial process CO_2 emissions remaining in 2050.

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Several emerging market and developing economies with a very large potential for producing renewables-based electricity and bioenergy are also a key source of carbon dioxide removal (CDR). This includes making use of renewable electricity sources to produce large quantities of biofuels with CCUS, some of which is exported, and to carry out direct air capture with carbon capture and storage (DACCS).

Per capita CO_2 emissions in advanced economies drop from around 8 tCO_2 per person in 2020 to around 3.5 tCO_2 in 2030, a level close to the average in emerging market and developing economies in 2020. Per capita emissions also fall in emerging market and developing economies, but from a much lower starting point. By the early 2040s, per capita emissions in both regions are broadly similar at around 0.5 tCO_2 per person.

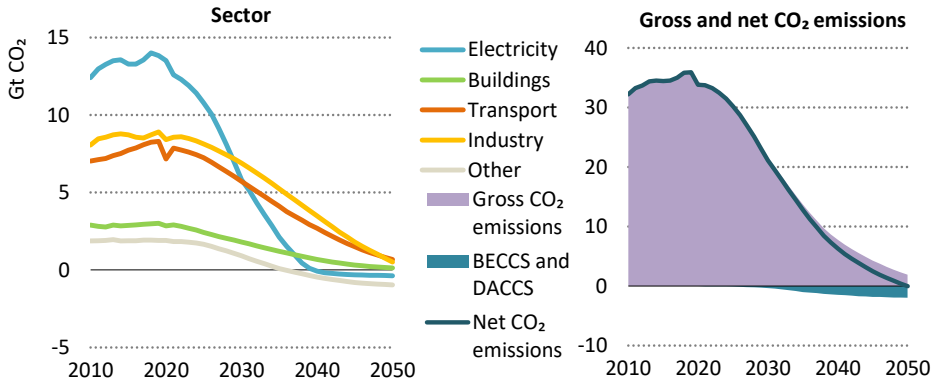
Cumulative global energy-related and industrial process CO_2 emissions between 2020 and 2050 amount to just over 460 Gt in the NZE. Assuming parallel action to address CO_2 emissions from agriculture, forestry and other land use (AFOLU) over the period to 2050 would result in around 40 Gt CO_2 from AFOLU (see section 2.7.2). This means that total CO_2 emissions from all sources – some 500 Gt CO_2 – are in line with the CO_2 budgets included in the IPCC SR1.5, which indicated that the total CO_2 budget from 2020 consistent with providing a 50% chance of limiting warming to 1.5 °C is 500 Gt CO_2 (IPCC, 2018).[4] As well as reducing CO_2 emissions to net-zero, the NZE seeks to reduce non-CO_2 emissions from the energy sector. Methane emissions from fossil fuel production and use, for example, fall from 115 million tonnes (Mt) methane in 2020 (3.5 Gt CO_2-equivalent [CO_2-eq])[5] to 30 Mt in 2030 and 10 Mt in 2050.

The fastest and largest reductions in global emissions in the NZE are initially seen in the electricity sector (Figure 2.3). Electricity generation was the largest source of emissions in 2020, but emissions drop by nearly 60% in the period to 2030, mainly due to major reductions from coal-fired power plants, and the electricity sector becomes a small net negative source of emissions around 2040. Emissions from the buildings sector fall by 40% between 2020 and 2030 thanks to a shift away from the use of fossil fuel boilers, and retrofitting the existing building stock to improve its energy performance. Emissions from industry and transport both fall by around 20% over this period, and their pace of emissions reductions accelerates during the 2030s as the roll-out of low-emissions fuels and other emissions reduction options is scaled up. Nonetheless, there are a number of areas in transport and industry in which it is difficult to eliminate emissions entirely – such as aviation and heavy industry – and both sectors have a small level of residual emissions in 2050. These residual emissions are offset with applications of BECCS and DACCS.

[4] This budget is based on Table 2.2 of the IPCC SR1.5 (IPCC, 2018). It assumes 0.53 °C additional warming from the 2006-2015 period to give a remaining CO_2 budget from 2018 of 580 Gt CO_2. There were around 80 Gt CO_2 emissions emitted from 2018 to 2020.

[5] Non-CO_2 gases are converted to CO_2-equivalents based on the 100-year global warming potentials reported by the IPCC 5th Assessment Report (IPCC, 2014). One tonne of methane is equivalent to 30 tonnes of CO_2.

Figure 2.3 ▷ Global net-CO_2 emissions by sector, and gross and net CO_2 emissions in the NZE



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Emissions from electricity fall fastest, with declines in industry and transport accelerating in the 2030s. Around 1.9 Gt CO_2 are removed in 2050 via BECCS and DACCS.

Notes: Other = agriculture, fuel production, transformation and related process emissions, and direct air capture. BECCS = bioenergy with carbon capture and storage; DACCS = direct air capture with carbon capture and storage. BECCS and DACCS includes CO_2 emissions captured and permanently stored.

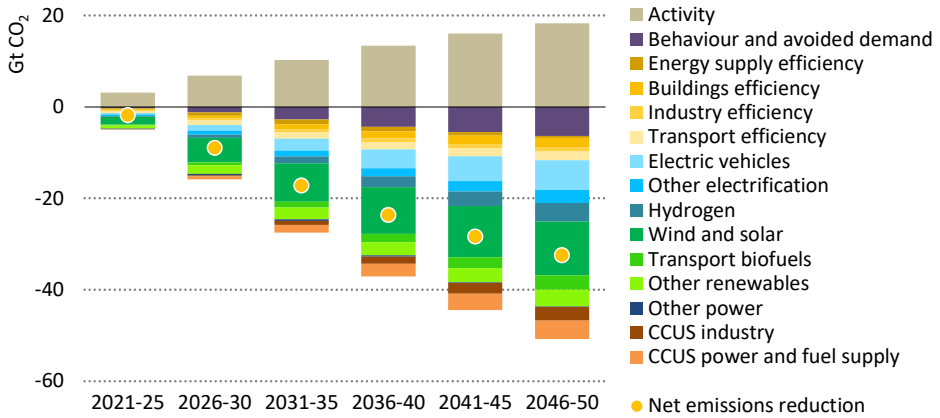
The NZE includes a systematic preference for all new assets and infrastructure to be as sustainable and efficient as possible, and this accounts for 50% of total emissions reductions in 2050. Tackling emissions from existing infrastructure accounts for another 35% of reductions in 2050, while behavioural changes and avoided demand, including materials efficiency[6] gains and modal shifts in the transport sector, provide the remaining 15% of emissions reductions (see section 2.5.2). A wide range of technologies and measures are deployed in the NZE to reduce emissions from existing infrastructure such as power plants, industrial facilities, buildings, networks, equipment and appliances. The NZE is designed to minimise stranded capital where possible, i.e. cases where the initial investment is not recouped, but in many cases early retirements or lower utilisation lead to stranded value, i.e. a reduction in revenue.

The rapid deployment of more energy-efficient technologies, electrification of end-uses and swift growth of renewables all play a central part in reducing emissions across all sectors in the NZE (Figure 2.4). By 2050, nearly 90% of all electricity generation is from renewables, as is around 25% of non-electric energy use in industry and buildings. There is also a major role for emerging fuels and technologies, notably hydrogen and hydrogen-based fuels, bioenergy and CCUS, especially in sectors where emissions are often most challenging to reduce.

[6] Materials efficiency includes strategies that reduce material demand, or shift to the use of lower emissions materials or lower emissions production routes. Examples include lightweighting and recycling.

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Figure 2.4 ▷ Average annual CO_2 reductions from 2020 in the NZE



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Renewables and electrification make the largest contribution to emissions reductions, but a wide range of measures and technologies are needed to achieve net-zero emissions

Notes: Activity = changes in energy service demand from economic and population growth. Behaviour = change in energy service demand from user decisions, e.g. changing heating temperatures. Avoided demand = change in energy service demand from technology developments, e.g. digitalisation.

2.4 Total energy supply and final energy consumption

2.4.1 Total energy supply[7]

Total energy supply falls to 550 exajoules (EJ) in 2030, 7% lower than in 2020 (Figure 2.5). This occurs despite significant increases in the global population and economy because of a fall in energy intensity (the amount of energy used to generate a unit of GDP). Energy intensity falls by 4% on average each year between 2020 and 2030. This is achieved through a combination of electrification, a push to pursue all energy and materials efficiency opportunities, behavioural changes that reduce demand for energy services, and a major shift away from the traditional use of bioenergy.[8] This level of improvement in energy intensity is much greater than has been achieved in recent years: between 2010 and 2020, average annual energy intensity fell by less then 2% each year.

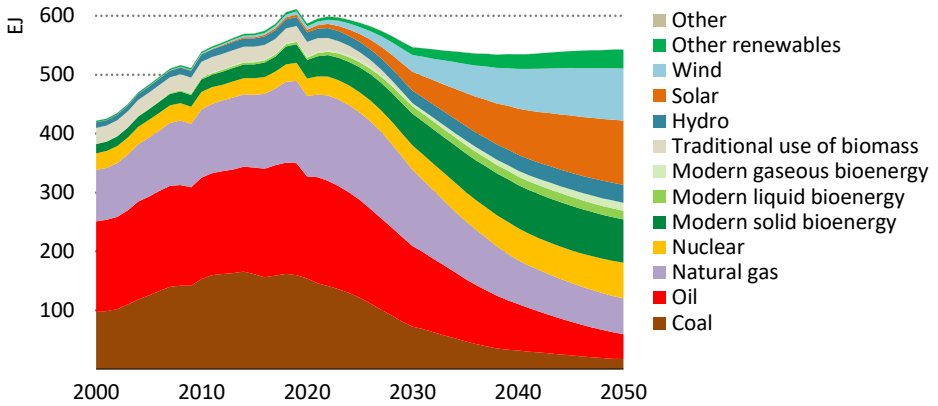
After 2030, continuing electrification of end-use sectors helps to reduce energy intensity further, but the emphasis on maximising energy efficiency improvements in the years up to

[7] The terms total primary energy supply (TPES) or total primary energy demand (TPED) have been renamed as total energy supply (TES) in accordance with the International Recommendations for Energy Statistics (IEA, 2020a).

[8] Modern forms of cooking require much less energy than the traditional use of biomass in inefficient stoves. For example, cooking with a liquefied petroleum gas stove uses around five-times less energy than the traditional use of biomass.

2030 limits the available opportunities in later years. At the same time, increasing production of new fuels, such as advanced biofuels, hydrogen and synthetic fuels, tends to push up energy use. As a result, the rate of decline in energy intensity between 2030 and 2050 slows to 2.7% per year. With continued economic and population growth, this means that total energy supply falls slightly between 2030 and 2040 but then remains broadly flat to 2050. Total energy supply in 2050 in the NZE is close to the level in 2010, despite a global population that is nearly 3 billion people higher and a global economy that is over three-times larger.

Figure 2.5 ▷ Total energy supply in the NZE



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Renewables and nuclear power displace most fossil fuel use in the NZE, and the share of fossil fuels falls from 80% in 2020 to just over 20% in 2050

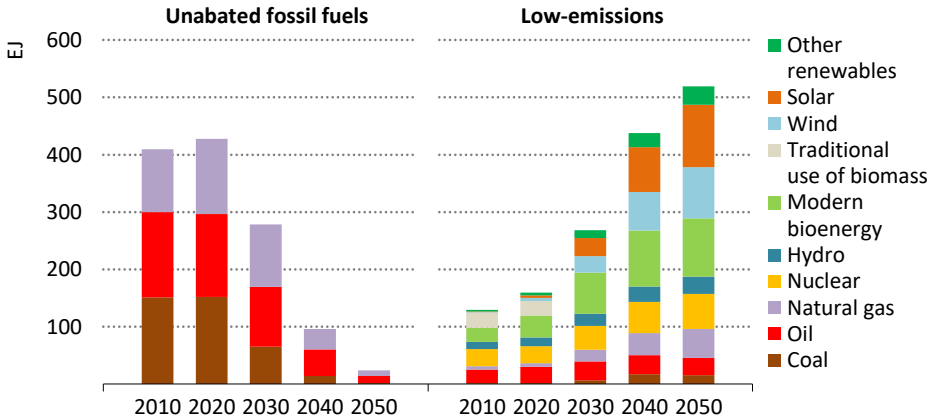
The energy mix in 2050 in the NZE is much more diverse than today. In 2020, oil provided 30% of total energy supply, while coal supplied 26% and natural gas 23%. In 2050, renewables provide two-thirds of energy use, split between bioenergy, wind, solar, hydroelectricity and geothermal (Figure 2.6). There is also a large increase in energy supply from nuclear power, which nearly doubles between 2020 and 2050.

There are large reductions in the use of fossil fuels in the NZE. As a share of total energy supply, they fall from 80% in 2020 to just over 20% in 2050. However, their use does not fall to zero in 2050: significant amounts are still used in producing non-energy goods, in plants with CCUS, and in sectors where emissions are especially hard to abate such as heavy industry and long-distance transport. All remaining emissions in 2050 are offset by negative emissions elsewhere (Box 2.2). Coal use falls from 5 250 million tonnes of coal equivalent (Mtce) in 2020 to 2 500 Mtce in 2030 and to less than 600 Mtce in 2050 – an average annual decline of 7% each year from 2020 to 2050. Oil demand dropped below 90 million barrels per day (mb/d) in 2020 and demand does not return to its 2019 peak: it falls to 72 mb/d in 2030 and 24 mb/d in 2050 – an annual average decline of more than 4% from 2020 to 2050. Natural gas use dropped to 3 900 billion cubic metres (bcm) in 2020, but exceeds its previous

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2019 peak in the mid-2020s before starting to decline as it is phased out in the electricity sector. Natural gas use declines to 3 700 bcm in 2030 and 1 750 bcm in 2050 – an annual average decline of just under 3% from 2020 to 2050.

Figure 2.6 ▷ Total energy supply of unabated fossil fuels and low-emissions energy sources in the NZE



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Some fossil fuels are still used in 2050 in the production of non-energy goods, in plants equipped with CCUS, and in sectors where emissions are hard to abate

Note: Low-emissions includes the use of fossil fuels with CCUS and in non-energy uses.

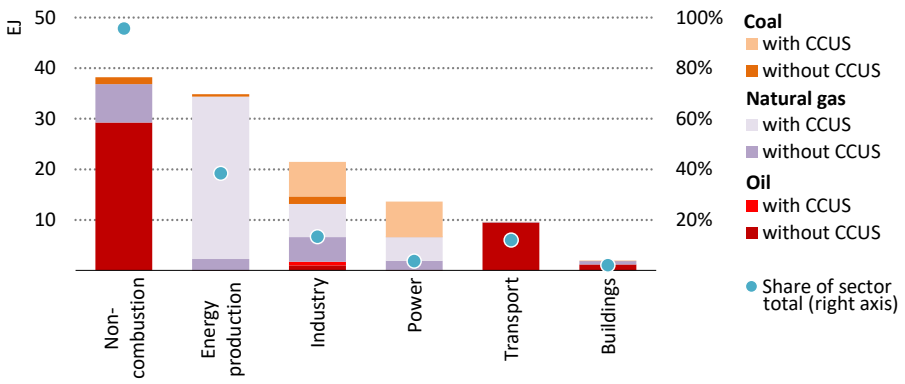
Box 2.2 ▷ Why does fossil fuel use not fall to zero in 2050 in the NZE?

In total, around 120 EJ of fossil fuels is consumed in 2050 in the NZE relative to 460 EJ in 2020. Three main reasons underlie why fossil fuel use does not fall to zero in 2050, even though the energy sector emits no CO_2 on a net basis:

- **Use for non-energy purposes**. More than 30% of total fossil fuel use in 2050 in the NZE – including 70% of oil use – is in applications where the fuels are not combusted and so do not result in any direct CO_2 emissions (Figure 2.7). Examples include use as chemical feedstocks and in lubricants, paraffin waxes and asphalt. There are major efforts to limit fossil fuel use in these applications in the NZE, for instance global plastic collection rates for recycling rising from 15% in 2020 to 55% in 2050, but fossil fuel use in non-energy applications still rises slightly to 2050.
- **Use with CCUS.** Around half of fossil fuel use in 2050 is in plants equipped with CCUS (around 3.5 Gt CO_2 emissions are captured from fossil fuels in 2050). Around 925 bcm of natural gas is converted to hydrogen with CCUS. In addition, around 470 Mtce of coal and 225 bcm of natural gas are used with CCUS in the electricity and industrial sectors, mainly to extend the operations of young facilities and reduce stranded assets.

- **Use in sectors where technology options are scarce.** The remaining 20% of fossil fuel use in 2050 in the NZE is in sectors where the complete elimination of emissions is particularly challenging. Mostly this is oil, as it continues to fuel aviation in particular. A small amount of unabated coal and natural gas are used in industry and in the production of energy. The unabated use of fossil fuel results in around 1.7 Gt CO_2 emissions in 2050, which are fully offset by BECCS and DACCS.

Figure 2.7 ▷ Fossil fuel use and share by sector in 2050 in the NZE



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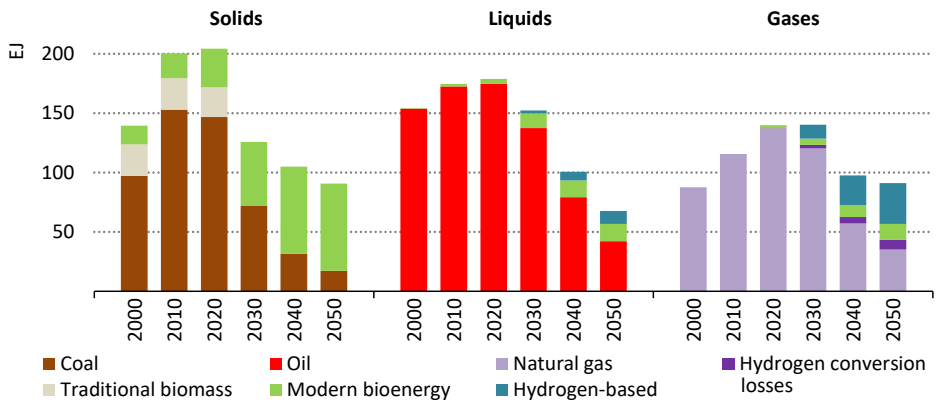
More than 30% of fossil fuel use in 2050 is not combusted and so does not result in direct CO_2 emissions, around 50% is paired with CCUS

Notes: Non-combustion includes use for non-emitting, non-energy purposes such as petrochemical feedstocks, lubricants and asphalt. Energy production includes fuel use for direct air capture.

Solid, liquid and gaseous fuels continue to play an important role in the NZE, which sees large increases in bioenergy and hydrogen (Figure 2.8). Around 40% of bioenergy used today is for the traditional use of biomass in cooking: this is rapidly phased out in the NZE. Modern forms of solid biomass, which can be used to reduce emissions in both the electricity and industry sectors, rise from 32 EJ in 2020 to 55 EJ in 2030 and 75 EJ in 2050, offsetting a large portion of a drop in coal demand. The use of low-emissions liquid fuels, such as ammonia, synthetic fuels and liquid biofuels, increases from 3.5 EJ (1.6 million barrels of oil equivalent per day [mboe/d]) in 2020 to just above 25 EJ (12.5 mboe/d) in 2050. The supply of low-emissions gases, such as hydrogen, synthetic methane, biogas and biomethane rises from 2 EJ in 2020 to 17 EJ in 2030 and 50 EJ in 2050. The increase in gaseous hydrogen production between 2020 and 2030 in the NZE is twice as fast as the fastest ten-year increase in shale gas production in the United States.

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Figure 2.8 ▷ Solid, liquid and gaseous fuels in the NZE



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Increases in low-emissions solids, liquids and gases from bioenergy, hydrogen and hydrogen-based fuels offset some of the declines in coal, oil and natural gas

Notes: Hydrogen conversion losses = consumption of natural gas when producing low-carbon merchant hydrogen using steam methane reforming. Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

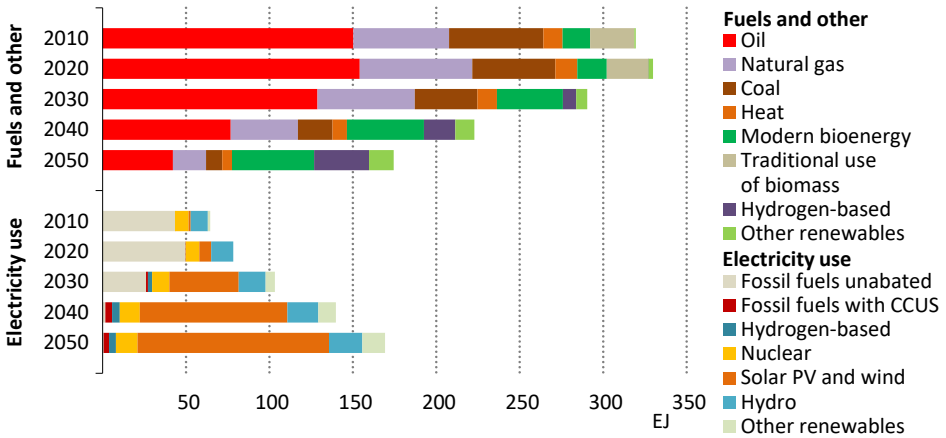
2.4.2 Total final consumption

Total final consumption worldwide rebounds marginally following its 5% drop in 2020, but it never returns to 2019 levels in the NZE (435 EJ). It falls by just under 1% each year on average between 2025 and 2050 to 340 EJ. Energy efficiency measures and electrification are the two main contributing factors, with behavioural changes and materials efficiency also playing a role. Without these improvements, final energy consumption in 2050 would be around 640 EJ, around 90% higher than the level in the NZE. Final consumption of electricity increases by 25% from 2020 to 2030, and by 2050 it is more than double the level in 2020. The increase in electricity consumption from end-uses sectors and from hydrogen production means that overall annual electricity demand growth is equivalent to adding an electricity market the size of India every year in the NZE. The share of electricity in global final energy consumption jumps from 20% in 2020 to 26% in 2030 and to around 50% in 2050 (Figure 2.9). The direct use of renewables in buildings and industry together with low-emissions fuels such as bioenergy and hydrogen-based fuels provide a further 28% of final energy consumption in 2050; fossil fuels comprise the remainder, most of which are used in non-emitting processes or in facilities equipped with CCUS.

In industry, most of the global emissions reductions in the NZE during the period to 2030 are delivered through energy and materials efficiency improvements, electrification of heat, and fuel switching to solar thermal, geothermal and bioenergy. Thereafter, CCUS and hydrogen play an increasingly important role in reducing CO_2 emissions, especially in heavy industries such as steel, cement and chemicals. Electricity consumption in industry more than doubles between 2020 and 2050, providing 45% of total industrial energy needs in 2050 (Figure 2.10).

The demand for merchant hydrogen in industry increases from less than 1 Mt today to around 40 Mt in 2050. A further 10% of industrial energy demand in 2050 is met by fossil fuels used in plants equipped with CCUS.

Figure 2.9 ▷ Global total final consumption by fuel in the NZE



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The share of electricity in final energy use jumps from 20% in 2020 to 50% in 2050

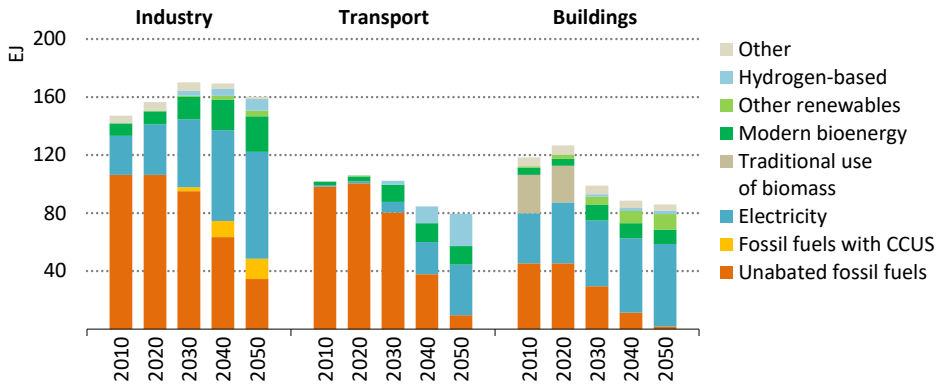
Note: Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

In transport, there is a rapid transition away from oil worldwide, which provided more than 90% of fuel use in 2020. In road transport, electricity comes to dominate the sector, providing more than 60% of energy use in 2050, while hydrogen and hydrogen-based fuels play a smaller role, mainly in fuelling long-haul heavy-duty trucks. In shipping, energy efficiency improvements significantly reduce energy needs (especially up to 2030), while advanced biofuels and hydrogen-based fuels, such as ammonia, increasingly displace oil. In aviation, the use of synthetic liquids and advanced biofuels grows rapidly, and their share of total energy demand rises from almost zero today to almost 80% in 2050. Overall, electricity becomes the dominant fuel in the transport sector globally by the early 2040s, and it accounts for around 45% of energy consumption in the sector in 2050 (compared with 1.5% in 2020). Hydrogen and hydrogen-based fuels account for nearly 30% of consumption (almost zero in 2020) and bioenergy for a further 15% (around 4% in 2020).

In buildings, the electrification of end-uses including heating leads to demand for electricity increasing by around 35% between 2020 and 2050: it becomes the dominant fuel, reaching 16 000 terawatt-hours (TWh) in 2050, and accounting for two-thirds of total buildings sector energy consumption. By 2050, two-thirds of residential buildings in advanced economies and around 40% of residential buildings in emerging market and developing economies are fitted with a heat pump. Onsite renewables-based energy systems such as solar water heaters and biomass boilers provide a further quarter of final energy use in the buildings sector in 2050 (up from 6% in 2020). Low-emissions district heating and hydrogen provide only 7% of energy use, but play a significant role in some regions.

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Figure 2.10 ▷ Global final energy consumption by sector and fuel in the NZE



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There is a wholesale shift away from unabated fossil fuel use to electricity, renewables, hydrogen and hydrogen-based fuels, modern bioenergy and CCUS in end-use sectors

Note: Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

Buildings energy consumption falls by 25% between 2020 and 2030, largely as a result of a major push to improve efficiency and to phase out the traditional use of solid biomass for cooking: it is replaced by liquefied petroleum gas (LPG), biogas, electric cookers and improved bioenergy stoves. Universal access to electricity is achieved by 2030, and this adds less than 1% to global electricity demand in 2030. Energy consumption in the buildings sector contracts by around 15% between 2030 and 2050 given continued efficiency improvements and electrification. By 2050, energy use in buildings is 35% lower than in 2020. Energy efficiency measures – including improving building envelopes and ensuring that all new appliances brought to market are the most efficient models available – play a key role in limiting the rise in electricity demand in the NZE. Without these measures, electricity demand in buildings would be around 10 000 TWh higher in 2050, or around 70% higher than the level in the NZE.

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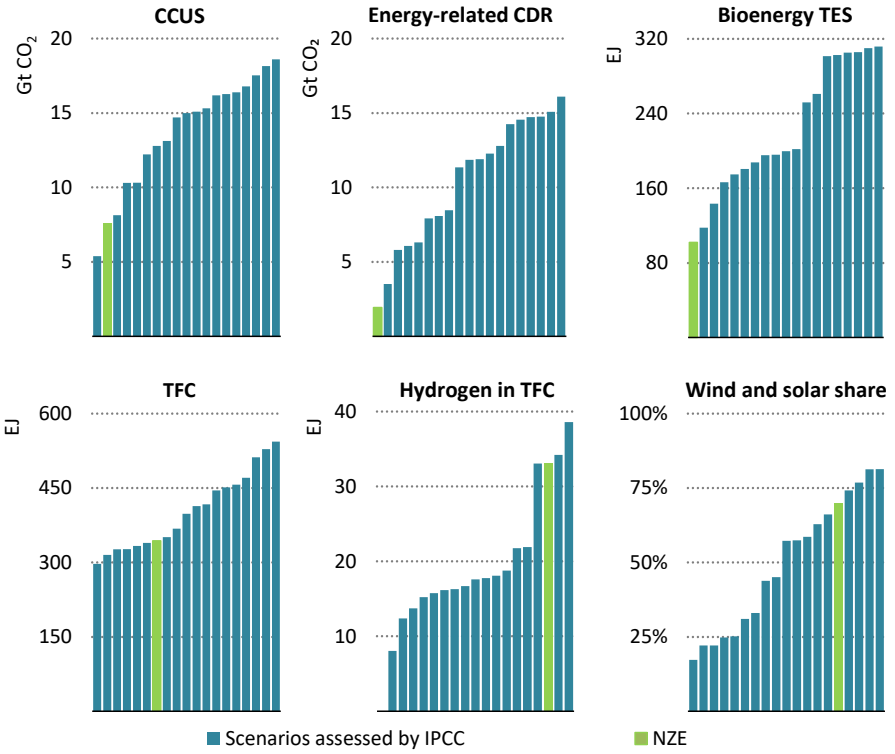
How does the NZE compare with similar 1.5 °C scenarios assessed by the IPCC?

The IPCC SR1.5 includes 90 individual scenarios that have at least a 50% chance of limiting warming in 2100 to 1.5 °C (IPCC, 2018).[9] Only 18 of these scenarios have net-zero CO_2 energy sector and industrial process emissions in 2050. In other words, only one-in-five of the 1.5 °C scenarios assessed by the IPCC have the same level of emissions reduction

[9] Includes 53 scenarios with no or limited temperature overshoot and 37 scenarios with a higher temperature overshoot.

ambition for the energy and industrial process sectors to 2050 as the NZE.[10] Some comparisons between these 18 scenarios and the NZE in 2050 (Figure 2.11):

Figure 2.11 ▷ Comparison of selected indicators of the IPCC scenarios and the NZE in 2050



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The NZE has the lowest level of energy-related CDR and bioenergy of any scenario that achieves net-zero energy sector and industrial process CO_2 emissions in 2050

Notes: CCUS = carbon capture, utilisation and storage; CDR = carbon direct removal; TES = total energy supply; TFC = total final consumption. Energy-related CDR includes CO_2 captured through bioenergy with CCUS and direct air capture with CCUS and put into permanent storage. Wind and solar share are given as a percentage of total electricity generation. Only 17 of the 18 scenarios assessed by the IPCC report hydrogen use in TFC.

- **Use of CCUS.** The scenarios assessed by the IPCC have a median of around 15 Gt CO_2 captured using CCUS in 2050, more than double the level in the NZE.
- **Use of CDR.** CO_2 emissions captured and stored from BECCS and DACCS in the IPCC scenarios range from 3.5-16 Gt CO_2 in 2050, compared with 1.9 Gt CO_2 in the NZE.

[10] The low-energy demand scenario has around 4.5 Gt CO_2 energy sector and industrial process emissions in 2050 and is not included in this comparison.

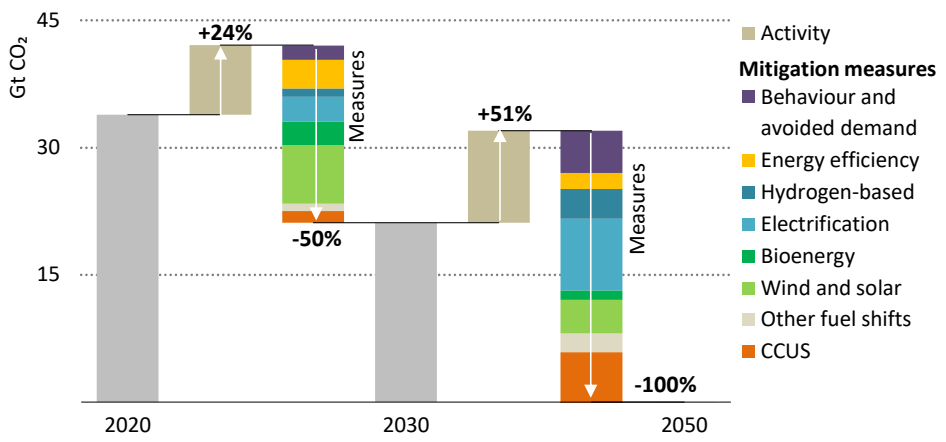
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- **Bioenergy.** The IPCC scenarios use a median of 200 EJ of primary bioenergy in 2050 (compared with 63 EJ today) and a number use more than 300 EJ. The NZE uses 100 EJ of primary bioenergy in 2050.
- **Energy efficiency.** Total final consumption in the IPCC scenarios range from 300-550 EJ in 2050 (compared with around 410 EJ in 2020). The NZE has final energy consumption of 340 EJ in 2050.
- **Hydrogen.** The IPCC scenarios have a median of 18 EJ hydrogen in total final consumption in 2050, compared with 33 EJ in the NZE.[11]
- **Electricity generation.** The shares of wind and solar in total electricity generation in 2050 in the IPCC scenarios range from around 15-80% with a median value of 50%. In the NZE, wind and solar provide 70% of total generation in 2050.

2.5 Key pillars of decarbonisation

Achieving the rapid reduction in CO_2 emissions over the next 30 years in the NZE requires a broad range of policy approaches and technologies (Figure 2.12). The key pillars of decarbonisation of the global energy system are energy efficiency, behavioural changes, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy and CCUS.

Figure 2.12 ▷ Emissions reductions by mitigation measure in the NZE, 2020-2050



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Solar, wind and energy efficiency deliver around half of emissions reductions to 2030 in the NZE, while electrification, CCUS and hydrogen ramp up thereafter

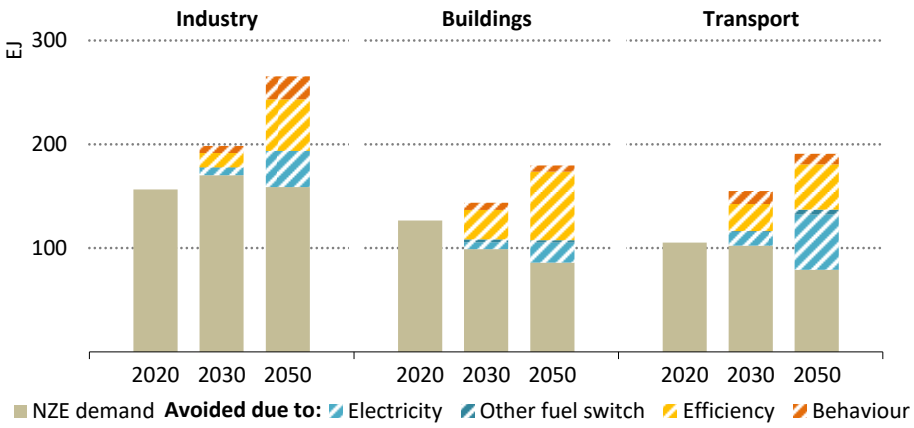
Notes: Activity = energy service demand changes from economic and population growth. Behaviour = energy service demand changes from user decisions, e.g. changing heating temperatures. Avoided demand = energy service demand changes from technology developments, e.g. digitalisation. Other fuel shifts = switching from coal and oil to natural gas, nuclear, hydropower, geothermal, concentrating solar power or marine.

[11] The NZE value for hydrogen includes the total energy content of hydrogen and hydrogen-based fuels consumed in final energy consumption.

2.5.1 Energy efficiency

Minimising energy demand growth through improvements in energy efficiency makes a critical contribution in the NZE. Many efficiency measures in industry, buildings, appliances and transport can be put into effect and scaled up very quickly. As a result, energy efficiency measures are front-loaded in the NZE, and they play their largest role in curbing energy demand and emissions in the period to 2030. Although energy efficiency improves further after 2030, its contribution to overall emissions reductions falls as other mitigation measures play an expanding role. Without the energy efficiency, behavioural changes and electrification measures deployed in the NZE, final energy consumption would be around 300 EJ higher in 2050, almost 90% above the 2050 level in the NZE (Figure 2.13). Efficiency improvements also help reduce the vulnerability of businesses and consumers to potential disruptions to electricity supplies.

Figure 2.13 ▷ Total final consumption and demand avoided by mitigation measure in the NZE



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Energy efficiency plays a key role in reducing energy consumption across end-use sectors

Notes: Other fuel switch includes switching to hydrogen-related fuels, bioenergy, solar thermal, geothermal, or district heat.

In the buildings sector, many efficiency measures yield financial savings as well as reducing energy use and emissions. In the NZE, there are immediate and rapid improvements in energy efficiency in buildings, mainly from large-scale retrofit programmes. Around 2.5% of existing residential buildings in advanced economies are retrofitted each year to 2050 in the NZE to comply with zero-carbon-ready building standards[12] (compared with a current retrofit rate of less than 1%). In emerging market and developing economies, building replacement

[12] A zero-carbon-ready building is highly energy efficient and uses either renewable energy directly or from an energy supply that will be fully decarbonised by 2050 in the NZE (such as electricity or district heat). A zero-carbon-ready building will become a zero-carbon building by 2050, without further changes to the building or its equipment (see Chapter 3).

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rates are higher and the annual rate of retrofits is around 2% through to 2050. By 2050, the vast majority of existing residential buildings are retrofitted to be zero-carbon buildings. Energy-related building codes are introduced in all regions by 2030 to ensure that virtually all new buildings constructed are zero-carbon-ready. Minimum energy performance standards and replacement schemes for low-efficiency appliances are introduced or strengthened in the 2020s in all countries. By the mid-2030s, nearly all household appliances sold worldwide are as efficient as the most efficient models available today.

In the transport sector, stringent fuel-economy standards and ensuring no new passenger cars running on internal combustion engines (ICEs) are sold globally from 2035 result in a rapid shift in vehicle sales toward much more efficient electric vehicles (EVs).[13] The impact on efficiency is seen in the 2030s, as the composition of the vehicle stock changes: electric cars make up 20% of all cars on the road in 2030 and 60% in 2040 (compared with 1% today). Continuous improvements in the fuel economy of heavy road vehicles take place through to 2050 as they switch to electricity or fuel cells, while efficiency in shipping and aviation improves as more efficient planes and ships replace existing stock.

In the industry sector, most manufacturing stock is already quite efficient, but there are still opportunities for energy efficiency improvements. Energy management systems, best-in-class industrial equipment such as electric motors, variable speed drives, heaters and grinders are installed, and process integration options such as waste heat recovery are exploited to their maximum economic potentials in the period to 2030 in the NZE. After 2030, the rate of efficiency improvement slows because many of the technologies needed to reduce emissions in industry in the NZE require more energy than their equivalent conventional technologies. The use of CCUS, for example, increases energy consumption to operate the capture equipment, and producing electrolytic hydrogen on-site requires additional energy than that needed for the main manufacturing process.

Table 2.3 ▷ Key global milestones for energy efficiency in the NZE

Sector	2020	2030	2050
Total energy supply	*2010-20*	*2020-30*	*2030-50*
Annual energy intensity improvement (MJ per USD GDP)	-1.6%	-4.2%	-2.7%
Industry			
Energy intensity of direct reduced iron from natural gas (GJ per tonne)	12	11	10
Process energy intensity of primary chemicals (GJ per tonne)	17	16	15
Transport			
Average fuel consumption of ICE heavy trucks fleet (index 2020=100)	100	81	63
Buildings			
Share of zero-carbon-ready buildings in total stock	<1%	25%	>85%
New buildings: heating & cooling energy consumption (index 2020=100)	100	50	20
Appliances: unit energy consumption (index 2020=100)	100	75	60

Notes: ICE = internal combustion engine; zero-carbon-ready buildings = see description in section 3.7.

[13] In 2020, the average battery electric car required around 30% of the energy of the average ICE car to provide the same level of activity.

2.5.2 Behavioural change

The wholescale transformation of the energy sector demonstrated in the NZE cannot be achieved without the active and willing participation of citizens. It is ultimately people who drive demand for energy-related goods and services, and societal norms and personal choices will play a pivotal role in steering the energy system onto a sustainable path. Just under 40% of emissions reductions in the NZE result from the adoption of low-carbon technologies that require massive policy support and investment but little direct engagement from citizens or consumers, e.g. technologies in electricity generation or steel production. A further 55% of emissions reductions require a mixture of the deployment of low-carbon technologies and the active involvement or engagement of citizens and consumers, e.g. installing a solar water heater or buying an EV. A final 8% of emissions reductions stem from behavioural changes and materials efficiency gains that reduce energy demand, e.g. flying less for business purposes (Figure 2.14). Consumer attitudes can also impact investment decisions by businesses concerned about public image.

In the NZE, behavioural change refers to changes in ongoing or repeated behaviour on the part of consumers which impact energy service demand or the energy intensity of an energy-related activity.[14] Reductions in energy service demand in the NZE also come from advances in technology, but these are not counted as behavioural changes. For example, increased digitalisation and a growing market share of smart appliances, such as smart thermostats or space-differentiated thermal controls reduce the necessity for people to play an active role in energy saving in homes over time in the NZE.

There are three main types of behavioural change included in the NZE. A wide range of government interventions could be used to motivate these changes (see section 2.7.1).

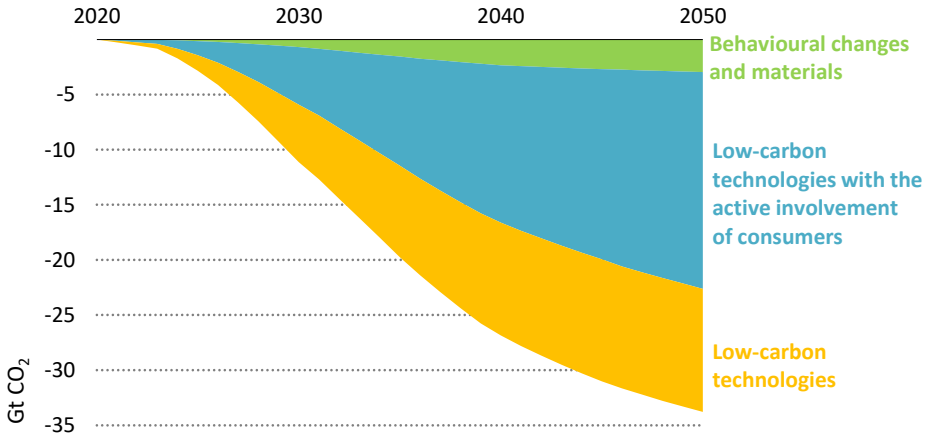
- **Reducing excessive or wasteful energy use.** This includes reducing energy use in buildings and on roads, e.g. by reducing indoor temperature settings, adopting energy saving practices in homes and limiting driving speeds on motorways to 100 kilometres per hour.
- **Transport mode switching.** This includes a shift to cycling, walking, ridesharing or taking buses for trips in cities that would otherwise be made by car, as well as replacing regional air travel by high-speed rail in regions where this is feasible. Many of these types of behavioural changes would represent a break in familiar or habitual ways of life and as such would require a degree of public acceptance and even enthusiasm. Many would also require new infrastructure, such as cycle lanes and high-speed rail networks, clear policy support and high quality urban planning.
- **Materials efficiency gains.** This includes reduced demand for materials, e.g. higher rates of recycling, and improved design and construction of buildings and vehicles. The scope for gains to some extent reflects societal preferences. For instance, in some places there

[14] This means, for example, that purchasing an electric heat pump instead of a gas boiler is not considered as a behavioural change, as it is both an infrequent event and does not necessarily impact energy service demand.

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has been a shift away from the use of single-use plastics in recent years, a trend that accelerates in the NZE. Gains in materials efficiency depend on a mixture of technical innovation in manufacturing and buildings construction, standards and regulations to support best-practice and ensure universal adoption of these innovations, and increased recycling in society at large.

Figure 2.14 ▷ Role of technology and behavioural change in emissions reductions in the NZE



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Around 8% of emissions reductions stem from behavioural changes and materials efficiency

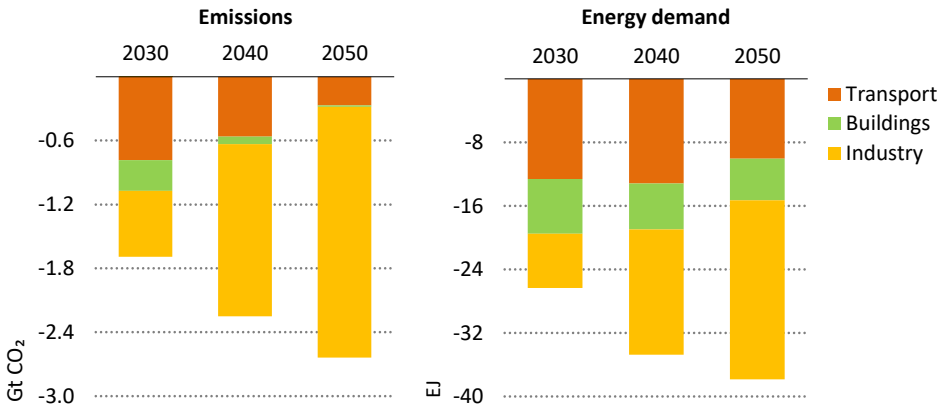
Notes: Low-carbon technologies include low-carbon electricity generation, low-carbon gases in end-uses and biofuels. Low-carbon technologies with the active involvement of citizens includes fuel switching, electrification and efficiency gains in end-uses. Behavioural changes and materials efficiency includes transport mode switching, curbing excessive or wasteful energy use, and materials efficiency measures.

Three-quarters of the emissions reductions from behavioural changes in the NZE are achieved through targeted government policies supported by infrastructure development, e.g. a shift to rail travel supported by high-speed railways. The remainder come from adopting voluntary changes in energy saving habits, mainly in homes. Even in this case, public awareness campaigns can help shape day-to-day choices about how consumers use energy. (Details of what governments can do to help bring about behavioural changes are discussed in Chapter 4).

Behavioural changes reduce energy-related activity by around 10-15% on average over the period to 2050 in the NZE, reducing overall global energy demand by over 37 EJ in 2050 (Figure 2.15). In 2030, around 1.7 Gt CO_2 emissions are avoided, 45% of which come from transport, notably through measures to phase out car use in cities and to improve fuel economy. For example, reducing speed limits on motorways to 100 km/h reduces emissions from road transport by 3% or 140 Mt CO_2 in 2030. A shift away from single occupancy car use towards ridesharing or cycling and walking in large cities saves a further 185 Mt CO_2. Around

40% of emissions savings in 2030 occur in industry because of improvements in materials efficiency and increased recycling, with the biggest impacts coming from reducing waste and improving the design and construction of buildings. The remainder of emissions savings in 2030 are from behavioural changes in buildings, for example adjusting space heating and cooling temperatures.

Figure 2.15 ▷ CO_2 emissions and energy demand reductions from behavioural changes and materials efficiency in the NZE



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By 2030, behaviour changes and materials efficiency gains reduce emissions by 1.7 Gt CO_2, and energy demand by 27 EJ; reductions increase further through to 2050

In 2050, the growing importance of low-emissions electricity and fuels in transport and buildings means that 90% of emissions reductions are in industry, predominantly in those sectors where it is most challenging to tackle emissions directly. Material efficiency alone reduces demand for cement and steel by 20%, saving around 1 700 Mt CO_2. Of the emissions reductions in transport in 2050, nearly 80% come from measures to reduce passenger aviation demand, with the remainder from road transport.

The scope, scale and speed of adoption of the behavioural changes in the NZE varies widely between regions, depending on several factors including the ability of existing infrastructure to support such changes and differences in geography, climate, urbanisation, social norms and cultural values. For example, regions with high levels of private car use today see a more gradual shift than others towards public transport, shared car use, walking and cycling; air travel is assumed to switch to high-speed rail on existing or potential routes only where trains could offer a similar journey time; and the potential for moderating air conditioning in buildings and vehicles takes into account seasonal effects and humidity. Wealthier regions generally have higher levels of per capita energy-related activity, and behavioural changes play an especially important role in these regions in reducing excessive or wasteful energy consumption.

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Most of the behavioural changes in the NZE would have some effect on nearly everyone's daily life, but none represents a radical departure from energy-reducing practices already experienced in many parts of the world today. For example, in Japan an awareness campaign has successfully reduced cooling demand in line with the reductions assumed in many regions in the NZE by 2040; legislation to limit urban car use has been introduced in many large cities; and speed limit reductions to around 100 km/h (the level adopted globally in the NZE by 2030) have been tested in the United Kingdom and Spain to reduce air pollution and improve safety.

Table 2.4 ▷ Key global milestones for behavioural change in the NZE

Sector	Year	Milestone
Industry	2020	• Global average plastics collection rate = 17%.
	2030	• Global average plastics collection rate = 27%. • Lightweighting reduces the weight of an average passenger car by 10%.
	2050	• Global average plastics collection rate = 54%. • Efficiency of fertiliser use improved by 10%.
Transport	2030	• Eco-driving and motorway speed limits of 100 km/h introduced. • Use of ICE cars phased out in large cities.
	2050	• Regional flights are shifted to high-speed rail where feasible. • Business and long-haul leisure air travel does not exceed 2019 levels.
Buildings	2030	• Space heating temperatures moderated to 19-20 °C on average. • Space cooling temperatures moderated to 24-25°C on average. • Excessive hot-water temperatures reduced.
	2050	• Use of energy-intensive materials per unit of floor area decreases by 30%. • Building lifetime extended by 20% on average.

Note: Eco-driving involves pre-emptive stopping and starting; ICE = internal combustion engine.

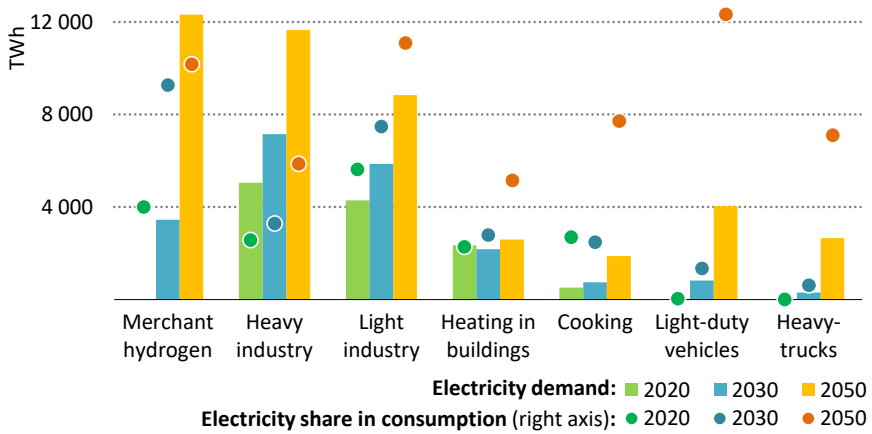
2.5.3 Electrification

The direct use of low-emissions electricity in place of fossil fuels is one of the most important drivers of emissions reductions in the NZE, accounting for around 20% of the total reduction achieved by 2050. Global electricity demand more than doubles between 2020 and 2050, with the largest absolute rise in electricity use in end-use sectors taking place in industry, which registers an increase of more than 11 000 TWh between 2020 and 2050. Much of this is due to the increasing use of electricity for low- and medium-temperature heat and in secondary scrap-based steel production (Figure 2.16).

In transport, the share of electricity increases from less than 2% in 2020 to around 45% in 2050 in the NZE. More than 60% of total passenger car sales globally are EVs by 2030 (compared with 5% of sales in 2020), and the car fleet is almost fully electrified worldwide by 2050 (the remainder are hydrogen-powered cars). The increase in electric passenger car sales globally over the next ten years is over twenty-times higher than the increase in ICE car sales over the last decade. Electrification is slower for trucks because it depends on higher

density batteries than those currently available on the market, especially for long-haul trucking, and on new high-power charging infrastructure: electric trucks nevertheless account for around 25% of total heavy truck sales globally by 2030 and around two-thirds in 2050. The electrification of shipping and aviation is much more limited and only gets under way after large improvements in battery energy density (see section 3.6) (Figure 2.17). In the NZE, demand for batteries for transport reaches around 14 TWh in 2050, 90-times more than in 2020. Growth in battery demand translates into an increasing demand for critical minerals. For example, demand for lithium for use in batteries grows 30-fold to 2030 and is more than 100-times higher in 2050 than in 2020 (IEA, 2021).

Figure 2.16 ▷ Global electricity demand and share of electricity in energy consumption in selected applications in the NZE



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Global electricity demand more than doubles in the period to 2050, with the largest rises to produce hydrogen and in industry

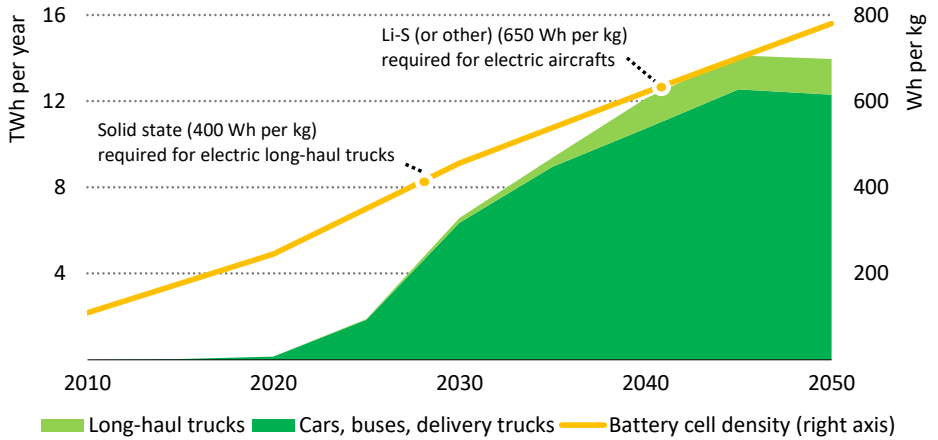
Notes: Merchant hydrogen = hydrogen produced by one company to sell to others. Light-duty vehicles = passenger cars and vans. Heavy trucks = medium-freight trucks and heavy-freight trucks.

In buildings, electricity demand is moderated in the NZE by a huge push to improve the efficiency of appliances, cooling, lighting and building envelopes. But a large increase in activity, along with the widespread electrification of heating through the use of heat pumps, means that electricity demand in buildings still rises steadily over the period reaching 66% of total energy consumption in buildings in 2050.

Alongside the growth in the direct use of electricity in end-use sectors, there is also a huge increase in the use of electricity for hydrogen production. Merchant hydrogen produced using electrolysis requires around 12 000 TWh in 2050 in the NZE, which is greater than current total annual electricity demand of China and the United States combined.

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Figure 2.17 ▷ Battery demand growth in transport and battery energy density in the NZE



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Nearly 20 battery giga-factories open every year to 2030 to satisfy battery demand for electric cars in the NZE; higher density batteries are needed to electrify long-haul trucks

Notes: Li-S = lithium-sulphur battery; Wh per kg = Watt hours per kilogramme.

The acceleration of electricity demand growth from 2% per year over the past decade to 3% per year through to 2050, together with a significantly increased share of variable renewable electricity generation, means that annual electricity sector investment in the NZE is three-times higher on average than in recent years. The rise in electricity demand also calls for extensive efforts to ensure the stability and flexibility of electricity supply through demand-side management, the operation of flexible low-emissions sources of generation including hydropower and bioenergy, and battery storage.

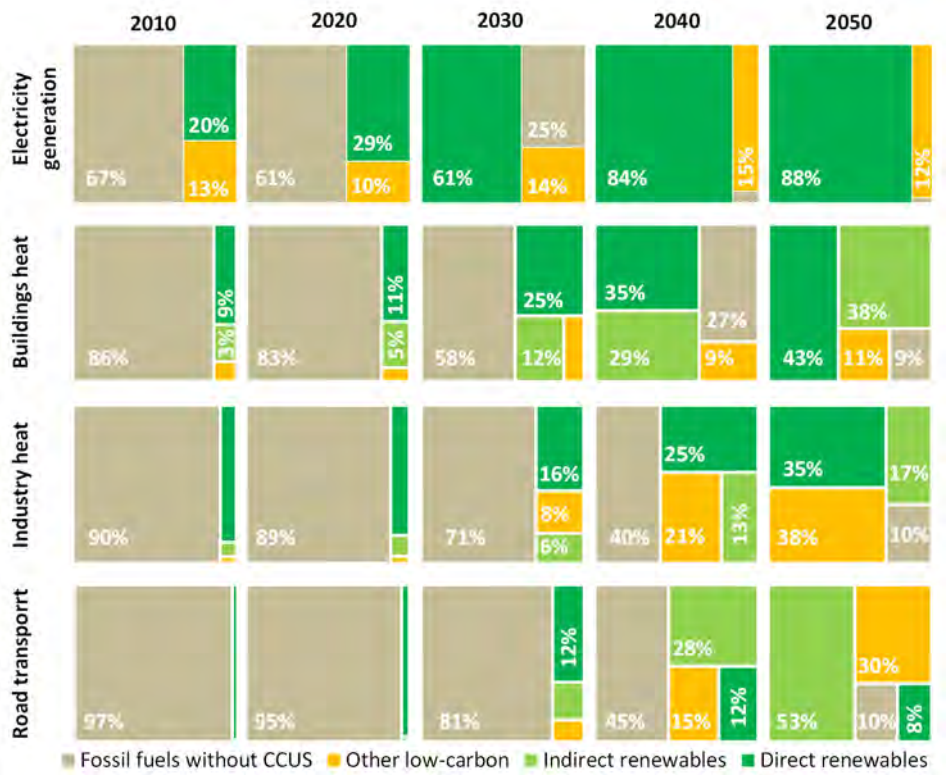
Table 2.5 ▷ Key global milestones for electrification in the NZE

Sector	2020	2030	2050
Share of electricity in total final consumption	20%	26%	49%
Industry			
Share of steel production using electric arc furnace	24%	37%	53%
Electricity share of light industry	43%	53%	76%
Transport			
Share of electric vehicles in stock: cars	1%	20%	86%
two/three-wheelers	26%	54%	100%
bus	2%	23%	79%
vans	0%	22%	84%
heavy trucks	0%	8%	59%
Annual battery demand for electric vehicles (TWh)	0.16	6.6	14
Buildings			
Heat pumps installed (millions)	180	600	1 800
Share of heat pumps in energy demand for heating	7%	20%	55%
Million people without access to electricity	786	0	0

2.5.4 Renewables

At a global level, renewable energy technologies are the key to reducing emissions from electricity supply. Hydropower has been a leading low-emission source for many decades, but it is mainly the expansion of wind and solar that triples renewables generation by 2030 and increases it more than eightfold by 2050 in the NZE. The share of renewables in total electricity generation globally increases from 29% in 2020 to over 60% in 2030 and to nearly 90% in 2050 (Figure 2.18). To achieve this, annual capacity additions of wind and solar between 2020 and 2050 are five-times higher than the average over the last three years. Dispatchable renewables are critical to maintain electricity security, together with other low-carbon generation, energy storage and robust electricity networks. In the NZE, the main dispatchable renewables globally in 2050 are hydropower (12% of generation), bioenergy (5%), concentrating solar power (2%) and geothermal (1%).

Figure 2.18 ▷ Fuel shares in total energy use in selected applications in the NZE



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Renewables are central to emissions reductions in electricity, and they make major contributions to cut emissions in buildings, industry and transport both directly and indirectly

Notes: Indirect renewables = use of electricity and district heat produced by renewables. Other low-carbon = nuclear power, facilities equipped with CCUS, and low-carbon hydrogen and hydrogen-based fuels.

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Renewables also play an important role in reducing emissions in buildings, industry and transport. Renewables can be used either indirectly, via the consumption of electricity or district heating that was produced by renewables, or directly, mainly to produce heat.

In transport, renewables play an important indirect role in reducing emissions by generating the electricity to power electric vehicles. They also contribute to direct emissions reductions through the use of liquid biofuels and biomethane.

In buildings, renewable energy is mainly used for water and space heating. The direct use of renewable energy rises from about 10% of heating demand globally in 2020 to 40% in 2050, about three-quarters of the increase is in the form of solar thermal and geothermal. Deep retrofits and energy-related building codes are paired with renewables whenever possible: almost all buildings with available roof space and sufficient solar insolation are equipped with solar thermal water heaters by 2050, as they are more productive per square metre than solar PV and as heat storage in water tanks is generally more cost-effective than storage of electricity. Rooftop solar PV, which produces renewable electricity onsite, is currently installed on around 25 million rooftops worldwide; the number increases to 100 million rooftops by 2030 and 240 million by 2050. A further 15% of heating in buildings in 2030 comes indirectly from renewables in the form of electricity, and this rises to almost 40% in 2050.

In industry, bioenergy is the most important direct renewable energy source for low- and medium-temperature needs in the NZE. Solar thermal and geothermal also produce low temperature heat for use in non-energy-intensive industries and ancillary or downstream processes in heavy industries. Bioenergy, solar thermal and geothermal together provide about 15% of industry heat demand in 2030, roughly double their share in 2010, and this increases to 40% in 2050. The indirect use of renewable energy via electricity adds 15% to the contribution that renewables make to total industry energy use in 2050.

Table 2.6 ▷ Key deployment milestones for renewables

Sector		2020	2030	2050
Electricity sector				
Renewables share in generation		29%	61%	88%
Annual capacity additions (GW):	Total solar PV	134	630	630
	Total wind	114	390	350
	– of which: Offshore wind	5	80	70
	Dispatchable renewables	31	120	90
End-uses sectors				
Renewable share in TFC		5%	12%	19%
Households with rooftop solar PV (million)		25	100	240
Share of solar thermal and geothermal in buildings		2%	5%	12%
Share of solar thermal and geothermal in industry final consumption		0%	1%	2%

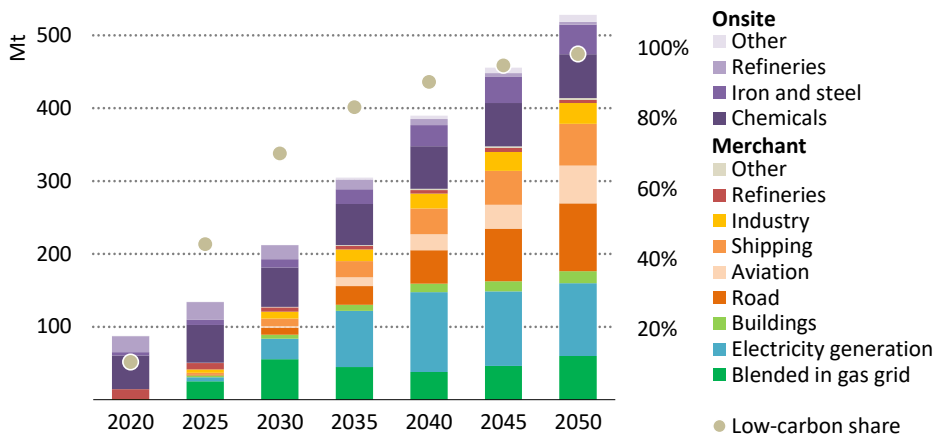
Note: TFC = total final consumption.

2.5.5 Hydrogen and hydrogen-based fuels

The initial focus for hydrogen use in the NZE is the conversion of existing uses of fossil energy to low-carbon hydrogen in ways that do not immediately require new transmission and distribution infrastructure. This includes hydrogen use in industry and in refineries and power plants, and the blending of hydrogen into natural gas for distribution to end-users.

Global hydrogen use expands from less than 90 Mt in 2020 to more than 200 Mt in 2030; the proportion of low-carbon hydrogen rises from 10% in 2020 to 70% in 2030 (Figure 2.19). Around half of low-carbon hydrogen produced globally in 2030 comes from electrolysis and the remainder from coal and natural gas with CCUS, although this ratio varies substantially between regions. Hydrogen is also blended with natural gas in gas networks: the global average blend in 2030 includes 15% of hydrogen in volumetric terms, reducing CO_2 emissions from gas consumption by around 6%.

Figure 2.19 ▷ Global hydrogen and hydrogen-based fuel use in the NZE



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The initial focus for hydrogen is to convert existing uses to low-carbon hydrogen; hydrogen and hydrogen-based fuels then expand across all end-uses

Note: Includes hydrogen and hydrogen contained in ammonia and synthetic fuels.

These developments facilitate a rapid scaling up of electrolyser manufacturing capacity and the parallel development of new hydrogen transport infrastructure. This leads to rapid cost reductions for electrolysers and for hydrogen storage, notably in salt caverns. Stored hydrogen is used to help balance both seasonal fluctuations in electricity demand and imbalances that may arise between the demand for hydrogen and its supply by off-grid renewable systems. During the 2020s, there is also a large increase in the installation of end-use equipment for hydrogen, including more than 15 million hydrogen fuel cell vehicles on the road by 2030.

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After 2030, low-carbon hydrogen use expands rapidly in all sectors in the NZE. In the electricity sector, hydrogen and hydrogen-based fuels provide an important low-carbon source of electricity system flexibility, mainly through retrofitting existing gas-fired capacity to co-fire with hydrogen, together with some retrofitting of coal-fired power plants to co-fire with ammonia. Although these fuels provide only around 2% of overall electricity generation in 2050, this translates into very large volumes of hydrogen and makes the electricity sector an important driver of hydrogen demand. In transport, hydrogen provides around one-third of fuel use in trucks in 2050 in the NZE: this is contingent on policy makers taking decisions that enable the development of the necessary infrastructure by 2030. By 2050, hydrogen-based fuels also provide more than 60% of total fuel consumption in shipping.

Of the 530 Mt of hydrogen produced in 2050, around 25% is produced within industrial facilities (including refineries), and the remainder is merchant hydrogen (hydrogen produced by one company to sell to others). Almost 30% of the low-carbon hydrogen used in 2050 takes the form of hydrogen-based fuels, which include ammonia and synthetic liquids and gases. An increasing share of hydrogen production comes from electrolysers, which account for 60% of total production in 2050. Electrolysers are powered by grid electricity, dedicated renewables in regions with excellent renewable resources and other low-carbon sources such as nuclear power. Rolling out electrolysers at the pace required in the NZE is a key challenge given the lack of manufacturing capacity today, as is ensuring the availability of sufficient electricity generation capacity. Global trade in hydrogen develops over time in the NZE, with large volumes exported from gas and renewables-rich areas in the Middle East, Central and South America and Australia to demand centres in Asia and Europe.

Table 2.7 ▷ Key deployment milestones for hydrogen and hydrogen-based fuels

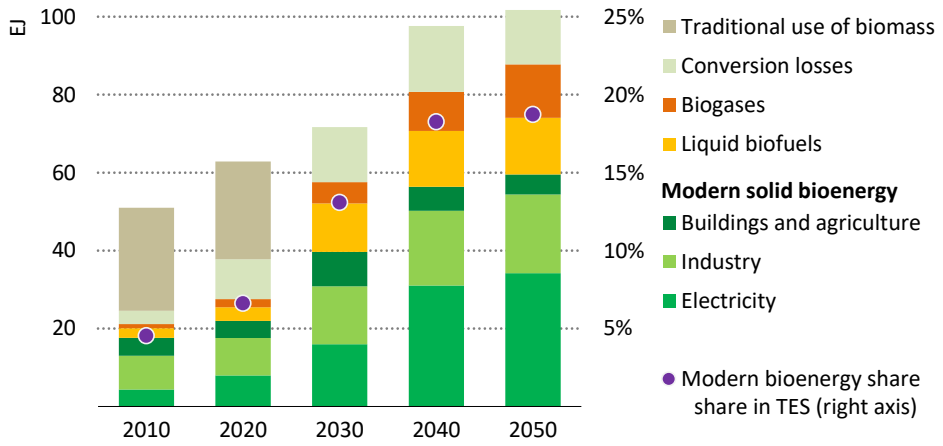
Sector	2020	2030	2050
Total production hydrogen-based fuels (Mt)	**87**	**212**	**528**
Low-carbon hydrogen production	9	150	520
share of fossil-based with CCUS	*95%*	*46%*	*38%*
share of electrolysis-based	*5%*	*54%*	*62%*
Merchant production	15	127	414
Onsite production	73	85	114
Total consumption hydrogen-based fuels (Mt)	**87**	**212**	**528**
Electricity	0	52	102
of which hydrogen	0	43	88
of which ammonia	0	8	13
Refineries	36	25	8
Buildings and agriculture	0	17	23
Transport	0	25	207
of which hydrogen	0	11	106
of which ammonia	0	8	44
of which synthetic fuels	0	5	56
Industry	51	93	187

Note: Hydrogen-based fuels are reported in million tonnes of hydrogen required to produce them.

2.5.6 Bioenergy

Global primary demand for bioenergy was almost 65 EJ in 2020, of which about 90% was solid biomass. Some 40% of the solid biomass was used in traditional cooking methods which is unsustainable, inefficient and polluting, and was linked to 2.5 million premature deaths in 2020. The use of solid biomass in this manner falls to zero by 2030 in the NZE, to achieve the UN Sustainable Development Goal 7. Increases in all forms of modern bioenergy more than offset this, with production rising from less than 40 EJ in 2020 to around 100 EJ in 2050 (Figure 2.20).[15] All bioenergy in 2050 comes from sustainable sources and the figures in the NZE for total bioenergy use are well below estimates of global sustainable bioenergy potential, thus avoiding the risk of negative impacts on biodiversity, fresh water systems, and food prices and availability (see section 2.7.2).

Figure 2.20 ▷ Total bioenergy supply in the NZE



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Modern bioenergy use rises to 100 EJ in 2050, meeting almost 20% of total energy needs. Global demand in 2050 is well below the assessed sustainable potential

Notes: TES = Total energy supply. Conversion losses occur during the production of biofuels and biogases.

Modern solid bioenergy use rises by about 3% each year on average to 2050. In the electricity sector, where demand reaches 35 EJ in 2050, solid bioenergy provides flexible low-emissions generation to complement generation from solar PV and wind, and it removes CO_2 from the atmosphere when equipped with CCUS. In 2050, electricity generation using bioenergy fuels reaches 3 300 TWh, or 5% of total generation. Bioenergy also provides around 50% of district heat production. In industry, where demand reaches 20 EJ in 2050, solid bioenergy provides high temperature heat and can be co-fired with coal to reduce the emissions intensity of

[15] Modern bioenergy includes biogases, liquid biofuels and modern solid biomass harvested from sustainable sources. It excludes the traditional use of biomass.

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existing generation assets. Demand is highest for paper and cement production: in 2050, bioenergy meets 60% of energy demand in the paper sector and 30% of energy demand for cement production. Modern solid bioenergy demand in buildings increases to nearly 10 EJ in 2030, most of it for use in improved cookstoves as unsustainable traditional uses of biomass disappear. Bioenergy is also increasingly used for space and water heating in advanced economies.

Household and village biogas digesters in rural areas provide a source of renewable energy and clean cooking for nearly 500 million households by 2030 in the NZE and total biogas use rises to 5.5 EJ in 2050 (from under 2 EJ in 2020).[16] Biomethane demand grows to 8.5 EJ, thanks to blending mandates for gas networks, with average blending rates increasing to above 80% in many regions by 2050. Half of total biomethane use is in the industry sector, where biomethane replaces natural gas as a source of process heat. The buildings and transport sectors each account for around a further 20% of biomethane consumption in 2050.

One of the key advantages of bioenergy is that it can use existing infrastructure. For example, biomethane can use existing natural gas pipelines and end-user equipment, while many drop-in liquid biofuels can use existing oil distribution networks and be used in vehicles with only minor or limited alterations. BioLPG – LPG derived from renewable feedstocks – is identical to conventional LPG and so can be blended and distributed in the same way. Sustainable bioenergy also provides a valuable source of employment and income for rural communities, reduces undue burdens on women often tasked with fuel collection, brings health benefits from reduced air pollution and proper waste management, and reduces methane emissions from inefficient combustion and the decomposition of waste.

Liquid biofuel consumption rises from 1.6 mboe/d in 2020 to 6 mboe/d in 2030 in the NZE, mainly used in road transport. After 2030, liquid biofuels grow more slowly to around 7 mboe/d in 2050 and their use shifts to shipping and aviation as electricity increasingly dominates road transport. Almost half of liquid biofuel use in 2050 is for aviation, where bio-kerosene accounts for around 45% of total fuel use in aircraft.

Bioenergy with carbon capture and storage (BECCS) plays a critical role in the NZE in offsetting emissions from sectors where the full elimination of emissions is very difficult to achieve. In 2050, around 10% of total bioenergy is used in facilities equipped with CCUS and around 1.3 Gt CO_2 is captured using BECCS. Around 45% of this CO_2 is captured in biofuels production, 40% in the electricity sector and the rest in heavy industry, notably cement production.

[16] Biogas is a mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen free environment. Biomethane is a near pure source of methane produced either by removing CO_2 and other contaminants from biogas or through the gasification of solid biomass (IEA, 2020b).

Table 2.8 ▷ Key deployment milestones for bioenergy

	2020	2030	2050
Total energy supply (EJ)	**63**	**72**	**102**
Share of advanced biomass feedstock	27%	85%	97%
Modern gaseous bioenergy (EJ)	**2.1**	**5.4**	**13.7**
Biomethane	0.3	2.3	8.3
Modern liquid bioenergy (mboe/d)	**1.6**	**6.0**	**7.0**
Advanced biofuels	0.1	2.7	6.2
Modern solid bioenergy (EJ)	**32**	**54**	**74**
Traditional use of solid biomass (EJ)	**25**	**0**	**0**
Million people using traditional biomass for cooking	2 340	0	0

Notes: mboe/d = million barrels of oil equivalent per day. Bioenergy from forest plantings is considered advanced when forests are sustainably managed (see section 2.7.2).

2.5.7 Carbon capture, utilisation and storage

CCUS can facilitate the transition to net-zero CO_2 emissions by: tackling emissions from existing assets; providing a way to address emissions from some of the most challenging sectors; providing a cost-effective pathway to scale up low-carbon hydrogen production rapidly; and allowing for CO_2 removal from the atmosphere through BECCS and DACCS.

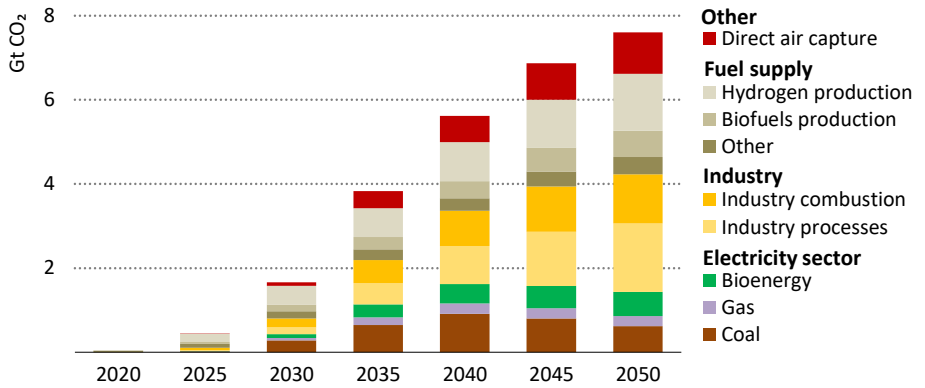
In the NZE, policies support a range of measures to establish markets for CCUS investment and to encourage use of shared CO_2 transport and storage infrastructure by those involved in the production of hydrogen and biofuels, the operation of industrial hubs, and retrofitting of existing coal-fired power plants. Capture volumes in the NZE increase marginally over the next five years from the current level of around 40 Mt CO_2 per year, reflecting projects currently under development, but there is a rapid expansion over the following 25 years as policy action bears fruit. By 2030, 1.6 Gt CO_2 per year is captured globally, rising to 7.6 Gt CO_2 in 2050 (Figure 2.21). Around 95% of total CO_2 captured in 2050 is stored in permanent geological storage and 5% is used to provide synthetic fuels. Estimates of global geological storage capacity are considerably above what is necessary to store the cumulative CO_2 captured and stored in the NZE. A total of 2.4 Gt CO_2 is captured in 2050 from the atmosphere through bioenergy with CO_2 capture and direct air capture, of which 1.9 Gt CO_2 is permanently stored and 0.5 Gt CO_2 is used to provide synthetic fuels in particular for aviation.

Energy-related and process CO_2 emissions in industry account for almost 40% of the CO_2 captured in 2050 in the NZE. CCUS is particularly important for cement manufacturing. Although efforts are pursued in the NZE to produce cement more efficiently, CCUS remains central to efforts to limit the process emissions that occur during cement manufacturing. The electricity sector accounts for almost 20% of the CO_2 captured in 2050 (of which around 45% is from coal-fired plants, 40% from bioenergy plants and 15% from gas-fired plants). CCUS-equipped power plants contribute just 3% of total electricity generation in 2050 but the volumes of CO_2 captured are comparatively large. In emerging market and developing economies, where large numbers of coal power plants have been built relatively recently,

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retrofits play an important role where there are storage opportunities. In advanced economies, gas-fired plants with CCUS play a bigger role, providing dispatchable electricity at relatively low cost in regions with cheap natural gas and existing networks. In 2030, around 50 GW of coal-fired power plants (4% of the total at that time) and 30 GW of natural gas power plants (1% of the total) are equipped with CCUS, and this rises to 220 GW of coal (almost half of the total) and 170 GW of natural gas (7% of the total) capacity in 2050. A further 30% of CO_2 captured in 2050 comes from fuel transformation, including hydrogen and biofuels production as well as oil refining. The remaining 10% is from DAC, which is rapidly scaled up from several of pilot projects today to 90 Mt CO_2 per year in 2030 and just under 1 Gt CO_2 per year by 2050.

Figure 2.21 ▷ Global CO_2 capture by source in the NZE



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By 2050, 7.6 Gt of CO_2 is captured per year from a diverse range of sources. A total of 2.4 Gt CO_2 is captured from bioenergy use and DAC, of which 1.9 Gt CO_2 is permanently stored.

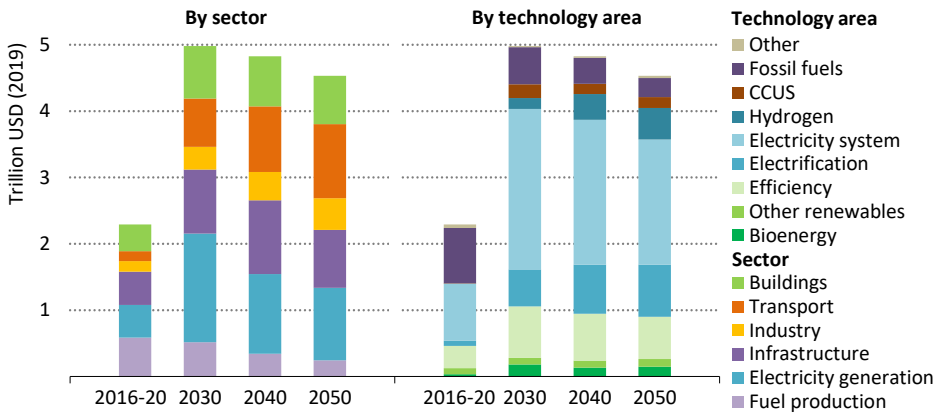
Table 2.9 ▷ Key global milestones for CCUS

	2020	2030	2050
Total CO_2 captured (Mt CO_2)	40	1 670	7 600
CO_2 captured from fossil fuels and processes	39	1 325	5 245
Power	3	340	860
Industry	3	360	2 620
Merchant hydrogen production	3	455	1 355
Non-biofuels production	30	170	410
CO_2 captured from bioenergy	1	255	1 380
Power	0	90	570
Industry	0	15	180
Biofuels production	1	150	625
Direct air capture	0	90	985
Removal	0	70	630

2.6 Investment

The radical transformation of the global energy system required to achieve net-zero CO_2 emissions in 2050 hinges on a big expansion in investment and a big shift in what capital is spent on. The NZE expands annual investment in energy from just over USD 2 trillion globally on average over the last five years to almost USD 5 trillion by 2030 and to USD 4.5 trillion by 2050 (Figure 2.22).[17] Total annual capital investment in energy in the NZE rises from around 2.5% of global GDP in recent years to about 4.5% in 2030 before falling back to 2.5% by 2050.

Figure 2.22 ▷ Annual average capital investment in the NZE



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Capital investment in energy rises from 2.5% of GDP in recent years to 4.5% by 2030; the majority is spent on electricity generation, networks and electric end-user equipment

Notes: Infrastructure includes electricity networks, public EV charging, CO_2 pipelines and storage facilities, direct air capture and storage facilities, hydrogen refuelling stations, and import and export terminals for hydrogen, fossil fuels pipelines and terminals. End-use efficiency investments are the incremental cost of improving the energy performance of equipment relative to a conventional design. Electricity systems include electricity generation, storage and distribution, and public EV charging. Electrification investments include spending in batteries for vehicles, heat pumps and industrial equipment for electricity-based material production routes.

The shift in what capital is spent on leads to annual investment in electricity generation rising from just over USD 500 billion over the last five years to more than USD 1 600 billion in 2030, before falling back as the cost of renewable energy technologies continues to decline. Annual nuclear investment rises too: it more than doubles by 2050 compared with current levels. Annual investment in fuel supply however drops from about USD 575 billion on average over

[17] Investment levels presented in this report include a broader accounting of efficiency improvements in buildings than reported in the IEA World Energy Investment (IEA, 2020c) and so differ from the numbers presented there.

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the last half-decade to USD 315 billion in 2030 and USD 110 billion in 2050. The share of fossil fuel supply in total energy sector investment drops from its 25% level in recent years to just 7% by 2050: this is partly offset by the rise in spending on low-emissions fuel supply, such as hydrogen, hydrogen-based fuels and bioenergy. Annual investment in these fuels increases to nearly USD 140 billion in 2050. Investment in transport increases significantly in the NZE from USD 150 per year in recent years to more than USD 1 100 billion in 2050: this stems mainly from the upfront cost of electric cars compared with conventional vehicles despite the decline in the cost of batteries.

By technology area, electrification is the dominant focus in the NZE. In addition to more investment in electricity generation, there is a huge increase in investment in expansion and modernisation of electricity networks. Annual investment rises from USD 260 billion on average in recent years to around USD 800 billion in 2030 and remains about that level to 2050. Such investment is needed to ensure electricity security in the face of rising electricity demand and the proportion of variable generation in the power mix. There is also a large increase in investment in the electrification of end-use sectors, which includes spending on EV batteries, heat pumps and electricity-based industrial equipment. In addition to investment in electrification, there is a moderate increase in investment in hydrogen to 2030 as production facilities are scaled up, and larger increases after as hydrogen use in transport expands: annual investment in hydrogen, including production facilities, refuelling stations and end-user equipment, reaches USD 165 billion in 2030 and over USD 470 billion in 2050. There is also an increase in global investment in CCUS (annual investment exceeds USD 160 billion by 2050 and in efficiency (around USD 640 billion annual investment by 2050, mostly for deep building retrofits and efficient appliances in the industry and buildings sectors).

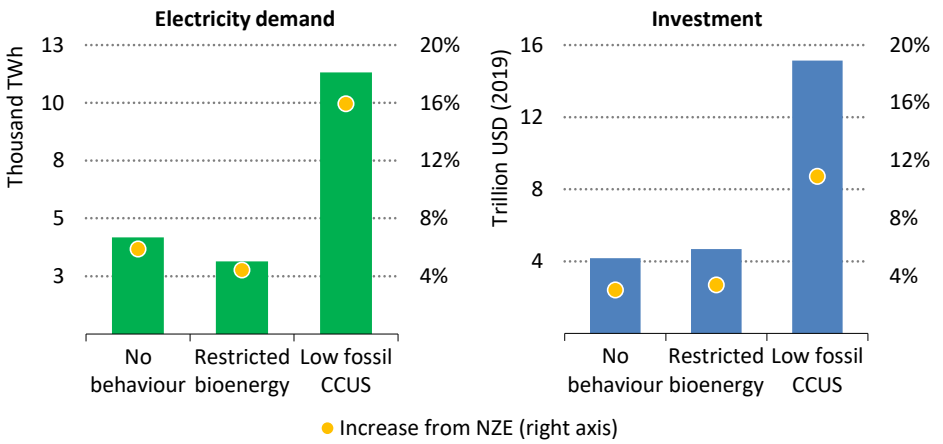
Financing the investment needed in the NZE involves redirecting existing capital towards clean energy technologies and substantially increasing the overall level of investment in energy. Most of this increase in investment comes from private sources, mobilised by public policies that create incentives, set appropriate regulatory frameworks and reform energy taxes. However, direct government financing is also needed to boost the development of new infrastructure projects and to accelerate innovation in technologies that are in the demonstration or prototype phase today. Projects in many emerging market and developing economies are often relatively reliant on public financing, and policies that ensure a predictable flow of bankable projects have an important role in boosting private investment in these economies, as does the scaling up of concessional debt financing and the use of development finance. There are extensive cross-country co-operation efforts in the NZE to facilitate the international flow of capital.

The large increase in capital investment in the NZE is partly compensated for by lower operating expenditure. Operating costs account today for a large share of the total cost of upstream fuel supply projects and fossil fuel generation projects: the clean technologies that play an increasing role in the NZE are characterised by much lower operating costs.

2.7 Key uncertainties

The road to net-zero emissions is uncertain for many reasons: we cannot be sure how underlying economic conditions will change, which policies will be most effective, how people and businesses will respond to market and policy signals, or how technologies and their costs will evolve from within or outside the energy sector. The NZE therefore is just one possible pathway to achieve net-zero emissions by 2050. Against this background, this section looks at what the implications would be if the assumptions in the NZE turn out to be off the mark with respect to behavioural change, bioenergy and CCUS for fossil fuels. These three areas were selected because the assumptions made about them involve a high degree of uncertainty and because of their critical contributions to achieve net-zero emissions by 2050.

Figure 2.23 ▷ Additional electricity demand in 2050 and additional investment between 2021-2050 for selected areas of uncertainty



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The absence of behaviour change, restrictions on bioenergy use and failure to develop fossil fuel CCUS would each raise investment to meet net-zero emissions by USD 4-15 trillion

Notes: No behaviour assumes none of the behavioural changes included in the NZE. Restricted bioenergy assumes no increase in land use for bioenergy production. Low fossil CCUS assumes no increase in fossil fuel-based CCUS apart from projects already approved or under construction.

Our analysis clearly highlights that more pessimistic assumptions would add considerably to both the costs and difficulty of achieving net-zero emissions by 2050 (Figure 2.23).

- Behavioural changes are important in reducing energy demand in transport, buildings and industry. If the changes in behaviour assumed in the NZE were not attainable, emissions would be around 2.6 Gt CO_2 higher in 2050. Avoiding these emissions through the use of additional low-carbon electricity and hydrogen would cost an additional USD 4 trillion.

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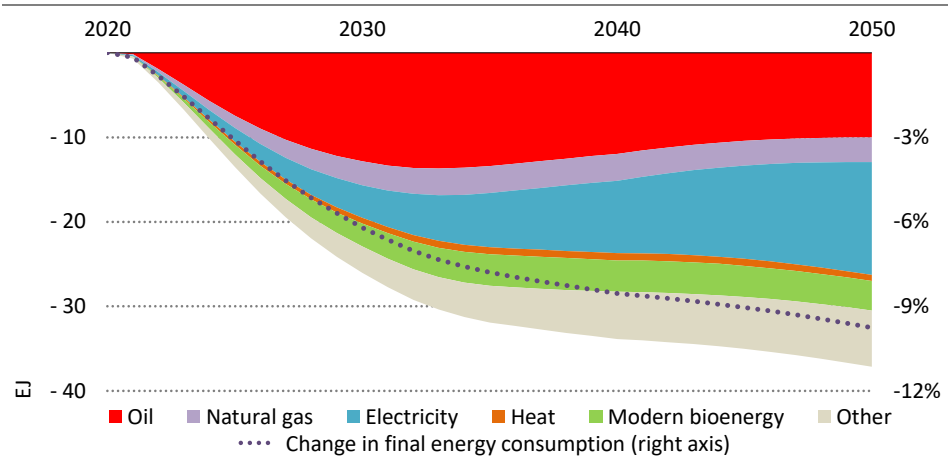
- Bioenergy use grows by 60% between 2020 and 2050 in the NZE and land use for its propagation increases by around 25%. Bioenergy use in 2050 in the NZE is well below current best estimates of global sustainable bioenergy potential, but there is a high degree of uncertainty concerning this level. If land use for bioenergy remains at today's level, bioenergy use in 2050 would be around 10% lower, and achieving net-zero emissions in 2050 would require USD 4.5 trillion extra investment.
- A failure to develop CCUS for fossil fuels would substantially increase the risk of stranded assets and would require around USD 15 trillion of additional investment in wind, solar and electrolyser capacity to achieve the same level of emissions reductions. It could also critically delay progress on BECCS and DACCS: if these cannot be deployed at scale, then achieving net-zero emissions by 2050 would be very much harder.

2.7.1 Behavioural change

Impact of behavioural changes in selected sectors in the NZE

Changes in the behaviour of energy consumers play an important role in cutting CO_2 emissions and energy demand growth in the NZE. Behavioural changes reduce global energy demand by 37 EJ in 2050, a 10% reduction in energy demand at that time, and without them cumulative emissions between 2021 and 2050 would be around 10% higher (Figure 2.24). Behavioural change plays a particularly important role in the transport sector.

Figure 2.24 ▷ Reduction in total final consumption due to behavioural changes by fuel in the NZE



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The impact of behaviour changes and materials efficiency on final energy consumption increases over time

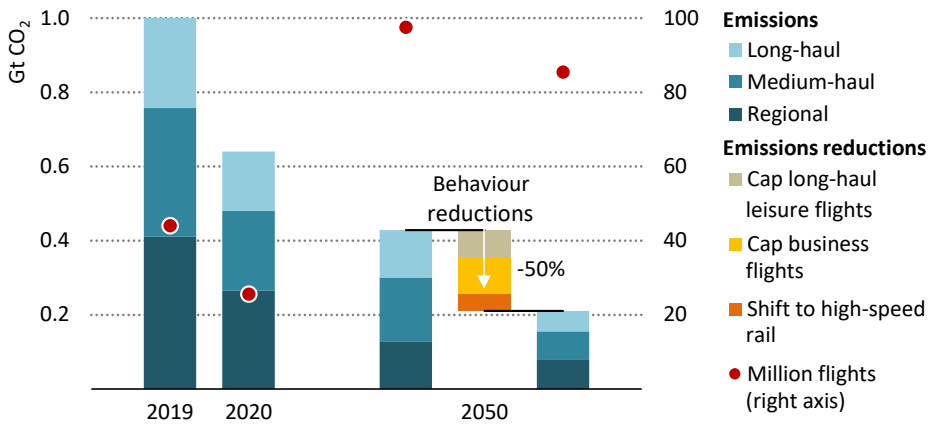
Note: Other includes coal, hydrogen, geothermal, solar thermal, synthetic oil and synthetic gas.

Passenger aviation. Demand would grow more than threefold globally between 2020 and 2050 in the absence of the assumed changes in behaviour in the NZE. About 60% of this

growth would occur in emerging market and developing economies. In the NZE, three changes lead to a 50% reduction in emissions from aviation in 2050, while reducing the number of flights by only 12% (Figure 2.25).

- Keeping air travel for business purposes at 2019 levels. Although business trips fell to almost zero in 2020, they accounted for just over one-quarter of air travel before the pandemic. This avoids around 110 Mt CO_2 in 2050 in the NZE.
- Keeping long-haul flights (more than six hours) for leisure purposes at 2019 levels. Emissions from an average long-haul flight are 35-times greater than from a regional flight (less than one hour). This affects less than 2% of flights but avoids 70 Mt CO_2 in 2050.
- A shift to high-speed rail. The opportunities for shifting regional flights to high-speed rail vary by region. Globally, we estimate that around 15% of regional flights in 2019 could have been shifted given existing rail infrastructure; future high-speed rail lines ensure that by 2050 around 17% could be shifted (IEA, 2019).[18] This would reduce emissions by around 45 Mt CO_2 in 2050 (high-speed trains generate no emissions in 2050 in the NZE).

Figure 2.25 ▷ Global CO_2 emissions from aviation and impact of behavioural changes in the NZE



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Demand for passenger aviation is set to grow significantly by 2050, but behavioural changes reduce emissions by 50% in 2050 despite reducing flights by only 12%

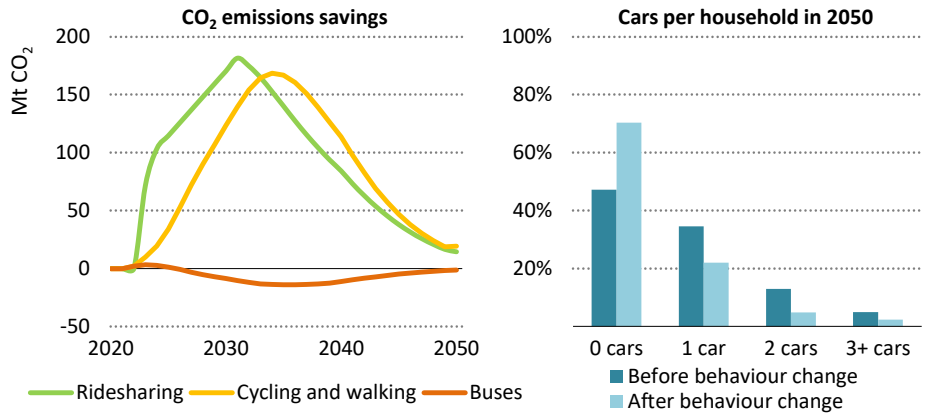
Notes: Long-haul = more than 6 hour flight; medium-haul = 1-6 hour flight; regional = less than 1 hour. Business flights = trips for work purposes; leisure flights = trips for leisure purposes. Average speeds vary by flight distance and range from 680-750 km/h.

[18] This assumes that: new rail routes avoid water bodies and tunnelling through elevated terrain; travel times are similar to aviation; and centres of demand are sufficiently large to ensure that high-speed rail is economically viable.

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Car use. A variety of new measures that aim to reduce the use of cars in cities and overall car ownership levels are assumed in the NZE. They lead to rapid growth in the rideshare market in urban areas, as well as phasing out polluting cars in large cities and replacing them with cycling, walking and public transport. The timing of these changes in the NZE depends on cities having the necessary infrastructure and public support to ensure a shift away from private car use. Between 20-50% of car trips are shifted to buses, depending on the city in question, with the remainder replaced by cycling, walking and public transport. These changes reduce emissions from cars in cities by more than 320 Mt CO_2 in total in the mid-2030s (Figure 2.26). Their impact on emissions fades over time as cars are increasingly electrified, but they still have a significant impact on curbing energy use in 2050.

Figure 2.26 ▷ Global CO_2 emissions savings and car ownership per household due to behavioural change in the NZE



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Policies discouraging car use in cities lead to rapid reductions in CO_2 emissions and lower car ownership levels, though the impact diminishes over time as cars are electrified

The gradual move away from cars in cities also has an impact on car ownership levels. Survey data indicates that car-share schemes and the provision of public transport reduces car ownership by up to 35%, with the biggest changes taking place in multiple car households (Jochem et al., 2020; Martin, Shaheen and Lidiker, 2010). Without behavioural changes, 35% of households would have a car in 2050; with behavioural changes this share falls to around 20% in the NZE, and two-car households fall from 13% of the total to less than 5%.

The changing patterns of mobility in cities in NZE have implications for materials demand. Reduced car ownership leads to a small drop in steel demand in 2050, saving around 40 Mt CO_2 in steel production. Increased cycling would need to be supported by building an estimated 80 000 km of new cycle lanes globally over the period to 2050, generating increased demand for cement and bitumen. This effect is small, however: the extra emissions associated with this would be less than 5% of the emissions avoided by lower car use.

How to bring about the behavioural changes in NZE

Regulations and mandates could enable roughly 70% of the emissions saved by behavioural changes in the NZE. Examples include:

- Upper speed limits, which are reduced over time in the NZE from their current levels to 100 km/h, cutting emissions from road vehicles by 3% in 2050.
- Appliance standards, which maximise energy efficiency in the buildings sector.
- Regulations covering heating temperatures in offices and default cooling temperatures for air conditioning units, which reduce excessive thermal demand.
- Changes initially tackled by market-based mechanisms, e.g. swapping regional flights for high-speed rail,[19] which can be addressed by regulation over time to mirror changes in public sentiment and consumer norms.

Market-based instruments use a mix of financial incentives and disincentives to influence decision making. They could enable around two-thirds of the emissions saved by behavioural changes in the NZE. Examples include:

- Congestion pricing and targeted interventions differentiated by vehicle type,[20] such as charges aimed at the most polluting vehicles, or preferential parking for clean cars.
- Transport demand measures that reduce travel, such as fuel taxes and distance-based vehicle insurance and registration fees (Byars, Wei and Handy, 2017).
- Information measures that help consumers to drive change, such as mandatory labelling of embodied or lifecycle emissions in manufacturing and a requirement for companies to disclose their carbon emissions.

Information and awareness measures could enable around 30% of the emissions saved by behavioural changes in the NZE. Examples include:

- Personalised and real-time travel planning information, which facilitates a switch to walking, cycling and public transport.
- Product labelling and public awareness campaigns in combination, which help make recycling widespread and habitual.
- Comparisons with consumption patterns of similar households, which can reduce wasteful energy use by up to 20% (Aydin, Brounen and Kok, 2018).

Not all the behavioural changes in the NZE would be equally easy to achieve everywhere, and policy interventions would need to draw on insights from behavioural science and take into account existing behavioural norms and cultural preferences. Some behavioural changes may be more socially acceptable than others. Citizen assemblies in the United Kingdom and

[19] A law banning domestic flights where a rail alternative of under two-and-a-half hours exists has been proposed in France (Assemblee Nationale, 2021).

[20] Congestion charging is currently used in 11 major cities and has been shown to reduce traffic volumes by up to 27%. Low-emissions zones charge vehicles to enter urban zones based vehicle type and currently exist in 15 countries (TFL, 2021; Tools of Change, 2014; European Commission, 2021).

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France indicate a large level of support for taxes on frequent and long-distance flyers and for banning polluting vehicles from city centres; conversely, measures that limit car ownership or reduce speed limits have gained less acceptance (Convention Citoyenne pour le Climat, 2021; Climate Assembly UK, 2020). Behavioural changes which reduce energy use in homes may be particularly well supported: a recent survey showed 85% support for line-drying clothes and switching off appliances, and only 20% of people felt that reducing temperature settings in homes was undesirable (Newgate Research and Cambridge Zero, 2021).

Table 2.10 ▷ Key behavioural changes in the NZE

	Policy options	Related policy-goals	Cost-effectiveness	Timeliness	Social acceptability	CO_2 emissions impact
Low-car cities • Phase out ICE cars from large cities. • Rideshare all urban car trips.	• Low-emissions zones. • Access restrictions. • Parking restrictions. • Registration caps. • Parking pricing. • Congestion charges. • Investment in cycling lanes and public transportation.	• Air pollution mitigation. • Public health. • Reduced congestion. • Urban space. • Beautification and liveability.	🟡	🟡	🟡	🟢
Fuel-efficient driving • Reduce motorway speeds to less than 100 km/h. • Eco-driving. • Raise air conditioning temperature in cars by 3 °C.	• Speed limits. • Real-time fuel efficiency displays. • Awareness campaigns.	• Road safety. • Reduced noise pollution.	🟢	🟢	🟡	🟢
Reduce regional flights • Replace all flights <1h where high-speed rail is a feasible alternative.	• High-speed rail investment. • Subsidies for high-speed rail travel. • Price premiums.	• Lower air pollution. • Lower noise pollution.	🔴	🔴	🟡	🟡
Reduce international flights • Keep air travel for business purposes at 2019 levels. • Keep long-haul flights for leisure at 2019 levels.	• Awareness campaigns. • Price premiums. • Corporate targets. • Frequent-flyer levies.	• Lower air pollution. • Lower noise pollution.	🟢	🟢	🟡	🟢
Space heating • Target average set-point temperatures of 19-20 °C.	• Awareness campaigns. • Consumption feedback. • Corporate targets.	• Public health. • Energy affordability.	🟢	🟢	🟢	🟢
Space cooling • Target average set-point temperatures of 24-25 °C.	• Awareness campaigns. • Consumption feedback. • Corporate targets.	• Public health. • Energy affordability.	🟢	🟢	🟢	🔴

🔴 = poor match 🟡 = neutral match 🟢 = good match

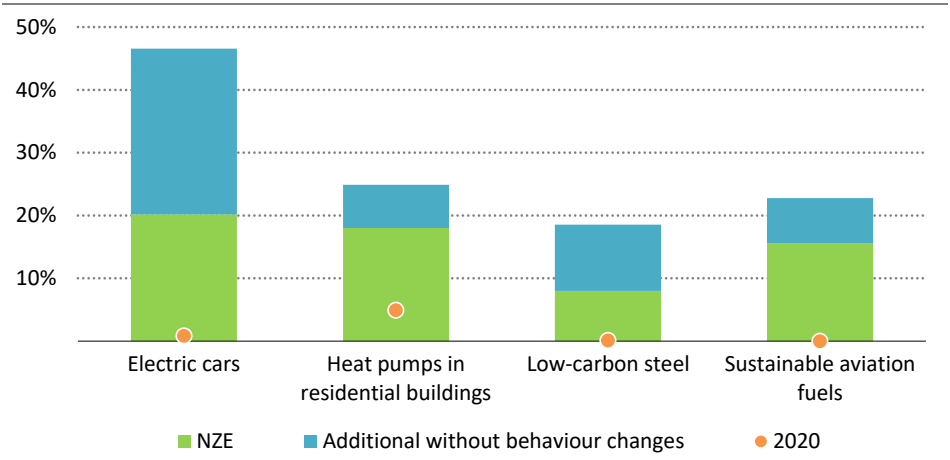
Notes: Large cities = cities over 1 million inhabitants. ICE = internal combustion engine. CO_2 emissions impact = cumulative reductions 2020-2050. Eco-driving = early upshifting as well as avoiding sudden acceleration, stops or idling. The number of jobs that can be done at home varies considerably by region, globally, an average of 20% of jobs can be done at home.

The behavioural changes in the NZE would bring wider benefits in terms of air pollution in cities, road safety, noise pollution, congestion and health. Attitudes to policy interventions can change quickly when co-benefits become apparent. For example, support for congestion charging in Stockholm jumped from less than 40% when the scheme was introduced to around 70% three years later; a similar trend was seen in Singapore, London and other cities, all of which experienced declines in air pollution after the introduction of charging (Tools of Change, 2014; DEFRA, 2012).

Are net-zero emissions by 2050 still possible without behavioural change?

If the behavioural changes described in the NZE were not to materialise, final energy use would be 27 EJ and emissions 1.7 Gt CO_2 higher in 2030, and they would be 37 EJ and 2.6 Gt CO_2 higher in 2050. This would further increase the already unprecedented ramp-up needed in low-carbon technologies. The share of EVs in the global car fleet would need to increase from around 20% in 2030 to 45% to ensure the same level of emissions reductions (Figure 2.27). Achieving the same reduction in emissions in homes would require electric heat pumps sales to reach 680 million in 2030 (compared with 440 million in the NZE). Without gains in materials efficiency, the share of low-carbon primary steel production would need to be more than twice as high in 2030 as in the NZE. In 2050, the use of sustainable aviation fuels would also need to rise to 7 mboe/d (compared with 5 mboe/d in the NZE). Emissions from cement and steel production would be 1.7 Gt CO_2 higher in 2050 than in the NZE, and so require increased deployment of CCUS in industry, deployment of electric arc furnaces and more use of low-carbon hydrogen.

Figure 2.27 ▷ Share of low-carbon technologies and fuels with and without behavioural change in 2030 in the NZE



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In the absence of behavioural changes, the share of low-emissions technologies in end-uses in 2030 would need to be much larger to achieve the same emissions as in the NZE

Notes: Electric cars = share of electric cars on the road globally. Sustainable aviation fuels = biojet kerosene and synthetic jet kerosene. Low-carbon steel refers to primary steel production.

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2.7.2 Bioenergy and land-use change

Modern forms of bioenergy play a key role in achieving net-zero emissions in the NZE. Bioenergy is a versatile renewable energy source that can be used in all sectors, and it can often make use of existing transmission and distribution infrastructure and end-user equipment. But there are constraints on expanding the supply of bioenergy: with finite potential for bioenergy production from waste streams, there are possible trade-offs between expanding bioenergy production, achieving sustainable development goals and avoiding conflicts with other land uses, notably food production.

The level of bioenergy use in the NZE takes account of these constraints: bioenergy demand in 2050 is around 100 EJ. The global sustainable bioenergy potential in 2050 has been assessed to be at least 100 EJ (Creutzig, 2015) and recent assessments estimate a potential between 150-170 EJ when integrating relevant UN Sustainable Development Goals (Frank, 2021; IPCC, 2019; IPCC, 2014; Wu, 2019). However, there is a high degree of uncertainty over the precise levels of this potential. Using modelling developed in co-operation with IIASA, here we examine the implications for achieving net-zero CO_2 emissions by 2050 if the available levels of sustainable bioenergy were to be lower. We also examine what would need to be done to achieve large reductions in emissions from agriculture, forestry and other land use (AFOLU).

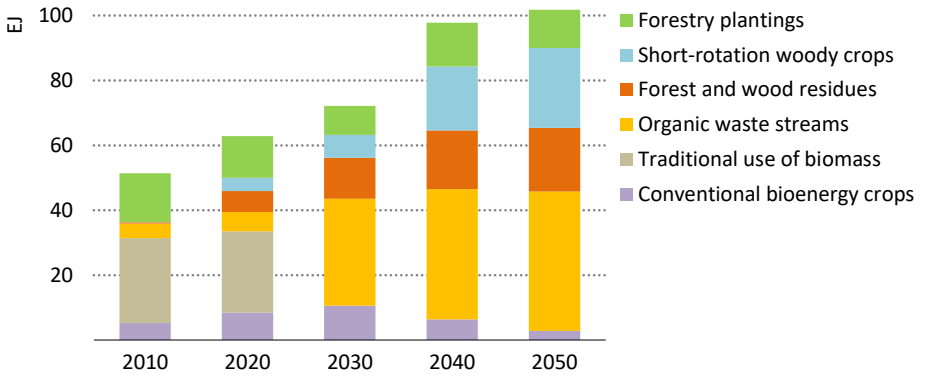
Ensuring a sustainable supply of bioenergy

Most liquid biofuels produced today come from dedicated bioenergy crops such as sugarcane, corn or oil crops, often known as conventional biofuels. The expanded use of feedstocks and arable land to produce these biofuels can conflict with food production. In the NZE, there is a shift towards the use of sustainable, certified agricultural products and wood. Biofuel production processes in the NZE use advanced conversion technologies coupled with CCUS where possible (see section 3.3.2). The emphasis is also on advanced bioenergy feedstocks, including waste streams from other processes, short-rotation woody crops and feedstocks that do not require the use of arable land. Advanced bioenergy accounts for the vast majority of bioenergy supply in the NZE by 2050. The use of conventional energy crops for biofuel production grows from around 9 EJ in 2020 to around 11 EJ in 2030, but then falls by 70% to 3 EJ in 2050 (including feedstocks consumed in the biofuel production processes).

Advanced bioenergy feedstocks that do not require land include organic waste streams from agriculture and industry, and woody residues from forest harvesting and wood processing. Investment in comprehensive waste collection and sorting in the NZE unlocks around 45 EJ of bioenergy supply from various organic waste streams which is primarily used to produce biogases and advanced biofuels (Figure 2.28). Woody residues from wood processing and forest harvesting provide a further 20 EJ of bioenergy in 2050 in the NZE – less than half of current best estimates of the total sustainable potential. Bioenergy can also be produced

from dedicated short-rotation woody crops (25 EJ of bioenergy supply in 2050).[21] Sustainably managed forestry fuelwood or plantations[22] and tree plantings integrated with agricultural production via agroforestry systems that do not conflict with food production or biodiversity provide just over 10 EJ of bioenergy in 2050.

Figure 2.28 ▷ Global bioenergy supply by source in the NZE



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Bioenergy use increases by around 60% between 2020 and 2050, while shifting away from conventional feedstocks and the traditional use of biomass

Note: Organic waste streams include agricultural residues, food processing, industrial and municipal organic waste streams; they do not require land area.

Source: IEA analysis based on IIASA data.

The total land area dedicated to bioenergy production in the NZE increases from 330 million hectares (Mha) in 2020 to 410 Mha in 2050. In 2050, around 270 Mha is forest, representing around one-quarter of the total area of global managed forests, and around 5% of total forest area. There is 130 Mha of land used for short-rotation advanced bioenergy crops in 2050 and 10 Mha for conventional bioenergy crops. There is no overall increase in cropland use for bioenergy production in the NZE from today's level and no bioenergy crops are developed on forested land in the NZE.[23] As well as allowing a much greater level of bioenergy crop production on marginal lands, woody energy crops can produce twice as much bioenergy per hectare as conventional bioenergy crops.

[21] Woody short-rotation coppice crops grown on crop land, pasture land or marginal lands not suited to food crops.

[22] Sustainable forestry management ensures that the carbon stock and carbon absorption capability of the forest is expanded or remains unchanged.

[23] Of the 140 Mha land used for bioenergy crops in 2050, 70 Mha are marginal lands or land currently used for livestock grazing and 70 Mha are cropland. There is a 60 Mha increase in cropland use for woody crops to 2050 in the NZE but this is offset by a reduction in cropland use for producing conventional biofuel feedstocks.

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Total land use for bioenergy in the NZE is well below estimated ranges of potential land availability that take full account of sustainability constraints, including the need to protect biodiversity hotspots and to meet the UN Sustainable Development Goal 15 on biodiversity and land use. The certification of bioenergy products and strict control of what land can be converted to expand forestry plantations and woody energy crops nevertheless is critical to avoid land-use conflict issues. Certification is also critical to ensure the integrity of CO_2 offsets (see Chapter 1), the use of which should be carefully managed and restricted to sectors that lack alternative mitigation options. A related land-use issue is how to tackle emissions that arise from outside the energy sector (Box 2.3).

Box 2.3 ▻ Balancing emissions from land use, agriculture and forestry

To limit the global temperature rise, all sources of GHG emissions need to decline to close to zero or to be offset with CDR. The energy sector accounted for around three quarters of total GHG emissions in recent years. The largest source of GHG emissions other than the energy sector is agriculture, forestry and other land use (AFOLU), which produced between 10-12 Gt CO_2-eq net GHG emissions in recent years.[24] CO_2 emissions from AFOLU were around 5-6 Gt CO_2, and nitrous oxide and methane emissions were around 5-6 Gt CO_2-eq (IPCC, 2019).

Options to reduce emissions from AFOLU and enhance removals include: halting deforestation; improving forest management practices; instituting farming practices that increase soil carbon levels; and afforestation. A number of companies have recently expressed interest in these sorts of nature-based solutions to offset emissions from their operations (see Chapter 1). For afforestation, converting around 170 Mha (roughly half the size of India) to forests would sequester around 1 Gt CO_2 annually by 2050.

Achieving net-zero energy-related and industrial process CO_2 emissions by 2050 in the NZE does not rely on any offsets from outside the energy sector. But commensurate action on AFOLU would help limit climate change. The energy-sector transformation in the NZE would reduce CO_2 emissions from AFLOU in 2050 by around 150 Mt CO_2 given the switch away from conventional crops and the increase in short rotation advanced-bioenergy crop production on marginal lands and pasture land. To reduce emissions from AFOLU further would require reducing deforestation by two-thirds by 2050, instituting improved forest management practices and planting around 250 Mha of new forests. The combined impact of these changes would reduce CO_2 emissions from AFOLU to zero by 2040 and absorb 1.3 Gt CO_2 annually by 2050. In this case, cumulative AFOLU CO_2 emissions between 2020 and 2050 would be around 40 Gt CO_2.

Non-CO_2 emissions from livestock, as well as other agricultural emissions, may be more difficult to mitigate given the link between livestock production and nitrous oxide and methane emissions. Changes to farming practices and technology improvements,

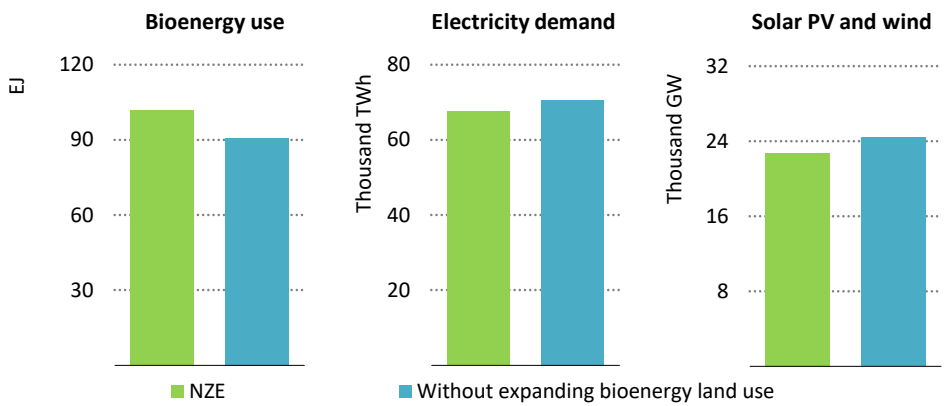
[24] AFOLU emissions are emissions from anthropogenic activities and do not include CO_2 emissions removal from the atmosphere by natural land sinks.

including changes to animal feed, could help to reduce these emissions, but it may be necessary to use afforestation to offset these emissions entirely. An alternative could be to reduce these emissions by reducing the demand for livestock products. For example, we estimate that reducing meat consumption in households with the highest levels of per capita consumption today to the global average level would reduce GHG emissions by more than 1 Gt CO_2-eq in 2050. Lower demand for livestock products would reduce the pasture needed globally for livestock by close to 200 Mha and the cropland that is used to grow feed for livestock by a further 80 Mha.

Are net-zero emissions by 2050 possible without expanding land use for bioenergy?

Estimates of the global sustainable bioenergy potential are subject to a high degree of uncertainty, in particular over the extent to which new land area could sustainably be converted to bioenergy production. As a result, the NZE takes a cautious approach to bioenergy use, with consumption in 2050 (100 EJ) well below the latest estimates that integrate relevant SDGs, which suggest a potential between 150-170 EJ. But it is possible that the land available to provide sustainable bioenergy is even more limited. Here we explore the implications for emissions of restricting land use for dedicated bioenergy crops and forestry plantations to around 330 Mha, which is what is used today.

Figure 2.29 ▷ Impact on electricity demand and ability to achieve net-zero emissions by 2050 without expanded bioenergy land use



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Achieving net-zero emissions without expanding bioenergy land use would require a further 3 200 TWh from solar PV and wind, increasing capacity in the NZE by nearly 10%

Limiting land use to 330 Mha would reduce available bioenergy supply in 2050 by more than 10 EJ. This would mostly take the form of a reduction in the availability of short-rotation woody energy crops, which are mainly used in the NZE in place of fossil fuels to provide high temperature heat for industrial processes and for electricity generation. Without bioenergy,

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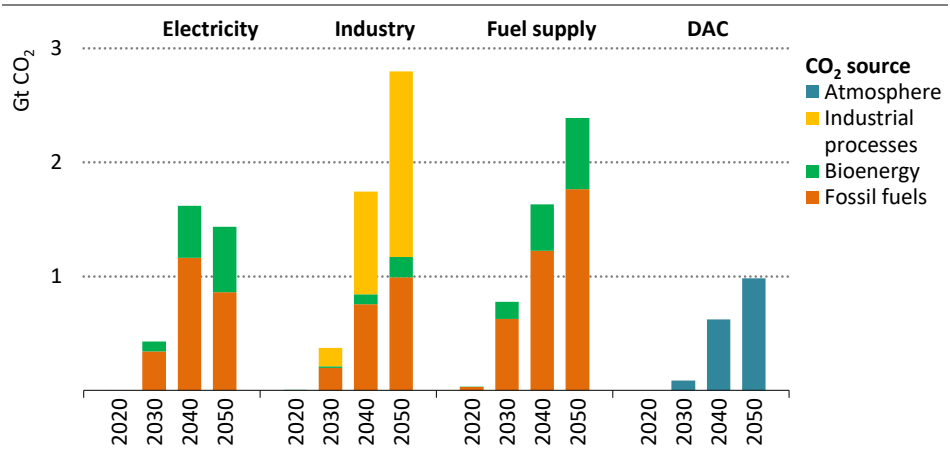
it is likely that hydrogen and synthetic methane would be used instead, and their production would require around 70 Mt of hydrogen in 2050 (15% more than in the NZE). If this were to be produced through the use of electrolysis it would require around 750 GW of electrolyser capacity and increase electricity demand in 2050 by around 3 200 TWh (Figure 2.29).

The additional electricity that would be needed could be produced using renewables, which would require an additional 1 700 GW of wind and solar PV capacity and almost 350 GW of additional battery capacity in 2050. Annual capacity additions during the 2030s would need to be 160 GW higher than in the NZE. The additional wind, solar, battery and electrolyser capacity, together with the electricity networks and storage needed to support this higher level of deployment would cost more than USD 5 trillion by 2050. This is USD 4.5 trillion more than would be needed if the use of bioenergy were to be expanded as envisaged in the NZE, and would increase the total investment needed in the NZE by 3%. While it might therefore be possible still to achieve net-zero emissions in 2050 without expanding land use for bioenergy, this would make the energy transition significantly more expensive.

2.7.3 CCUS applied to emissions from fossil fuels

A total of 7.6 Gt CO_2 is captured in 2050 in the NZE, almost 50% of which is from fossil fuel combustion, 20% is from industrial processes, and around 30% is from bioenergy use with CO_2 capture and DAC (Figure 2.30). The use of CCUS with fossil fuels provides almost 70% of the total growth in CCUS to 2030 in the NZE. Yet the prospects for the rapid scaling up of CCUS are very uncertain for economic, political and technical reasons. Here we look at the implications for reaching net-zero emissions in 2050 if fossil fuel CCUS does not expand beyond existing and planned projects.

Figure 2.30 ▷ CCUS by sector and emissions source in the NZE



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Fossil fuel emissions account for almost 70% of total CO_2 capture in 2030 and almost 50% in 2050

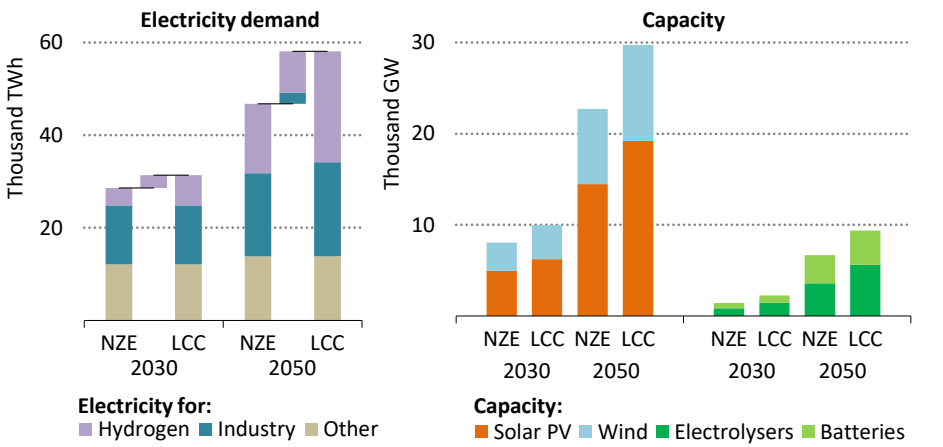
Note: DAC = direct air capture.

Are net-zero emissions by 2050 possible without fossil fuel-based CCUS?

Fossil fuel-based CCUS applications comprise most of the CCUS projects added to 2030 in the NZE. These projects help to reduce risks for other non-fossil fuel CCUS applications that are essential to reach net zero. In view of the challenges that fossil fuel-based CCUS projects face, we have constructed a *Low CCUS Case (LCC)* in which no new fossil fuel CCUS projects are developed beyond those already under construction or approved for development. In the LCC, CO_2 emissions captured from fossil fuels are only around 150 Mt in 2050, compared with 3 600 Mt in 2050 in the NZE.

In industry, the lack of new fossil fuel CCUS projects leads in the LCC to 1.2 Gt of additional CO_2 emissions compared with the NZE in 2050. It would be necessary to use alternative technologies to eliminate these emissions in order to achieve net zero by 2050. A number of technologies that are at the prototype stage of development would be needed, such as electric cement kilns or electric steam crackers for high-value chemicals production (see Box 2.4). Assuming that these technologies could be demonstrated and deployed at scale, this would increase electricity demand by around 2 400 TWh and hydrogen demand in industry by around 45 Mt in 2050. It would also be necessary to replace the 145 Mt of hydrogen that is produced in the NZE from fossil fuels equipped with CCUS. Provision of this 190 Mt of hydrogen through electrolysis would require an additional 2 000 GW capacity of electrolysers in 2050 (almost 60% more than in the NZE) and an additional 9 000 TWh of electricity (Figure 2.31).

Figure 2.31 ▷ Impacts of achieving net-zero emissions by 2050 without expanded fossil fuel-based CCUS



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Failure to deploy fossil fuel-based CCUS would significantly increase electricity demand and require much more solar, wind and electrolyser capacity

Note: LCC = Low CCUS Case where CCUS applied to fossil fuels is restricted to projects under construction or approved for development today.

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Box 2.4 ▷ Technology innovation in the NZE

Innovation is key to developing new clean energy technologies and advancing existing ones. The importance of innovation increases as we get closer to 2050 because existing technologies will not be able to get us all the way along the path to net-zero emissions. Almost 50% of the emissions reductions needed in 2050 in the NZE depend on technologies that are at the prototype or demonstration stage, i.e. are not yet available on the market (see Chapter 4).

After a new idea makes its way from the drawing board to the laboratory and out into the world, there are four key stages in the clean energy innovation pipeline (IEA, 2020d). But the pathway to maturity can be long and success is not guaranteed.

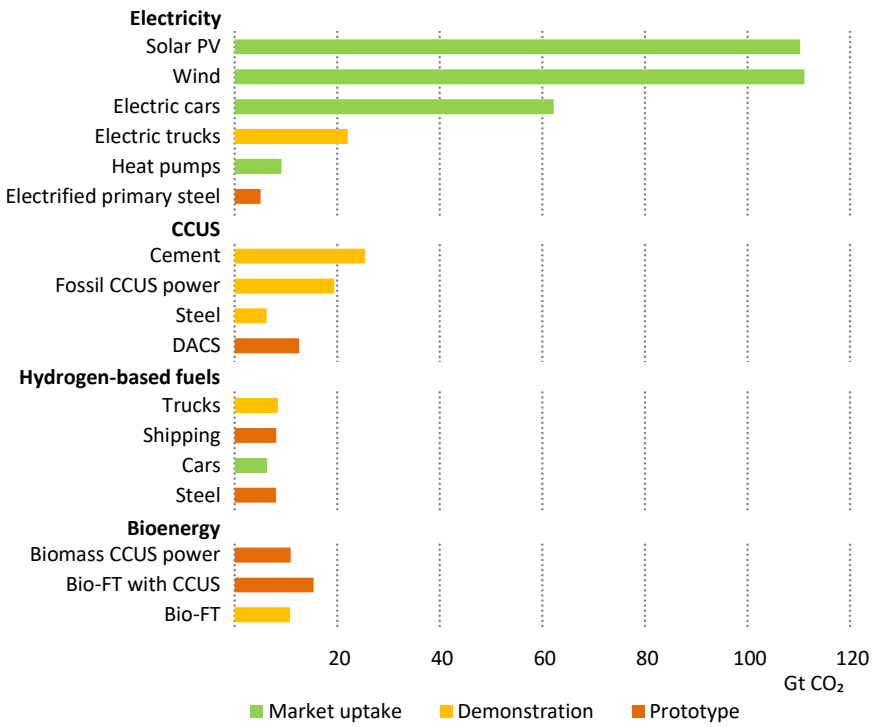
- **Prototype.** A concept is developed into a design and then into a prototype for a new device, e.g. a furnace that produces steel with pure hydrogen instead of coal.
- **Demonstration.** The first examples of a new technology are introduced at the size of a full-scale commercial unit, e.g. a system that captures CO_2 emissions from cement plants.
- **Market uptake.** The technology is being deployed in a number of markets. However, it either has a cost and performance gap with established technologies (e.g. electrolysers for hydrogen production) or it is competitive but there are still barriers, such as integration with existing infrastructure or consumer preferences, to reaching its full market potential (e.g. heat pumps). Policy attention is needed in both cases to stimulate wider diffusion to reduce costs and to overcome existing barriers, with more of the costs and risks being borne gradually by the private sector.
- **Maturity.** The technology has reached market stability, and new purchases or installations are constant or even declining in some environments as newer technologies start to compete with the stock of existing assets, e.g. hydropower turbines.

Innovation is critical in the NZE to bring new technologies to market and to improve emerging technologies, including for electrification, CCUS, hydrogen and sustainable bioenergy. The degree of reliance on innovation in the NZE varies across sectors and along the various steps of the value chains involved (Figure 2.32).

- **Electrification.** Almost 30% of the 170 Gt CO_2 cumulative emissions reductions from the use of low-emissions electricity in the NZE comes from technologies that are currently at prototype or demonstration stage, such as electricity-based primary steel production or electric trucks.
- **Hydrogen.** Not all steps of the low-carbon hydrogen value chain are available on the market today. The majority of demand technologies, such as hydrogen-based steel production, are only at the demonstration or prototype stage. These deliver more than 75% of the cumulative emissions reductions in the NZE related to hydrogen.

- **CCUS.** Around 55% of the cumulative emissions reductions that come from CCUS in the NZE are from technologies that are at the demonstration or prototype stage today. While CO_2 capture has been in use for decades in certain industrial and fuel transformation processes, such as ammonia production and natural gas processing, it is still being demonstrated at a large scale in many of the other possible applications.
- **Bioenergy.** Around 45% of the cumulative emissions reductions in the NZE related to sustainable bioenergy come from technologies that are at the demonstration or prototype stage today, mainly for the production of biofuels.

Figure 2.32 ▷ Cumulative CO_2 emissions reductions for selected technologies by maturity category in the NZE



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CCUS, hydrogen and bioenergy technologies are less mature than electrification. Most technologies for heavy industry and trucks are at early stages of development.

Notes: Bio-FT = Biomass gasification with Fischer-Tropsch synthesis. Maturity levels are the technology design at the most advanced stage.

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In the electricity sector, it would be necessary to produce an additional 11 300 TWh of electricity for industry and fuel transformation and to replace virtually all of the electricity generated from fossil fuel powered plants equipped with CCUS in 2050 in the NZE. Using renewables, this would require an additional 7 000 GW of wind and solar PV capacity in 2050. This is around 30% more than in the NZE, and would mean that annual capacity additions of solar PV and wind during the 2030s would need to reach 1 300 GW (300 GW more than in the NZE). To accommodate this additional level of variable renewables and to provide the flexibility that is available from fossil fuel CCUS equipped plants in the NZE, around 660 GW more battery capacity would be needed in 2050 (20% more than in the NZE in in 2050), together with additional 110 GW of other dispatchable capacity.

Reducing the rate of adding CCUS at existing coal- and gas-fired generation plants in the LCC would also raise the risk of stranded assets. We estimate that up to USD 90 billion of existing coal- and gas-fired capacity could be stranded in 2030 and up to USD 400 billion by 2050. Investment in fossil fuel-based CCUS in the NZE to 2050 is around USD 650 billion, which would be avoided in the LCC. But additional investment is required in the LCC for extra wind, solar and electrolyser capacity, for electricity-based routes in heavy industry, and for expanded electricity networks and storage to support this higher level of deployment. As a result, the additional cumulative investment to reach net-zero emissions in 2050 in the LCC is USD 15 trillion higher than in the NZE.

Failure to develop CCUS for fossil fuels would also be likely to delay or prevent the development of other CCUS applications. Without fossil fuel-based CCUS, the number of users and the volumes of the CO_2 transport and storage infrastructure deployed around industrial clusters would be reduced. Fewer actors and more limited pools of capital would be available to incur the high upfront costs of infrastructure, as well as other risks associated with the initial roll-out of CCUS infrastructure clusters. In addition, there would be fewer spill-over learning and cost-reduction benefits from developing fossil fuel-based CCUS, making the successful demonstration and scale up of more nascent CCUS technologies much less likely. A delay in the development of other CCUS technologies would have a major impact on the prospect of getting to net-zero emissions in 2050. For example, CCUS is the only scalable low-emissions option to remove CO_2 from the atmosphere and to almost eliminate emissions from cement production. If progress in these technologies were delayed and could not be deployed at scale, then achieving net-zero emissions by 2050 would be vastly more difficult.

Sectoral pathways to net-zero emissions by 2050

SUMMARY

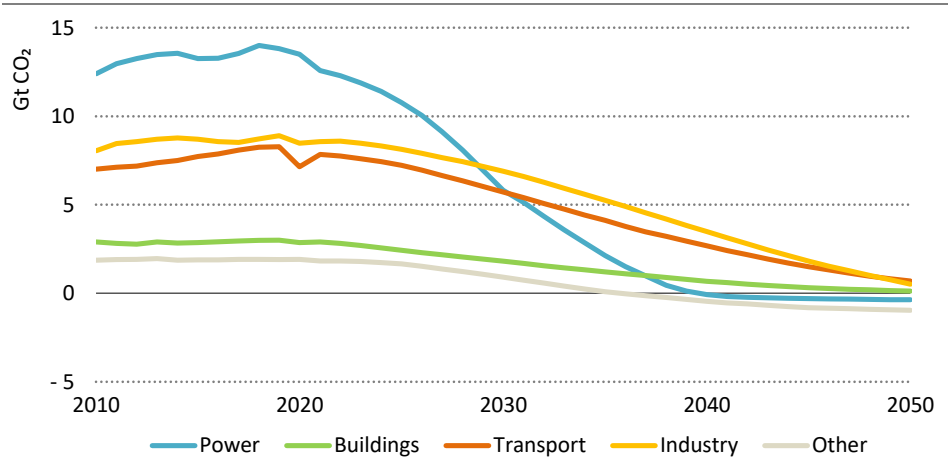
- Fossil fuel use falls drastically in the Net-Zero Emissions Scenario (NZE) by 2050, and no new oil and natural gas fields are required beyond those that have already been approved for development. No new coal mines or mine extensions are required. Low-emissions fuels – biogases, hydrogen and hydrogen-based fuels – see rapid growth. They account for almost 20% of global final energy in 2050, compared with 1% in 2020. More than 500 Mt of low-carbon hydrogen is produced in 2050, of which about 60% is produced using electrolysis that accounts for 20% of global electricity generation in 2050. Liquid biofuels provide 45% of global aviation fuel in 2050.
- Electricity demand grows rapidly in the NZE, rising 40% from today to 2030 and more than two-and-a-half-times to 2050, while emissions from generation fall to net-zero in aggregate in advanced economies by 2035 and globally by 2040. Renewables drive the transformation, up from 29% of generation in 2020 to 60% in 2030 and nearly 90% in 2050. From 2030 to 2050, 600 GW of solar PV and 340 GW of wind are added each year. The least-efficient coal plants are phased out by 2030 and all unabated coal by 2040. Investment in electricity grids triples to 2030 and remains elevated to 2050.
- In industry**,** emissions drop by 20% to 2030 and 90% to 2050. Around 60% of heavy industry emissions reductions in 2050 in the NZE come from technologies that are not ready for market today: many of these use hydrogen or CCUS. From 2030, all new industry capacity additions are near-zero emissions. Each month from 2030, the world equips 10 new and existing heavy industry plants with CCUS, adds 3 new hydrogen-based industrial plants and adds 2 GW of electrolyser capacity at industrial sites.
- In transport, emissions drop by 20% to 2030 and 90% to 2050. The initial focus is on increasing the operational and technical efficiency of transport systems, modal shifts, and the electrification of road transport. By 2030, electric cars account for over 60% of car sales (4.6% in 2020) and fuel cell or electric vehicles are 30% of heavy truck sales (less than 0.1% in 2020). By 2035, nearly all cars sold globally are electric, and by 2050 nearly all heavy trucks sold are fuel cell or electric. Low-emissions fuels and behavioural changes help to reduce emissions in long-distance transport, but aviation and shipping remain challenging and account for 330 Mt CO_2 emissions in 2050.
- In buildings**,** emissions drop by 40% to 2030 and more than 95% to 2050. By 2030, around 20% of the existing building stock worldwide is retrofitted and all new buildings comply with zero-carbon-ready building standards. Over 80% of the appliances sold are the most efficient models available by 2025 in advanced economies and by the mid-2030s worldwide. There are no new fossil fuel boilers sold from 2025, except where they are compatible with hydrogen, and sales of heat pumps soar. By 2050, electricity provides 66% of energy use in buildings (33% in 2020). Natural gas use for heating drops by 98% in the period to 2050.

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3.1 Introduction

The Net-Zero Emissions by 2050 Scenario (NZE) involves a global energy system transformation that is unparalleled in its speed and scope. This chapter looks at how the main sectors are transformed, as well as the specific challenges and opportunities this involves (Figure 3.1). It covers the supply of fossil and low-emissions fuels, electricity generation and the three main end-use sectors – industry, transport and buildings. For each sector, we set out some key technology and infrastructure milestones on which the NZE depends for its successful delivery. Further we discuss what key policy decisions are needed, and by when, to achieve these milestones. Recognising that there is no single pathway to achieve net-zero emissions by 2050 and that there are many uncertainties related to clean energy transitions, in this chapter we also explore the implications of choosing not to rely on certain fuels, technologies or emissions reduction options across the transformation and end-use sectors.

Figure 3.1 ▷ CO_2 emissions by sector in the NZE



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Emissions fall fastest in the power sector, with transport, buildings and industry seeing steady declines to 2050. Reductions are aided by the increased availability of low-emissions fuels

Note: Other = agriculture, fuel production, transformation and related process emissions, and direct air capture.

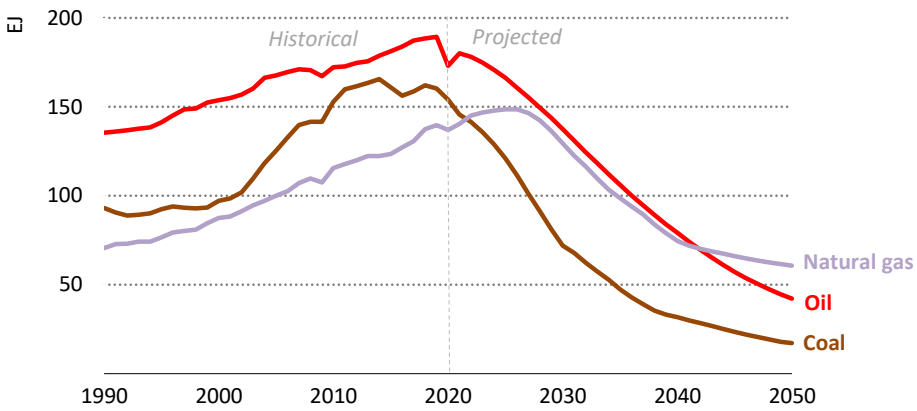
3.2 Fossil fuel supply

3.2.1 Energy trends in the Net-Zero Emissions Scenario

Coal use declines from 5 250 million tonnes of coal equivalent (Mtce) in 2020 to 2 500 Mtce in 2030 and to less than 600 Mtce in 2050. Even with increasing deployment of carbon capture, utilisation and storage (CCUS), coal use in 2050 is 90% lower than in 2020

(Figure 3.2). Oil demand never returns to its 2019 peak and it declines from 88 million barrels per day (mb/d) in 2020 to 72 mb/d in 2030 and to 24 mb/d in 2050, a fall of almost 75% between 2020 and 2050. Natural gas quickly rebounds from the dip in demand in 2020 and rises through to the mid-2020s, reaching a peak of around 4 300 billion cubic metres (bcm), before dropping to 3 700 bcm in 2030 and to 1 750 bcm in 2050. By 2050, natural gas use is 55% lower than in 2020.

Figure 3.2 ▷ Coal, oil and natural gas production in the NZE



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Between 2020 and 2050, demand for coal falls by 90%, oil by 75%, and natural gas by 55%

Oil

The trajectory of oil demand in the NZE means that no exploration for new resources is required and, other than fields already approved for development, no new oil fields are necessary. However, continued investment in existing sources of oil production are needed. On average oil demand in the NZE falls by more than 4% per year between 2020 and 2050. If all capital investment in producing oil fields were to cease immediately, this would lead to a loss of over 8% of supply each year. If investment were to continue in producing fields but no new fields were developed, then the average annual loss of supply would be around 4.5% (Figure 3.3). The difference is made up by fields that are already approved for development.

These dynamics are reflected in the oil price in the NZE, which drops to around USD 35/barrel in 2030 and USD 25/barrel in 2050. This price trajectory is largely determined by the operating costs for fields currently in operation, and only a very small volume of existing production would need to be shut in. However, income from oil production in all countries is much lower in the NZE than in recent years,[1] and the NZE projects significant stranded

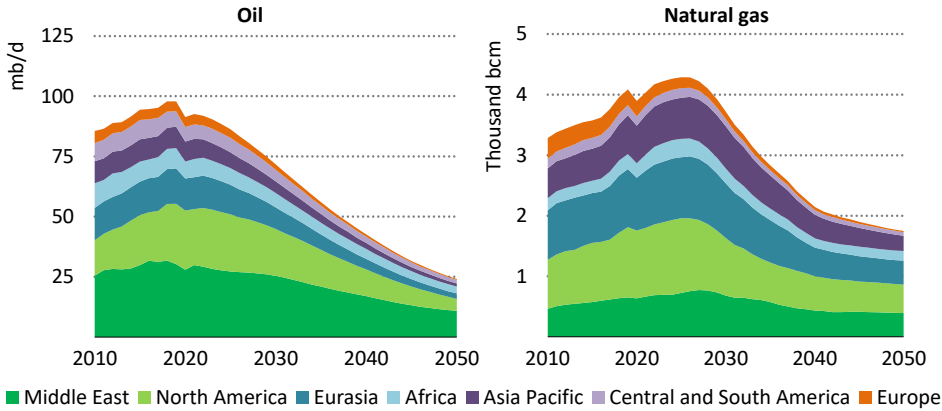
[1] Governments may also reduce or eliminate upstream taxes to ensure that production costs are below the oil price to maintain domestic production.

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capital and stranded value.[2] The oil price in the NZE would be sufficient in principle to cover the cost of developing new fields for the lowest cost producers, including those in the Middle East, but it is assumed that major resource holders do not proceed with investment in new fields because doing so would create significant additional downward pressure on prices.

The refining sector also faces major challenges in the NZE. Refinery throughput drops considerably and there are significant changes in product demand. With rapid electrification of the vehicle fleet, there is a major drop in demand for traditional refined products such as gasoline and diesel, while demand for non-combusted products such as petrochemicals increases. In recent years, around 55% of oil demand was for gasoline and diesel, but this drops to less than 15% in 2050, while the share of ethane, naphtha and liquefied petroleum gas (LPG) rises from 20% in recent years to almost 60% in 2050. This shift accentuates the drop in oil demand for refiners, and refinery runs fall by 85% between 2020 and 2050. Refiners are used to coping with changing demand patterns, but the scale of the changes in the NZE would inevitably lead to refinery closures, especially for refineries not able to concentrate primarily on petrochemical operations or the production of biofuels.

Figure 3.3 ▷ Oil and natural gas production in the NZE



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No new oil and natural gas fields are required beyond those already approved for development. Supply is increasingly concentrated in a few major producing countries

Natural gas

No new natural gas fields are needed in the NZE beyond those already under development. Also not needed are many of the liquefied natural gas (LNG) liquefaction facilities currently under construction or at the planning stage. Between 2020 and 2050, natural gas traded as

[2] Stranded capital is capital investment in fossil fuel infrastructure that is not recovered over the operating lifetime of the asset because of reduced demand or reduced prices resulting from climate policies. Stranded value is a reduction in the future revenue generated by an asset or asset owner assessed at a given point in time because of reduced demand or reduced prices resulting from climate policies (IEA, 2020a).

LNG falls by 60% and trade by pipeline falls by 65%. During the 2030s, global natural gas demand declines by more than 5% per year on average, meaning that some fields may be closed prematurely or shut in temporarily. Declines in natural gas demand slow after 2040, and more than half of natural gas use globally in 2050 is to produce hydrogen in facilities with CCUS. The large level of hydrogen, also produced using electrolysis, and biomethane in the NZE, means that the decline in total gaseous fuels is more muted than the decline in natural gas. This has important implications for the future of the gas industry (see Chapter 4).

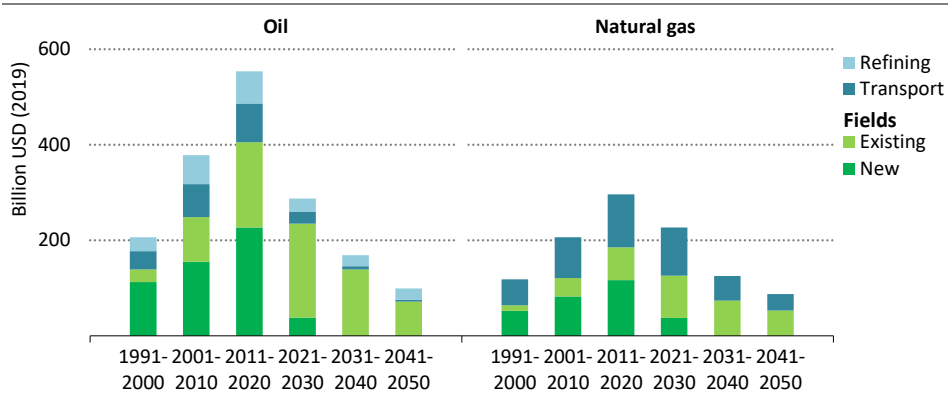
Coal

No new coal mines or extensions of existing ones are needed in the NZE as coal demand declines precipitously. Demand for coking coal falls at a slightly slower rate than for steam coal, but existing sources of production are sufficient to cover demand through to 2050. Such a decline in coal demand would have major consequences for employment in coal mining regions (see Chapter 4). There is a slowdown in the rate of decline in the 2040s as coal production facilities are increasingly equipped with CCUS: in the NZE, around 80% of coal produced in 2050 applies CCUS.

3.2.2 Investment in oil and gas

Upstream oil and gas investment averages about USD 350 billion each year from 2021 to 2030 in the NZE (Figure 3.4). This is similar to the level in 2020, but around 30% lower than average levels during the previous five years. Once fields under development start production, all of the upstream investment in the NZE is to support operations in existing fields; after 2030, total annual upstream investment is around USD 170 billion each year.

Figure 3.4 ▷ Investment in oil and natural gas supply in the NZE



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Once fields under development start production, all upstream oil and gas investment is spent on maintaining production at existing fields

Note: Investment in new fields in the 2021-2030 period is for projects that are already under construction or have been approved.

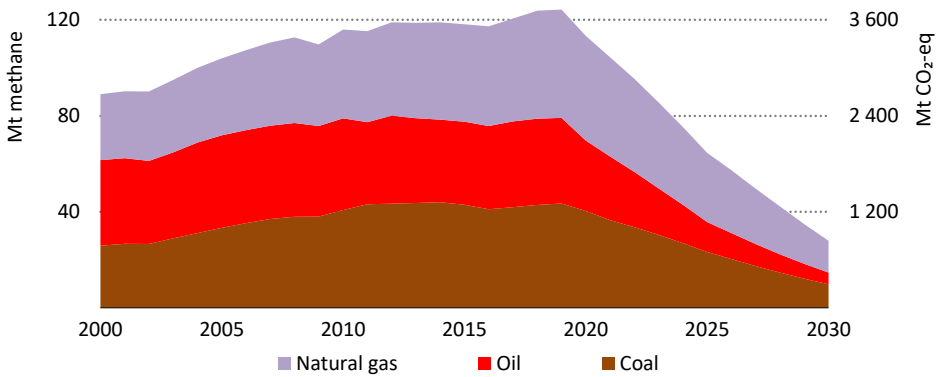
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3.2.3 Emissions from fossil fuel production

Emissions from the supply chains of coal, oil and natural gas fall dramatically in the NZE. The global average greenhouse gas (GHG) emissions intensity of oil production today is just under 100 kilogrammes of carbon-dioxide equivalent (kg CO_2-eq) per barrel. Without changes, a large proportion of global production would become uneconomic, as CO_2 prices are applied to the full value chains of fossil fuels. For example, by 2030 the CO_2 price in advanced economies in the NZE is USD 100 per tonne of CO_2 (tCO_2), which would add USD 10 to the cost of producing each barrel at today's average level of emissions intensity.

Methane constitutes about 60% of emissions from the coal and natural gas supply chains and about 35% of emissions from the oil supply chain. In the NZE, total methane emissions from fossil fuels fall by around 75% between 2020 and 2030, equivalent to a 2.5 gigatonne of carbon-dioxide equivalent (Gt CO_2-eq) reduction in GHG emissions (Figure 3.5). Around one-third of this decline is a result of an overall reduction in fossil fuel consumption, but the larger share comes from a huge increase in the deployment of emissions reduction measures and technologies, which leads to the elimination of all technically avoidable methane emissions by 2030 (IEA, 2020a).

Figure 3.5 ▷ Methane emissions from coal, oil and natural gas in the NZE



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Methane emissions from fossil fuels fall by 75% between 2020 and 2030 as result of a concerted global effort to deploy all available reduction measures and technologies

Note: Mt = million tonnes.

Actions to reduce the emissions intensity of existing oil and gas operations in the NZE leads to: the end of all flaring; the use of CCUS with centralised sources of emissions (including to capture natural sources of CO_2 that are often extracted with natural gas); and significant electrification of upstream operations (often making use of off-grid renewable energy sources).

The NZE inevitably brings significant challenges for fossil fuel industries and those who work in them, but it also brings opportunities. Coal mining declines dramatically in the NZE, but the mining of minerals needed for clean energy transitions increases very rapidly, and mining expertise is likely to be highly valued in this context. The oil and gas industry could play a key role in helping to develop at scale a number of clean energy technologies such as CCUS, low-carbon hydrogen, biofuels and offshore wind. Scaling up these technologies and bringing down their costs will rely on large-scale engineering and project management capabilities, qualities that are a good match to those of large oil and gas companies. These issues, including the question of how to help those affected by the major changes implied by the NZE, are discussed in more detail in Chapter 4.

3.3 Low-emissions fuel supply

3.3.1 Energy trends in the Net-Zero Emissions Scenario

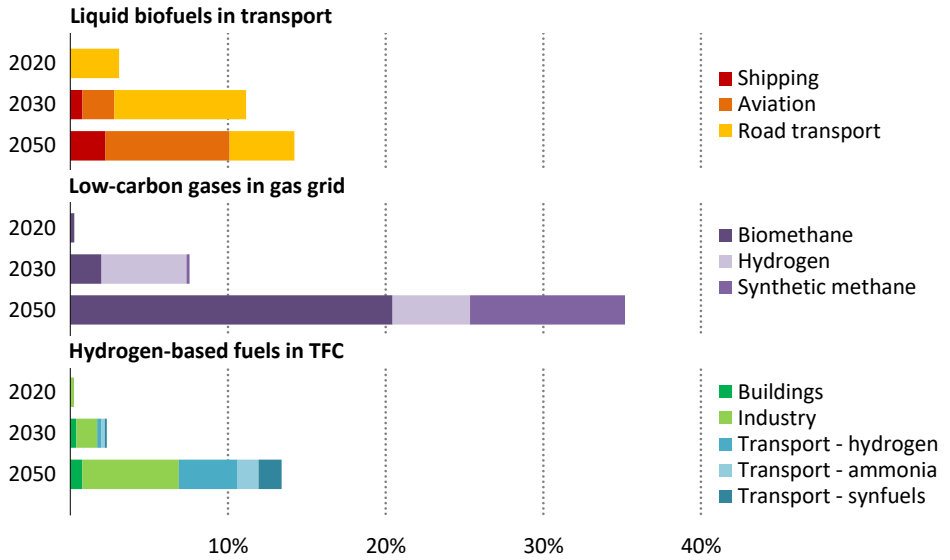
Reaching net-zero emissions will require low-emissions fuels[3] where energy needs cannot easily or economically be met by electricity (Figure 3.6). This is likely to be the case for some modes of long-distance transport (trucks, aviation and shipping) and of heat and feedstock supply in heavy industry. Some low-emissions fuels are effectively drop-in, i.e. they are compatible with the existing fossil fuel distribution infrastructure and end-use technologies, and require few if any modifications to equipment or vehicles.

Low-emissions fuels today account for just 1% of global final energy demand, a share that increases to 20% in 2050 in the NZE. Liquid biofuels meet 14% of global transport energy demand in 2050, up from 4% in 2020; hydrogen-based fuels meet a further 28% of transport energy needs by 2050. Low-carbon gases (biomethane, synthetic methane and hydrogen) meet 35% of global demand for gas supplied through networks in 2050, up from almost zero today. The combined share of low-carbon hydrogen and hydrogen-based fuels in total final energy use worldwide reaches 13% in 2050. Hydrogen and ammonia also provide important low-emissions sources of power system flexibility and contribute 2% of overall electricity generation in 2050, which is enough to make the electricity sector an important driver of hydrogen demand.

[3] Low-emissions fuels refer to liquid biofuels, biogas and biomethane, and hydrogen-based fuels (hydrogen, ammonia and synthetic hydrocarbon fuels) that do not emit CO_2 from fossil fuels directly when used and also emit very little when being produced. For example, hydrogen produced from natural gas with CCUS and high capture rates (90% or higher) is considered a low-emissions fuel, but not if produced without CCUS.

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Figure 3.6 ▷ Global supply of low-emissions fuels by sector in the NZE



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Low-emissions fuels in the form of liquid biofuels, biomethane, hydrogen-based fuels help to decarbonise sectors where direct electrification is challenging

Notes: TFC = total final consumption. Low-carbon gases in the gas grid refers to the blending of biomethane, hydrogen and synthetic methane with natural gas in a gas network for use in buildings, industry, transport and electricity generation. Synfuels refer to synthetic hydrocarbon fuels produced from hydrogen and CO_2. Final energy consumption of hydrogen includes, in addition to the final energy consumption of hydrogen, ammonia and synthetic hydrocarbon fuels, the on-site hydrogen production in the industry sector.

3.3.2 Biofuels[4]

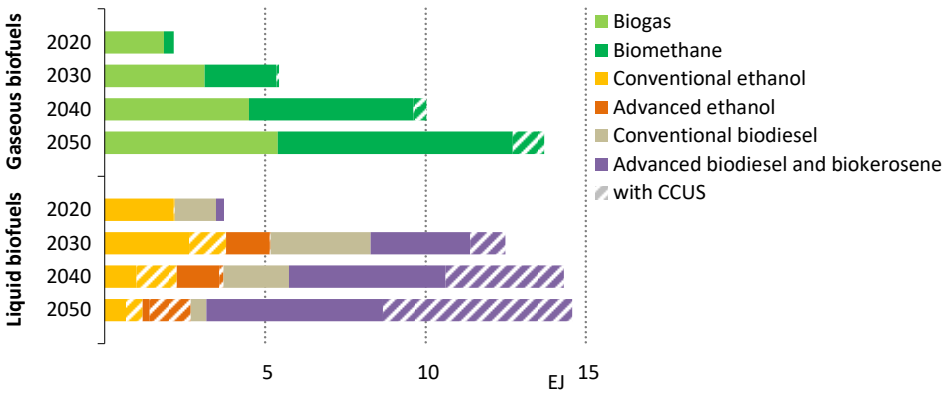
Around 10% of the global primary supply of modern bioenergy (biomass excluding traditional uses for cooking) was consumed as liquid biofuels for road transport and 6% was consumed as biogases (biogas and biomethane) to provide power and heat in 2020, with the rest directly used for electricity generation and heating in the residential sector. Supply accelerates sharply in the NZE with liquid biofuels expanding by a factor of almost four and biogases increasing by a factor of six by 2050.

All but about 7% of liquid biofuels for transport are currently produced from conventional crops such as sugarcane, corn and soybeans. Such crops directly compete with arable land that can be used for food production, which limits the scope for expanding output. So most of the growth in biofuels in the NZE comes from advanced feedstocks such as wastes and residues and woody energy crops grown on marginal lands and cropland not suitable for food

[4] Liquids and gases produced from bioenergy.

production (see section 2.7.2). Advanced liquid biofuel production technology using woody feedstock expands rapidly over the next decade in the NZE, and its contribution to liquid biofuels jumps from less than 1% in 2020 to almost 45% in 2030 and 90% in 2050 (Figure 3.7). By 2030, production reaches 2.7 million barrels of oil equivalent per day (mboe/d) by 2030, underpinned by biomass gasification using the Fischer-Tropsch process (bio-FT) and cellulosic ethanol, mostly to produce drop-in substitutes for diesel and jet kerosene. Advanced liquid biofuel production increases by an additional 130% to more than 6 mboe/d in 2050, the bulk of which is biokerosene.

Figure 3.7 ▷ Global biofuels production by type and technology in the NZE



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Liquid biofuel production quadruples while that of biogases expands sixfold between 2020 and 2050, underpinned by the development of sustainable biomass supply chains

Notes: EJ = exajoules; CCUS = carbon capture, utilisation and storage. Conventional ethanol refers to production using food energy crops. Advanced ethanol refers to production using wastes and residues and non-food energy crops grown on marginal and non-arable land. Conventional biodiesel includes fatty acid and methyl esters (FAME) route using food energy crops. Advanced biodiesel includes biomass-based Fischer-Tropsch and HEFA routes using wastes, residues and non-food energy crops grown on marginal and non-arable land. Biomethane includes biogas upgrading and biomass gasification-based routes.

Production using these feedstocks is mostly under development today. Current output capacity, principally cellulosic ethanol, is about 2.5 thousand barrels of oil equivalent per day (kboe/d). The NZE assumes that projects currently in the pipeline in Japan, the United Kingdom and the United States will bring these technologies to the market within the next few years. The scale up required for all advanced liquid biofuels (including from waste oils) over the next decade is equivalent to building one 55 kboe/d biorefinery every ten weeks (the world's largest biorefinery has capacity of 28 kboe/d).

The supply of these biofuels after 2030 shifts rapidly in the NZE from passenger vehicles and light trucks, where electrification is increasingly the order of the day, to heavy road freight, shipping and aviation. Ammonia makes inroads into shipping. Advanced liquid biofuels increase their share of the global aviation fuel market from 15% in 2030 to 45% in 2050.

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Advanced biofuels such as hydrogenated esters and fatty acids (HEFA) and bio-FT are able to adjust their product slates (up to a point) from renewable diesel to biokerosene, and existing ethanol plants, especially those that can be retrofitted with CCUS or integrated with cellulosic feedstock, also make a contribution.

The supply of biogases increases even more than liquid biofuels. Injection into gas networks expands from under 1% of total gas volume in 2020 to almost 20% in 2050, reducing the emissions intensity of the network-based gas. Biomethane is mostly produced by upgrading biogas produced from anaerobic digestion of feedstocks such as agricultural residues like manure and biogenic municipal solid waste, thereby avoiding methane emissions that would otherwise be released. Due to the dispersed nature of these feedstocks, this assumes the construction of thousands of injection sites and associated distribution lines every year. Biogas and biomethane are also used as clean cooking fuels and in electricity generation in the NZE.

The production of biofuels can be combined with CCUS at a relatively low cost in some biofuel production routes (ethanol, bio-FT, biogas upgrading) because the processes involved release very pure streams of CO_2. In the NZE, the use of biofuels with CCUS results in annual carbon dioxide removal (CDR) of 0.6 Gt CO_2 in 2050, which offset residual emissions in transport and industry.

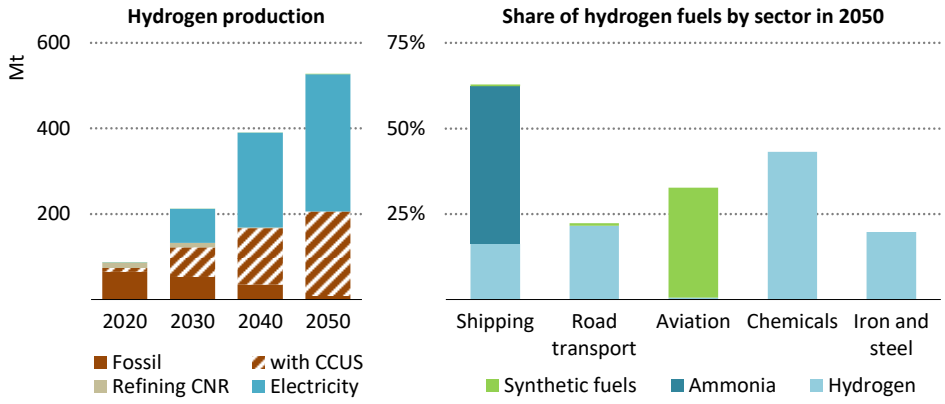
3.3.3 Hydrogen and hydrogen-based fuels

Hydrogen use in the energy sector today is largely confined to oil refining and the production of ammonia and methanol in the chemicals industry. Global hydrogen demand was around 90 million tonnes (Mt) in 2020, mainly produced from fossil fuels (mostly natural gas) and emitting close to 900 Mt CO_2. Both the amount needed and the production route of hydrogen change radically in the NZE. Demand increases almost sixfold to 530 Mt in 2050, of which half is used in heavy industry (mainly steel and chemicals production) and in the transport sector; 30% is converted into other hydrogen-based fuels, mainly ammonia for shipping and electricity generation, synthetic kerosene for aviation and synthetic methane blended into gas networks; and 17% is used in gas-fired power plants to balance increasing electricity generation from solar PV and wind and to provide seasonal storage. Overall, hydrogen-based fuels[5] account for 13% of global final energy demand in 2050 (Figure 3.8).

Ammonia is used today as feedstock in the chemical industry, but in the NZE it is also used as fuel in various energy applications, benefitting from its lower transport cost and higher energy density than hydrogen. Ammonia accounts for around 45% of global energy demand for shipping in 2050 in the NZE. Co-firing with ammonia is also a potential early option to reduce CO_2 emissions in existing coal-fired power plants. The toxicity of ammonia means that its handling is likely to be limited to professionally trained operators, which could restrict its potential.

[5] Hydrogen-based fuels are defined as hydrogen, ammonia as well as synthetic hydrocarbon fuels produced from hydrogen and CO_2.

Figure 3.8 ▷ Global production of hydrogen by fuel and hydrogen demand by sector in the NZE



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Hydrogen production jumps sixfold by 2050, driven by water electrolysis and natural gas with CCUS, to meet rising demand in shipping, road transport and heavy industry

Note: Refining CNR = hydrogen by-product from catalytic naphtha reforming at refineries.

Synthetic kerosene meets around one-third of global aviation fuel demand in 2050 in the NZE. Its manufacture at bioenergy-fired power or biofuel production plants requires CO_2 captured from the atmosphere. CO_2 from these sources can be considered carbon neutral, as it results in no net emissions when the fuel is used. There is scope for the co-production of advanced liquid biofuels and synthetic liquid fuels from hydrogen and CO_2, with the integration of the two processes reducing the overall liquid fuel production costs. Alongside synthetic liquid fuels, enough synthetic methane is produced from hydrogen and CO_2 in 2050 to meet 10% of demand for network supplied gas in the buildings, industry and transport sectors.

By 2050, hydrogen production in the NZE is almost entirely based on low-carbon technologies: water electrolysis accounts for more than 60% of global production, and natural gas in combination with CCUS for almost 40%. Global electrolyser capacity reaches 850 gigawatts (GW) by 2030 and 3 600 GW by 2050, up from around 0.3 GW today. Electrolysis absorbs close to 15 000 terawatt-hours (TWh), or 20% of global electricity supply in 2050, largely from renewable resources (95%), but also from nuclear power (3%) and fossil fuels with CCUS (2%). Natural gas use for hydrogen production with CCUS is 925 bcm in 2050, or around 50% of global natural gas demand, with 1.8 Gt CO_2 being captured.

Scaling up deployment of technologies and related manufacturing capacity will be critical to reducing costs. Water electrolysers are available on the market today and hydrogen production from natural gas with CCUS has been demonstrated at a commercial scale (there are seven plants in operation around the world). The choice between the two depends on

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economic factors, mainly the cost of natural gas and electricity, and on whether CO_2 storage is available. For natural gas with CCUS, production costs in the NZE are around USD 1-2 per kilogramme (kg) of hydrogen in 2050, with gas costs typically accounting for 15-55% of total production costs. For water electrolysis, learning effects and economies of scale result in CAPEX cost reductions of 60% in the NZE by 2030 compared to 2020. Production cost reductions hinge on lowering the cost of low-carbon electricity, as electricity accounts for 50-85% of total production costs, depending on the electricity source and region. The average cost of producing hydrogen from renewables drops in the NZE from USD 3.5-7.5/kg today to around USD 1.5-3.5/kg in 2030 and USD 1-2.5/kg in 2050 – essentially about the same as the cost of producing with natural gas with CCUS.

Converting hydrogen into other energy carriers, such as ammonia or synthetic hydrocarbon fuels, involves even higher costs. But it results in fuels that can be more easily transported and stored, and which are also often compatible with existing infrastructure or end-use technologies (as in the case of ammonia for shipping or synthetic kerosene for aviation). For ammonia, the additional synthesis step increases the production costs by around 15% compared with hydrogen (mainly due to additional conversion losses and equipment costs).

The relatively high cost of synthetic hydrocarbon fuels explains why their use is largely restricted to aviation in the NZE, where alternative low-carbon options are limited. Synthetic kerosene costs were USD 300-700/barrel in 2020: although these costs fall to USD 130-300/barrel by 2050 in the NZE as the costs of electricity from renewables and CO_2 feedstocks decline, the cost of synthetic kerosene remains far higher than the projected USD 25/barrel cost of conventional kerosene in 2050 in the NZE. The supply of CO_2, captured from bioenergy equipped with CCUS or direct air capture (DAC), needed to make these fuels is a relevant cost factor, accounting for USD 15-70/barrel of the cost of synthetic hydrocarbon fuels in 2050. Closing these cost gaps implies penalties for fossil kerosene or support measures for synthetic kerosene corresponding to a CO_2 price of USD 250-400/tonne.

Increasing global demand for low-carbon hydrogen in the NZE provides a means for countries to export renewable electricity resources that could not otherwise be exploited. For example, Chile and Australia announced ambitions to become major exporters in their national hydrogen strategies. With declining demand for natural gas in the NZE, gas-producing countries could join this market by exporting hydrogen produced from natural gas with CCUS. Long-distance transport of hydrogen, however, is difficult and costly because of its low energy density, and can add around USD 1-3/kg of hydrogen to its price. This means that, depending on each country's own circumstances, producing hydrogen domestically may be cheaper than importing it, even if domestic production costs from low-carbon electricity or natural gas with CCUS are relatively high. International trade nevertheless becomes increasingly important in the NZE: around half of global ammonia and a third of synthetic liquid fuels are traded in 2050.

3.3.4 Key milestones and decision points

Table 3.1 ▷ Key milestones in transforming low-emissions fuels

Sector	2020	2030	2050
Bioenergy			
Share of modern biofuels in modern bioenergy (excluding conversion losses)	20%	45%	48%
Advanced liquid biofuels (mboe/d)	0.1	2.7	6.2
Share of biomethane in total gas networks	<1%	2%	20%
CO_2 captured and stored from biofuels production (Mt CO_2)	1	150	625
Hydrogen			
Production (Mt H_2)	87	212	528
of which: low-carbon (Mt H_2)	9	150	520
Electrolyser capacity (GW)	<1	850	3 585
Electricity demand for hydrogen-related production (TWh)	1	3 850	14 500
CO_2 captured from hydrogen production (Mt CO_2)	135	680	1 800
Number of export terminals at ports for hydrogen and ammonia trade	0	60	150

Note: mboe/d = million barrels of oil equivalent per day; Mt = million tonnes; H_2 = hydrogen.

Biofuels

Several sustainability frameworks considering net lifecycle GHG emissions and other sustainability indicators exist in different regions, e.g. the Renewable Energy Directive II in the European Union, RenovaBio in Brazil and the Low-C Fuel Standards in California. However, the scope, methodology and sustainability metrics of these frameworks differ. Global consensus on a sustainability framework and indicators within the next few years would help stimulate investment; this should be a priority. Such a framework should cover all forms of bioenergy (liquid, gaseous and solid) and other low-emissions fuels, and should strive for continuous environmental performance improvement. Certification schemes ideally should be developed in parallel.

Another early priority is for governments to assess national sustainable biomass feedstock potential as soon as possible to establish the quantities and types of wastes, residues and marginal lands suitable for energy crops. Assessments should provide the basis for national roadmaps for all liquid and gaseous biofuels, and strategies for low-emissions fuels. Early decisions will be needed in this context about how to support the sustainable collection of wastes and residues from the forestry, agriculture, animal and food industries and from advanced municipal solid waste sorting systems: in the NZE, support measures are in place by 2025. Measures might usefully include low-emissions fuels standards that incentivise the use of biofuels as feedstock. International knowledge-sharing would help with the design of such measures and assist efficient dissemination of best practices from regions with existing collection systems, e.g. for forestry residues in Nordic countries and used cooking oil collection in Europe, China and Southeast Asia countries.

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Governments will also need to decide how best to support biogas installations and distribution in order to move away from traditional uses of biomass for cooking and heating by 2030. Such practices remain widespread in some developing countries. They are best tackled as part of broader programmes to promote clean cooking alongside improving access to electricity and LPG.

Decisions will be needed by 2025 on how best to create markets for sustainable biofuels and close the cost gap between biofuels and fossil fuels. Measures will need to incentivise the rapid development and deployment of advanced liquid biofuel technologies in end-use sectors (particularly heavy-duty trucking, shipping and aviation), using mechanisms such as low-carbon fuel standards, biofuel mandates and CO_2 removal credits. Measures that could boost the scaling up of advanced biofuels production in the next four years include: incentives for co-processing bio-oil in existing oil refineries or fully converting oil refineries to biorefineries; retrofitting ethanol plants with CCUS; and integrating cellulosic ethanol production with existing ethanol plants.

New infrastructure will be needed to provide for the injection of more biomethane into gas networks and to transport and store the CO_2 captured from ethanol and bio-FT biofuel plants. Governments should prioritise the co-development of biogas upgrading facilities and biomethane injection sites by 2030, ensuring that particular attention is paid to minimising fugitive biomethane emissions from the supply chain. Where biomass availability allows, governments may see value in encouraging the deployment of biofuel plants with CCUS near existing industrial hubs where integrated CCUS projects are planned, such as the Humber region in the United Kingdom.

Hydrogen-based fuels

An immediate priority should be for governments to assess the opportunities and challenges of developing a low-carbon hydrogen industry as part of national hydrogen strategies or roadmaps. Decisions will be needed on whether to produce hydrogen domestically from low-carbon electricity via water electrolysis or from gas with CCUS or a combination of both, or whether to rely on imported hydrogen-based fuels. Building technology leadership along the hydrogen supply chain could help create jobs and stimulate economic growth.

Decisions will be needed during the next decade on how best to bring down the costs of low-carbon hydrogen production. Switching existing hydrogen production in industry and oil refining from unabated fossil fuels to low-carbon hydrogen is one possible way to ramp up low-carbon hydrogen production in applications that have large demand already available. Financial support instruments, such as contracts for differences, could help to reduce the current cost gap of low-carbon hydrogen production compared to existing unabated production from fossil fuels.

Decisions will also be needed on how best to scale up hydrogen. Industrial ports could be a good starting point, since they may provide access to low-carbon hydrogen supply in the form of offshore wind or CO_2 storage. They also offer scope to promote new port-related

uses for hydrogen, e.g. shipping and delivery trucks, and they could become the first nodes of an international hydrogen trade network. The establishment of hydrogen trade will require the development of methodologies to determine the carbon footprint of the different hydrogen production routes and the adoption of guarantees of origin and certification schemes for low-carbon hydrogen (and hydrogen-based fuels).

Blending hydrogen into existing gas networks offers another early avenue to scale up low-carbon hydrogen production and trigger cost reductions. International harmonisation of safety standards and national regulations on allowed concentrations of hydrogen in gas grids would help with this, as would the adoption of blending quotas or low-emissions fuel standards.

Repurposing existing gas pipelines, where technically feasible, with declining natural gas demand and connecting large hydrogen demand hubs to transport hydrogen could result in low cost and low regret opportunities to kick-start the development of new hydrogen infrastructure. Developing the infrastructure for hydrogen at the pace required in the NZE would involve considerable investment risks along the value chain of production, transport and demand ranging from hydrogen production technologies through to low-emissions electricity generation and CO_2 transport and storage. Governments and local authorities could play an important role by co-ordinating the planning processes among the various stakeholders; direct public investment or public-private partnerships could help to develop necessary shared infrastructure for hydrogen; and international co-operation and cross-border initiatives could help to share investment burdens and risks and so facilitate large-scale deployments, as in the EU Important Projects of Common European Interest.

3.4 Electricity sector

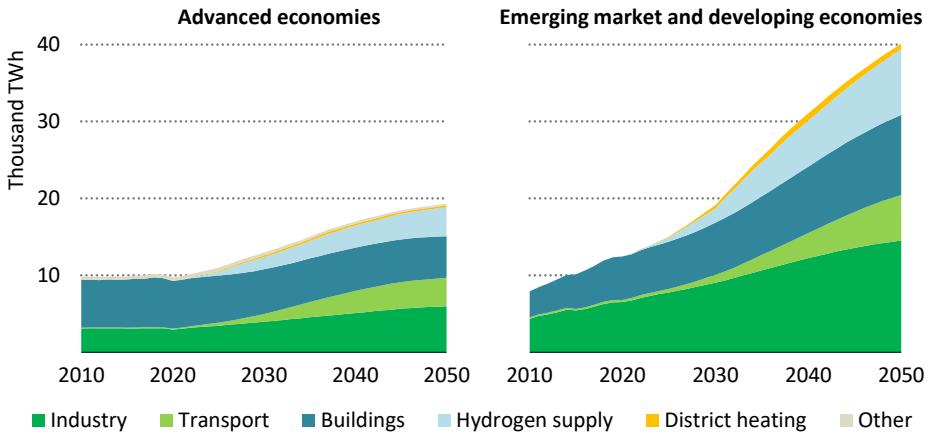
3.4.1 Energy and emissions trends in the Net-Zero Emissions Scenario

The NZE involves both a significant increase in electricity needs – the result of an increase in economic activity, rapid electrification of end-uses and expansion of hydrogen production by electrolysis – and a radical transformation in the way electricity is generated. Global electricity demand was 23 230 TWh in 2020 with an average growth rate of 2.3% per year over the previous decade. It climbs to 60 000 TWh in 2050 in the NZE, an average increase of 3.2% per year.

Emerging market and developing economies account for 75% of the projected global increase in electricity demand to 2050 (Figure 3.9). Their demand increases by half by 2030 and triples by 2050, driven by expanding population and rising incomes and living standards, as well new sources of demand linked to decarbonisation. In advanced economies, electricity demand returns to growth after a decade-long lull, nearly doubling between 2020 and 2050, driven mostly by end-use electrification and hydrogen production.

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Figure 3.9 ▷ Electricity demand by sector and regional grouping in the NZE



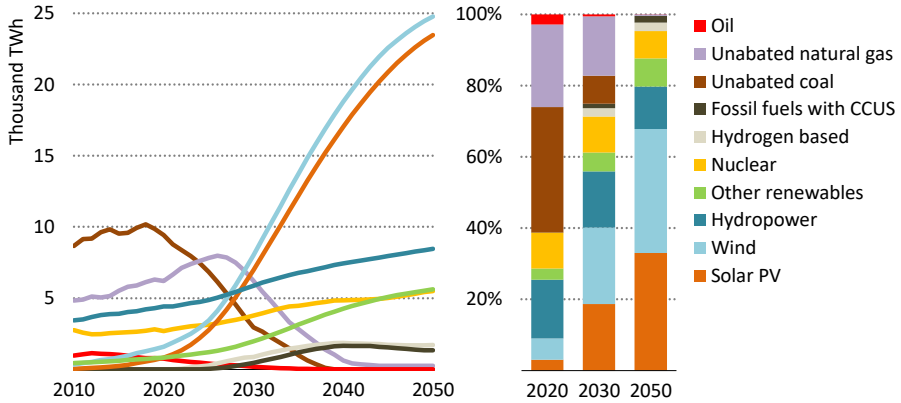
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Electrification of end-uses and hydrogen production raise electricity demand worldwide, with a further boost to expand services in emerging market and developing economies

The transformation of the electricity sector is central to achieving net-zero emissions in 2050. Electricity generation is the single largest source of energy-related CO_2 emissions today, accounting for 36% of total energy-related emissions. CO_2 emissions from electricity generation worldwide totalled 12.3 Gt in 2020, of which 9.1 Gt was from coal-fired generation, 2.7 Gt from gas-fired plants and 0.6 Gt from oil-fired plants. In the NZE, CO_2 emissions from electricity generation fall to zero in aggregate in advanced economies in the 2030s. They fall to zero in emerging market and developing economies around 2040.

Renewables contribute most to decarbonising electricity in the NZE: global generation from renewables nearly triples by 2030 and grows eightfold by 2050 (Figure 3.10). This raises the share of renewables in total output from 29% in 2020 to over 60% in 2030 and nearly 90% in 2050. Solar PV and wind race ahead, becoming the leading sources of electricity globally before 2030: each generates over 23 000 TWh by 2050, equivalent to about 90% of all electricity produced in the world in 2020. Pairing battery storage systems with solar PV and wind to improve power system flexibility and maintain electricity security becomes commonplace in the late 2020s, complemented by demand response for short duration flexibility and hydropower or hydrogen for flexibility across days or even seasons. Hydropower is the largest low-carbon source of electricity today and steadily grows in the NZE, doubling by 2050. Generation using bioenergy – in dedicated plants and as biomethane delivered through gas networks – doubles to 2030 and increases nearly fivefold by 2050.

Figure 3.10 ▷ Global electricity generation by source in the NZE



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Solar and wind power race ahead, raising the share of renewables in total generation from 29% in 2020 to nearly 90% in 2050, complemented by nuclear, hydrogen and CCUS

Nuclear power also makes a significant contribution in the NZE, its output rising steadily by 40% to 2030 and doubling by 2050, though its overall share of generation is below 10% in 2050. At its peak in the early 2030s, global nuclear capacity additions reach 30 GW per year, five-times the rate of the past decade. In advanced economies, lifetime extensions for existing reactors are pursued in many countries as they are one of the most cost-effective sources of low-carbon electricity (IEA, 2019), while new construction expands to about 4.5 GW per year on average from 2021 to 2035, with an increasing emphasis on small modular reactors. Despite these efforts, the nuclear share of total generation in advanced economies falls from 18% in 2020 to 10% in 2050. Two-thirds of new nuclear power capacity in the NZE is built in emerging market and developing economies mainly in the form of large-scale reactors, where the fleet of reactors quadruples to 2050. This raises the share of nuclear in electricity generation in those countries from 5% in 2020 to 7% in 2050 (as well as nuclear meeting 4% of commercial heat demand in 2050).

Nuclear power technologies have advanced in recent years, with several first-of-a-kind large-scale reactors completed that include enhanced safety features. While projects have been completed on schedule in China, Russia and the United Arab Emirates, there have been substantial delays and cost overruns in Europe and the United States. Small modular reactors and other advanced reactor designs are moving towards full-scale demonstration, with scalable designs, lower upfront costs and the potential to improve the flexibility of nuclear power in terms of both operations and outputs, e.g. electricity, heat or hydrogen.

Retrofitting coal- and gas-fired capacity with CCUS or co-firing with hydrogen-based fuels enables existing assets to contribute to the transition while cutting emissions and supporting electricity security. The best opportunities for CCUS are at large, young facilities with

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available space to add capture equipment and in locations with CO_2 storage options or demand for use. Opportunities are concentrated in China for coal-fired power plants and the United States for gas-fired capacity. While they provide just 2% of total generation from 2030 to 2050 in the NZE, retrofitted plants capture a total of 15 Gt CO_2 emissions over the period.

Carbon capture technologies remain at an early stage of commercialisation. Two commercial power plants have been equipped with CCUS over the past five years, and there are currently 18 CCUS power projects in development worldwide. Completing these projects in a timely manner and driving down costs through learning-by-doing will be critical to further expansion. An alternative would be to retrofit existing coal- and gas-fired power plants to co-fire high shares of hydrogen-based fuels. In the NZE, hydrogen-based fuels generate 900 TWh of electricity in 2030 and 1 700 TWh in 2050 in this way (about 2.5% of global generation in both years). A large-scale (1 GW) demonstration project to co-fire with 20% ammonia is underway in 2021, with aims to move towards ammonia-only combustion. Manufacturers have signalled that future gas turbine designs will be capable of co-firing high shares of hydrogen. While the investment needed to co-fire hydrogen-based fuels looks to be modest, relatively high fuel costs point to targeted applications to support power system stability and flexibility rather than bulk power.

The global use of unabated fossil fuels in electricity generation is sharply reduced in the NZE. Unabated coal-fired generation is cut by 70% by 2030, including the phase-out of unabated coal in advanced economies, and phased out in all other regions by 2040. Large-scale oil-fired generation is phased out in the 2030s. Generation using natural gas without carbon capture rises in the near term, replacing coal, but starts falling by 2030 and is 90% lower by 2040 compared with 2020.

The electricity sector is the first to achieve net-zero emissions mainly because of the low costs, widespread policy support and maturity of an array of renewable energy technologies. Solar PV is first among them: it is the cheapest new source of electricity in most markets and has policy support in more than 130 countries. Onshore wind is also a market-ready low cost technology that is widely supported and can be scaled up quickly, rivalling the low costs of solar PV where conditions are good, though it faces public opposition and extensive permitting and licensing processes in several markets. Offshore wind technology has been maturing rapidly in recent years; its deployment is poised to accelerate in the near term. The current focus is on fixed-bottom installations, but floating offshore wind starts to make a major contribution from around 2030 in the NZE, helping to unlock the enormous potential that exists around the world. Hydropower, bioenergy and geothermal technologies are well established, mature and flexible renewable energy sources. As dispatchable generating options, they will be critical to electricity security, complemented by batteries, which have seen sharp cost reductions, have proven their ability to provide high-value grid services and can be built in a matter of months in most locations. Concentrating solar and marine power are less mature technologies, but innovation could see them make important contributions in the long term.

3.4.2 Key milestones and decision points

Table 3.2 ▷ Key milestones in transforming global electricity generation

Category	
Decarbonisation of electricity sector	• Advanced economies in aggregate: 2035. • Emerging market and developing economies: 2040.
Hydrogen-based fuels	• Start retrofitting coal-fired power plants to co-fire with ammonia and gas turbines to co-fire with hydrogen by 2025.
Unabated fossil fuel	• Phase out all subcritical coal-fired power plants by 2030 (870 GW existing plants and 14 GW under construction). • Phase out all unabated coal-fired plants by 2040. • Phase out large oil-fired power plants in the 2030s. • Unabated natural gas-fired generation peaks by 2030 and is 90% lower by 2040.

Category	2020	2030	2050
Total electricity generation (TWh)	26 800	37 300	71 200
Renewables			
Installed capacity (GW)	2 990	10 300	26 600
Share in total generation	29%	61%	88%
Share of solar PV and wind in total generation	9%	40%	68%
Carbon capture, utilisation and storage (CCUS) generation (TWh)			
Coal and gas plants equipped with CCUS	4	460	1 330
Bioenergy plants with CCUS	0	130	840
Hydrogen and ammonia			
Average blending in global coal-fired generation (without CCUS)	0%	3%	100%
Average blending in global gas-fired generation (without CCUS)	0%	9%	85%
Unabated fossil fuels			
Share of unabated coal in total electricity generation	35%	8%	0.0%
Share of unabated natural gas in total electricity generation	23%	17%	0.4%
Nuclear power	*2016-20*	*2021-30*	*2031-50*
Average annual capacity additions (GW)	7	17	24
Infrastructure			
Electricity networks investment in USD billion (2019)	260	820	800
Substations capacity (GVA)	55 900	113 000	290 400
Battery storage (GW)	18	590	3 100
Public EV charging (GW)	46	1 780	12 400

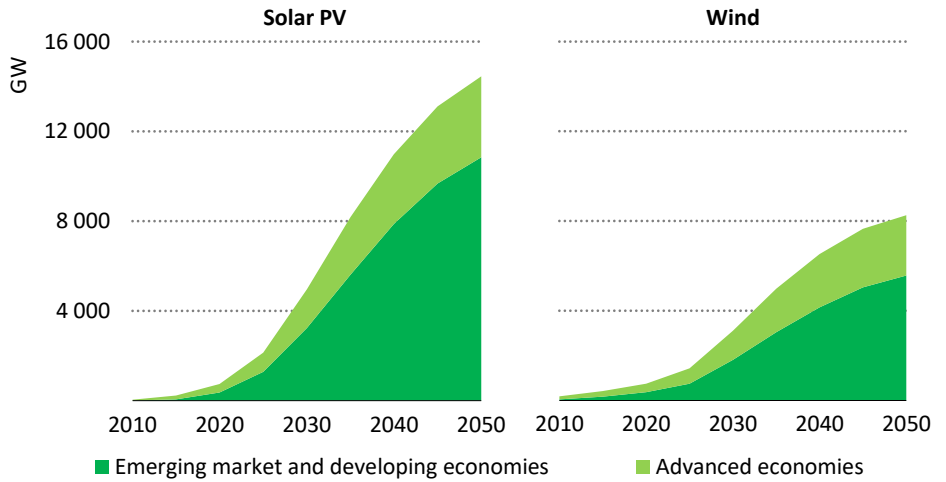
Note: GW = gigawatts; GVA = gigavolt amperes.

Transforming the electricity sector in the way envisioned in the NZE involves large capacity additions for all low-emissions fuels and technologies. Global renewables capacity more than triples to 2030 and increases ninefold to 2050. From 2030 to 2050, this means adding more than 600 GW of solar PV capacity per year on average and 340 GW of wind capacity per year including replacements (Figure 3.11), while offshore wind becomes increasingly important

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over time (over 20% of total wind additions from 2021 to 2050, compared with 7% in 2020). The annual deployment of battery capacity in the electricity sector needs to scale up in parallel, from 3 GW in 2019 to 120 GW in 2030 and over 240 GW in 2040. Retrofitting existing coal- and gas-fired power plants also needs to get underway.

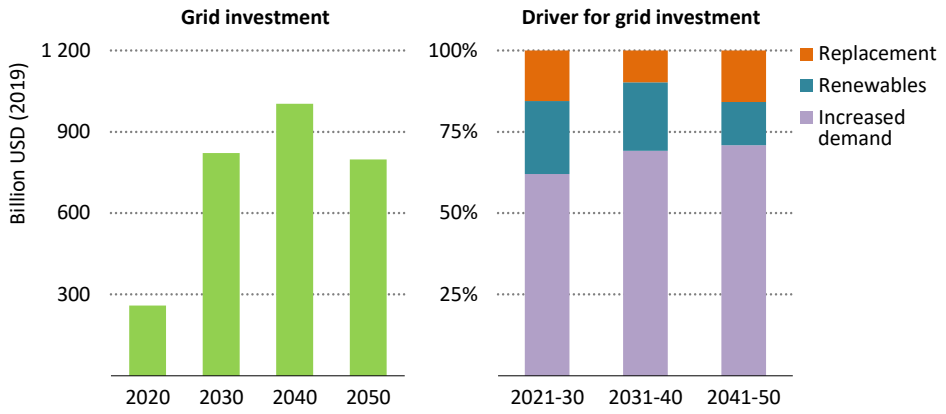
Figure 3.11 ▷ Solar PV and wind installed capacity in the NZE



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Solar PV and wind need to scale up rapidly to decarbonise electricity, with total solar PV capacity growing 20-fold and wind 11-fold by 2050

Figure 3.12 ▷ Global investment in electricity networks in the NZE



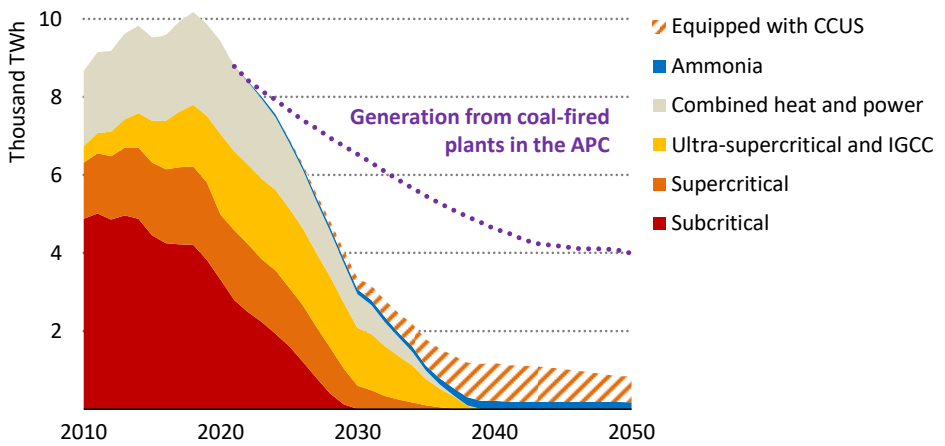
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Electricity network investment triples to 2030 and remains elevated to 2050, meeting new demand, replacing ageing infrastructure and integrating more renewables

Investment in electricity networks will be crucial to achieving this transformation. Global electricity networks that took over 130 years to build need to more than double in total length by 2040 and increase by another 25% by 2050. Total grid investment needs to rise to USD 820 billion by 2030, and USD 1 trillion in 2040, before falling back after electricity is fully decarbonised and the growth of renewables slows to match demand growth (Figure 3.12). Replacing ageing infrastructure is an important part of network investment through to 2050 in the NZE.

Governments face several key decisions in the electricity sector if they are to follow the pathway to net-zero emissions by 2050 envisioned in the NZE particularly about how to best use existing power plants. For retrofits of coal- or gas-fired capacity, either with carbon capture or co-firing with hydrogen-based fuels (or full conversion), decisions are needed to support first-of-a-kind projects before 2030 before widespread retirement of unabated plants becomes necessary. For other fossil fuel power stations, decisions about phase outs are needed. Coal-fired power plants should be phased out completely by 2040 unless retrofitted, starting with the least-efficient designs by 2030 (Figure 3.13). This would require shutting 870 GW of existing subcritical coal capacity globally (11% of all power capacity) and international collaboration to facilitate substitutes. By 2040, all large-scale oil-fired power plants should be phased out. Natural gas-fired generation remains an important part of electricity supply through to 2050, but strong government support will be needed to ensure that CCUS is deployed soon and on a large scale.

Figure 3.13 ▷ Coal-fired electricity generation by technology in the NZE



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Coal-fired power accounted for 27% of global energy CO_2 emissions in 2020, and in the NZE, all subcritical plants are phased out by 2030 and all plants without CCUS by 2040

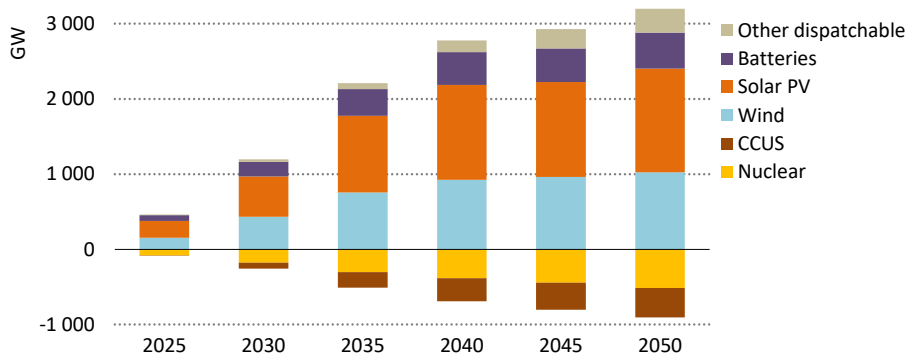
Notes: APC = Announced Pledges Case; IGCC = integrated gasification combined-cycle. Ammonia includes co-firing and full conversion of coal plants.

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The path to net-zero emissions could be facilitated by early government action to help move several technologies that provide power system flexibility through the demonstration phases and bring them to market. Expanding the set of energy storage technologies to complement batteries and addressing emerging needs for longer duration seasonal storage would be of particular value. Technical solutions to support the stability of power grids with high shares of solar and wind would also benefit from research and development (R&D) support.

There are three important sets of decisions to be made concerning nuclear power: lifetime extensions; pace of new construction; and advances in nuclear power technology. In advanced economies, decisions need to be made about new construction and the large number of nuclear power plants that may be retired over the next decade absent action to extend their lifetimes and make the required investment. Without further lifetime extensions and new projects beyond those already under construction, nuclear power output in advanced economies will decline by two-thirds over the next two decades (IEA, 2019). In emerging market and developing economies, there are decisions to be made about the pace of new nuclear power construction. From 2011 to 2020, an average of 6 GW of new nuclear capacity came online each year. By 2030, the rate of new construction increases to 24 GW per year in the NZE. The third set of decisions concerns the extent of government support for advanced nuclear technologies, particularly those related to small modular reactors and high-temperature gas reactors, both of which can expand markets for nuclear power beyond electricity.

Figure 3.14 ▷ Additional global alternative capacity needed in a Low Nuclear and CCUS Case



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Sharply reducing the roles of nuclear power and carbon capture would require even faster growth in solar PV and wind, making achieving the net zero goal more costly and less likely

Note: The Low Nuclear and CCUS Case assumes that global nuclear power output is about 60% lower in 2050 than in the NZE due to no additional lifetime extensions or new nuclear projects in advanced economies and no expansion of the current pace of construction in emerging market and developing economies, and that the amount of coal- and gas-fired capacity equipped with CCUS is 99% lower than in the NZE.

Failing to take timely decisions on nuclear power and CCUS would raise the costs of a net-zero emissions pathway and add to the risk of not meeting the goal by placing an additional burden on wind and solar to scale up even more quickly than in the NZE (Figure 3.14). In a *Low Nuclear and CCUS Case*, we assume that global nuclear power output is 60% lower in 2050 than in the NZE as a result of no additional nuclear lifetime extensions or new projects in advanced economies and no expansion of the current pace of construction in emerging market and developing economies, and that only the announced CCUS projects are completed (representing 1% of the CCUS capacity added in the NZE).

Our analysis indicates that the burden of replacing those sources of low-carbon generation would fall mainly on solar PV and wind power, calling for 2 400 GW more capacity than in the NZE – an amount far exceeding their combined global capacity in operation in 2020 (Figure 3.14). There would also be a need for about 480 GW of battery capacity above and beyond the 3 100 GW deployed in the NZE, plus more than 300 GW of other dispatchable capacity to meet demand in all seasons and ensure system adequacy. This would call for an additional USD 2 trillion investment in power plants and related grid assets (net of lower investment in nuclear and CCUS). Taking account of avoided fuel costs, the estimated total additional cost of electricity to consumers between 2021 and 2050 is USD 260 billion.

3.5 Industry

3.5.1 Energy and emission trends in the Net-Zero Emissions Scenario

As the second-largest global source of energy sector CO_2 emissions, industry has a vital contribution to make in achieving the net zero goal. Industrial CO_2 emissions[6] (including from energy use and production processes) totalled about 8.4 Gt in 2020. Advanced economies accounted for around 20% and emerging market and developing economies for around 80%, although complex global supply chains for the production of materials and manufacturing mean that advanced economies generally consume far more finished goods than they produce.

Three heavy industries – chemicals, steel and cement – account for nearly 60% of all industrial energy consumption and around 70% of CO_2 emissions from the industry sector. Production is highly concentrated in emerging market and developing economies, which account for 70-90% of the combined output of these commodities (Figure 3.15). China alone was responsible for almost 60% of both steel and cement production in 2020. These bulk materials are essential inputs to our modern way of life, with few cost-competitive substitutes; the challenge is to carry on producing these materials without emitting CO_2.

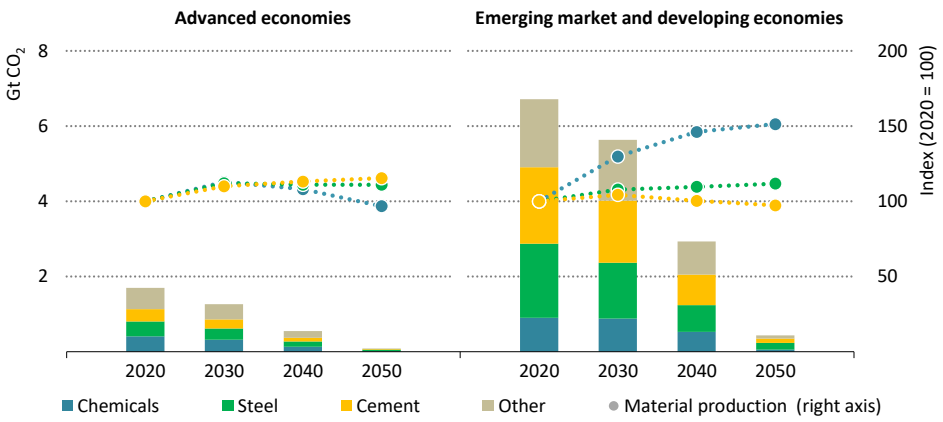
The outlook for global materials demand in the NZE is one of plateaus and small increases. This is in stark contrast with the growth seen during the last two decades when global steel

[6] All CO_2 emissions in this section refer to direct CO_2 emissions from the industry sector unless otherwise specified.

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demand rose by 2.1-times, cement by 2.4-times and plastics (a key group of material outputs from the chemical sector) by 1.9-times in response to global economic and population expansion. When economies are developing, per capita material demand tends to rise rapidly to build up stocks of goods and infrastructure. As economies mature, future demand stems primarily from the need to refurbish and replace these stocks, the levels of which tend to saturate. In the NZE, flattening or even declining demand in many countries around the world leads to slower global demand growth. Some countries such as India see higher growth in steel and cement production, while production in China declines considerably following its industrial boom period after the turn of the millennium.

Figure 3.15 ▷ Global CO_2 emissions from industry by sub-sector in the NZE



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The majority of residual emissions in industry in 2050 come from heavy industries in emerging market and developing economies

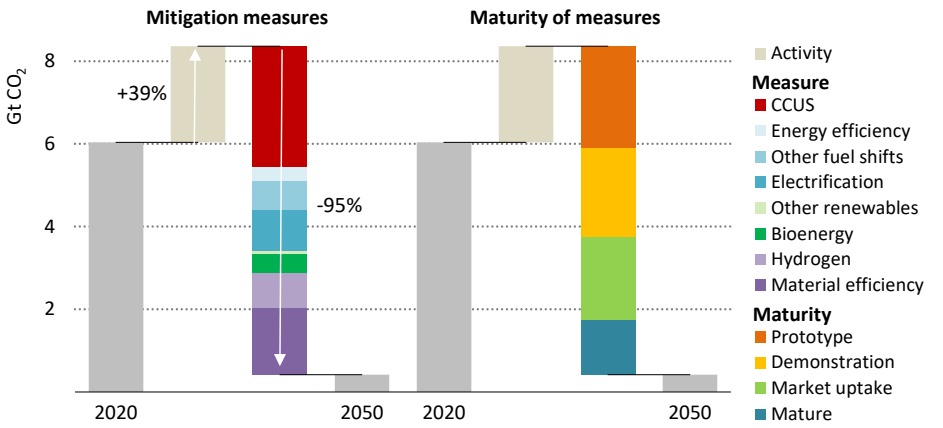
Note: Other includes the production of aluminium, paper, other non-metallic minerals and other non-ferrous metals, and a series of light industries.

Certain segments of material demand increase rapidly to support the required expansion of energy-related infrastructure in the NZE, notably renewable electricity generation and transport infrastructure. The additional infrastructure required for these two segments by 2050 relative to today alone contributes roughly 10% of steel demand in 2050. But co-ordinated cross-sectoral strategies, including modal shifts in transport and building renovation, as well as other changes in design, manufacturing methods, construction practices and consumer behaviour, more than offset this increase. Overall, global demand for steel in 2050 is 12% higher than today, primary chemicals is 30% higher and cement demand is broadly flat.

CO_2 emissions from heavy industry decline by 20% by 2030 and 93% by 2050 in the NZE. Optimising the operational efficiency of equipment, adopting the best available technologies for new capacity additions and measures to improve material efficiency play an important

part in this. However, there are limits to how much emissions can be reduced by these measures. Almost 60% of emissions reductions in 2050 in the NZE are achieved using technologies that are under development today (large prototype or demonstration scale) (Figure 3.16).

Figure 3.16 ▷ Global CO_2 emissions in heavy industry and reductions by mitigation measure and technology maturity category in the NZE



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An array of measures reduces emissions in heavy industry, with innovative technologies like CCUS and hydrogen playing a critical role

Hydrogen and CCUS technologies together contribute around 50% of the emissions reductions in heavy industry in 2050 in the NZE. These technologies enable the provision of large amounts of high-temperature heat, which in many cases cannot be easily provided by electricity with current technologies, and help to reduce process emissions from the chemical reactions inherent in some industrial production. Bioenergy also makes a contribution in a wide array of industrial applications.

Aside from the need for high-temperature heat and process emissions, two factors explain the slower pace of emissions reductions in heavy industries relative to other areas of the energy system. First, the ease with which many industrial materials and products can be traded globally means that markets are competitive and margins are low. This leaves little room to absorb additional costs stemming from the adoption of more expensive production pathways. It will take time to develop robust global co-operation and technology transfer frameworks or domestic solutions to enable a level playing field for these technologies. Second, heavy industries use capital-intensive and long-lived equipment, which slows the deployment of innovative low-emission technologies. Capacity additions in the period to 2030 – before a large-scale roll-out of innovative processes can take place – largely explain the persistence of industrial emissions in 2050, more than 80% of which are in emerging market and developing economies. Strategically timed investment in low-carbon technologies could help minimise early retirements (Box 3.1).

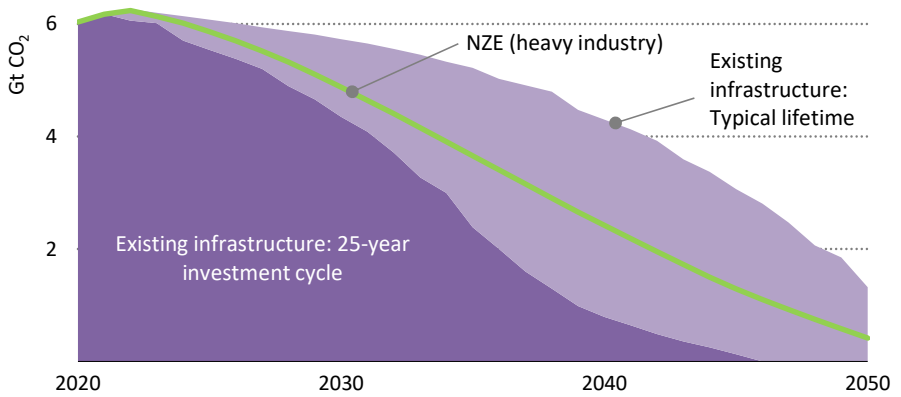
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Box 3.1 ▻ Investment cycles in heavy industry

For heavy industry, the year 2050 is just one investment cycle away. Average lifetimes of emissions-intensive assets such as blast furnaces and cement kilns are around 40 years. After about 25 years of operation, however, plants often undergo a major refurbishment to extend their lifetimes.

The challenge is to ensure that innovative near-zero emissions industrial technologies that are at large prototype and demonstration stage today reach markets within the next decade, when around 30% of existing assets will have reached 25 years of age and thus face an investment decision. If these innovative technologies are not ready, or not used even if ready, this would have a major negative impact on the pace of emissions reductions or risk an increase in stranded assets (Figure 3.17). Conversely, if they are ready, and if existing plants are retrofit or replaced with them at the 25-year investment decision point, this could reduce projected cumulative emissions to 2050 from existing heavy industry assets by around 40%. The critical window of opportunity from now to 2030 should not be missed.

Figure 3.17 ▻ CO_2 emissions from existing heavy industrial assets in the NZE



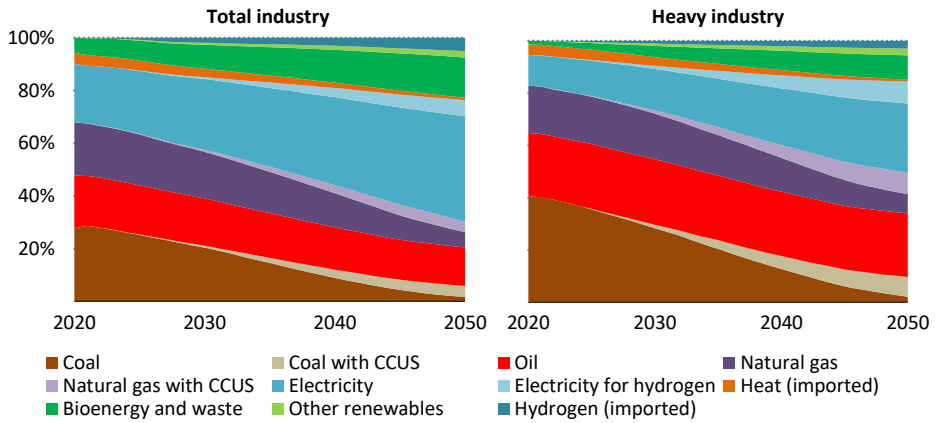
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Intervening at the end of the next 25-year investment cycle could help unlock 60 Gt CO_2, around 40% of projected emissions from existing heavy industry assets

The energy mix in industry changes radically in the NZE. The share of fossil fuels in total energy use declines from around 70% today to 30% in 2050. The vast majority of fossil fuels still being used then are in heavy industries, mainly as chemical feedstock (50%) or in plants equipped with CCUS (around 30%). Electricity is the dominant fuel in industrial energy demand growth, with its share of total industrial energy consumption rising from 20% in 2020 to 45% in 2050. Some 15% of this electricity is used to produce hydrogen. Bioenergy plays an important role, contributing 15% of total energy use in 2050, but sustainable supplies are

limited, and it is also in high demand in the power and transport sectors. Renewable solar and geothermal technologies to provide heat make a small but fast growing contribution (Figure 3.18).

Figure 3.18 ▷ Global final industrial energy demand by fuel in the NZE



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Fossil fuel use in industry is halved by 2050, replaced primarily by electricity and bioenergy

Notes: Industrial energy consumption includes chemical feedstock and energy consumed in blast furnaces and coke ovens. Hydrogen refers to imported hydrogen and excludes captive hydrogen generation. Electricity for hydrogen refers to electricity used in the production of captive hydrogen via electrolysis.

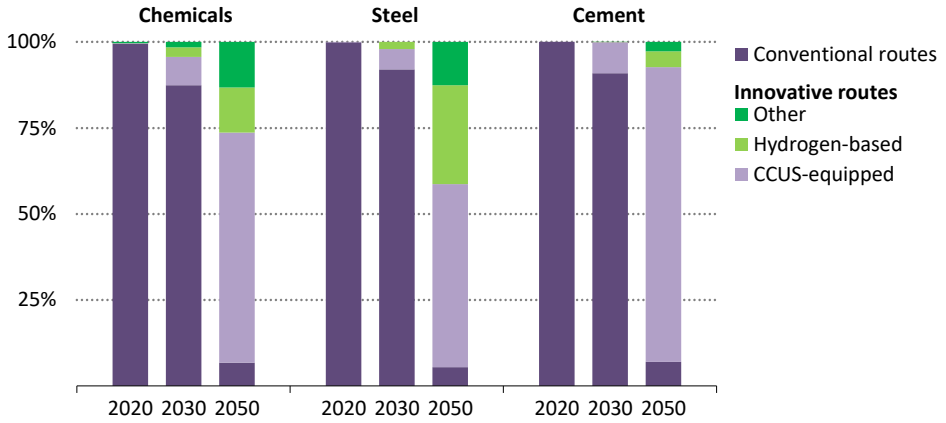
Chemicals production

In the NZE, emissions from the chemicals sub-sector fall from 1.3 Gt in 2020 to 1.2 Gt in 2030 and around 65 Mt in 2050. The share of fossil fuels in total energy use falls from 83% in 2020 (mostly oil and natural gas), to 76% in 2030 and 61% in 2050. Oil remains the largest fuel used in primary chemicals production by 2050 in the NZE, along with smaller quantities of gas and coal.

Technologies that are currently available on the market account for almost 80% of the emissions savings achieved globally in the chemical industry by 2030 in the NZE relative to today. They include recycling and re-use of plastics and more efficient use of nitrogen fertilisers, which reduce the demand for primary chemicals, and measures to increase energy efficiency. Beyond 2030, the bulk of emissions reductions result from the use of technologies whose integration in chemical processes is under development today, including certain CCUS applications and electrolytic hydrogen generated directly from variable renewable electricity (Figure 3.19). CCUS-equipped conventional routes and pyrolysis technologies are most competitive in regions with access to low cost natural gas, while electrolysis is the favoured option in regions where the deployment of CCUS is impeded by a lack of infrastructure or public acceptance.

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Figure 3.19 ▷ Global industrial production of bulk materials by production route in the NZE



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Near-zero emissions routes dominate cement, primary steel and chemicals production by 2050, with key roles for CCUS and hydrogen-based technologies

Notes: CCUS = carbon capture, utilisation and storage. Chemicals refers to the production of primary chemicals (ethylene, propylene, benzene, toluene, mixed xylenes, ammonia and methanol). Steel refers to primary steel production. Other includes innovative processes that utilise bioenergy and directly electrify production. Hydrogen-based refers to electrolytic hydrogen. Fossil fuel-based hydrogen with CCUS is included in the CCUS-equipped category.

Iron and steel production

In the NZE, global CO_2 emissions from the iron and steel sub-sector fall from 2.4 Gt in 2020 to 1.8 Gt in 2030 and 0.2 Gt in 2050, as the unabated use of fossil fuels falls sharply. Their share of the overall fuel mix drops from 85% today to just over 30% in 2050. The steel industry remains one of the last sectors using significant amounts of coal in 2050, primarily due to its importance as a chemical reduction agent, albeit mostly in conjunction with CCUS.

The NZE sees a radical technological transformation of the iron and steel sub-sector based largely on a major shift from coal to electricity. By 2050, electricity and other non-fossil fuels account for nearly 70% of final energy demand in the sector, up from just 15% in 2020. This shift is driven by technologies such as scrap-based electric arc furnaces (EAF), hydrogen-based direct reduced iron (DRI) facilities, iron ore electrolysis and the electrification of ancillary equipment. The share of coal in total energy use drops from 75% in 2020 to 22% by 2050 in the NZE, of which 90% is used in conjunction with CCUS.

Technologies that are currently on the market deliver around 85% of emissions savings in steel production to 2030. They include material and energy efficiency measures and a major increase in scrap-based production – which requires only around one-tenth of the energy of primary steel production – driven primarily by increased scrap availability as more products reach their end-of-life. Partial hydrogen injection into commercial blast furnaces and DRI

furnaces gain pace in the mid-2020s, building on pilot projects testing the practice today. After 2030, the bulk of emission reductions come from the use of technologies that are under development, including hydrogen-based DRI and iron ore electrolysis. Several CCUS-equipped process technologies are deployed in parallel, including innovative smelting reduction, natural gas-based DRI production (particularly in regions with low natural gas prices) and innovative blast furnace retrofit arrangements in regions with relatively young plants.

Cement production

Producing a tonne of cement today generates around 0.6 tonnes CO_2 on average, two-thirds of which are process emissions generated from carbon released from the raw materials used. Fossil fuels – mostly coal plus some petroleum coke – account for 90% of thermal energy needs.

Increased blending of alternative materials into cement to replace a portion of clinker (the active and most emissions-intensive ingredient), lower demand for cement and energy efficiency measures deliver around 40% of the emissions savings in 2030 compared with 2020. Through use of blended cements, the global clinker-to-cement ratio declines from 0.71 in 2020 to 0.65 in 2030. The ratio continues to decline after 2030, but more slowly, reaching 0.57 in 2050 (blended cements could reach a clinker-to-cement ratio as low as 0.5, but market application potential depends on regional contexts). Limestone and calcined clay are the main alternative materials used in blended cements by 2050. Since 0.5 is the lowest technically achievable clinker-to-cement ratio, other measures are needed to achieve deeper emission reductions.

After 2030 in the NZE, the bulk of emissions reductions come from the use of technologies that are under development today. CCUS is the most important, accounting for 55% of reductions in 2050 relative to today. In many cases, it is more cost-effective in the NZE to apply CCUS to fossil fuel combustion emissions than to switch to zero-emissions energy sources. Coal use is eliminated from cement production by 2050, when natural gas accounts for about 40% of thermal energy (up from 15% today), biomass and renewable waste for a further 35% (up from less than 5% today), hydrogen and direct electrification for just about 15%, and oil products and non-renewable waste for the remainder. Constraints on the availability of sustainable biomass supplies prevent it from claiming a higher share. Direct electrification of cement kilns is at the small prototype stage today, and so only starts to be deployed after 2040 on a small scale. From the 2040s, hydrogen provides around 10% of thermal energy needs in cement kilns, although blending of small amounts begins earlier. Innovative types of cement based on alternative binding materials that limit or avoid the generation of process emissions, and even enable CO_2 capture during the curing process, are either still at much earlier stages of development relative to other options like CCUS, or have limited applicability.

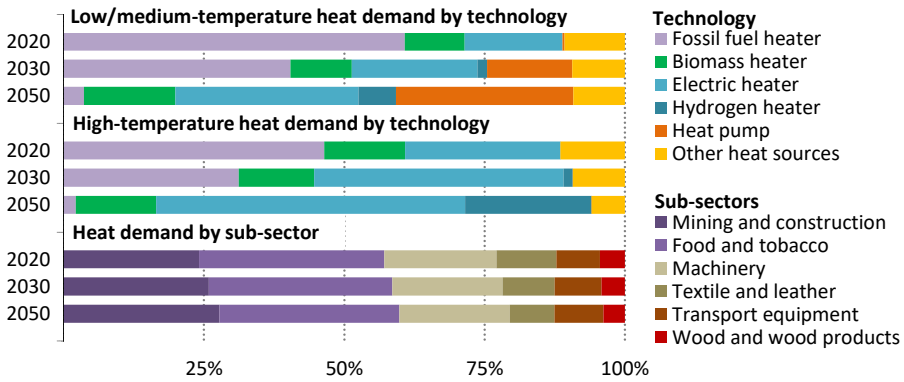
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Box 3.2 ▷ What about other industry sub-sectors?

Steel, cement and chemicals are not the only outputs from the industry sector. It also includes other energy-intensive sub-sectors such as aluminium, paper, other non-metallic minerals and non-ferrous metals, as well as light industries that produce vehicles, machinery, food, timber, textiles and other consumer goods, together with the energy consumed in construction and mining operations.

Emissions from the light industries decline by around 30% by 2030 and around 95% by 2050 in the NZE. In contrast to the heavy industries, most of the technologies required for deep emission reductions in these sub-sectors are available on the market and ready to deploy. This is in part because more than 90% of total heat demand is low/medium-temperature, which can be more readily and efficiently electrified.

Figure 3.20 ▷ Share of heating technology by temperature level in light industries in the NZE



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The share of electricty in satisfying heat demand for light industries rises from less than 20% today to around 40% in 2030 and about 65% in 2050

Notes: Light industries excludes non-specified industrial energy consumption. Low/medium-temperature heat corresponds to 0-400 °C and high-temperature heat to >400 °C. Other heat sources includes solar thermal and geothermal heaters, as well as imported heat from the power and fuel transformation sector.

Electricity accounts for around 40% of heat demand by 2030 and about 65% by 2050. For low- (<100 °C) and some medium- (100-400 °C) temperature heat, electrification includes an important role for heat pumps (accounting for about 30% of total heat demand in 2050). In the NZE, around 500 MW of heat pumps need to be installed every month over the next 30 years. Along with electrification, there are smaller roles for hydrogen and bioenergy for high-temperature heat (>400 °C), accounting for around 20% and around 15% respectively of total energy demand in 2050 (Figure 3.20). The rate of electrolyser capacity deployment is much lower than heavy industries, but the unit sizes will also be

much smaller. About 5% of heat demand is satisfied by direct use of renewables, including solar thermal and geothermal heating technologies.

Energy efficiency also plays a critical role in these manufacturing industries, notably through increased efficiency in electric motors (conveyers, pumps and other driven systems). By 2030, 90% of the motor sales in other industries are Class 3 or above.

3.5.2 Key milestones and decision points

Table 3.3 ▷ Key milestones in transforming global heavy industry sub-sectors

Category	
Heavy industry	• 2035: virtually, all capacity additions are innovative low-emissions routes.
Industrial motors	• 2035: all electric motors sales are best in class.

Category	2020	2030	2050
Total industry			
Share of electricity in total final consumption	21%	28%	46%
Hydrogen demand (Mt H_2)	51	93	187
CO_2 captured (Mt CO_2)	3	375	2 800
Chemicals			
Share of recycling: reuse in plastics collection	17%	27%	54%
reuse in secondary production	8%	14%	35%
Hydrogen demand (Mt H_2)	46	63	83
with on-site electrolyser capacity (GW)	0	38	210
Share of production via innovative routes	1%	13%	93%
CO_2 captured (Mt CO_2)	2	70	540
Steel			
Recycling, re-use: scrap as share of input	32%	38%	46%
Hydrogen demand (Mt H_2)	5	19	54
with on-site electrolyser capacity (GW)	0	36	295
Share of primary steel production: hydrogen-based DRI-EAF	0%	2%	29%
iron ore electrolysis-EAF	0%	0%	13%
CCUS-equipped processes	0%	6%	53%
CO_2 captured	1	70	670
Cement			
Clinker to cement ratio	0.71	0.65	0.57
Hydrogen demand (Mt H_2)	0	2	12
Share of production via innovative routes	0%	9%	93%
CO_2 captured (Mt CO_2)	0	215	1 355

Note: DRI = direct reduced iron; EAF = electric arc furnace.

From 2030 onwards, all new capacity additions in industry in the NZE feature near-zero emissions technologies. Much of the heavy industry capacity that will be added and replaced

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in the coming years is in emerging market and developing economies; they may expect financial support from advanced economies. Each month from 2030 to 2050, the NZE implies an additional 10 industrial plants equipped with CCUS, three additional fully hydrogen-based industrial plants and 2 GW of extra electrolyser capacity at industrial sites. While challenging, this is achievable. For comparison, about 12 heavy industrial facilities were built from scratch on average per month in China alone from 2000 to 2015. By 2050, nearly all production in heavy industry is with near-zero emissions technologies.

Decisive action from governments is imperative to achieve clean energy transitions in heavy industry at the scale and pace envisioned in the NZE. Within the next two years, governments in advanced economies will need to take decisions about funding for R&D for critical near-zero emissions industrial technologies and for mitigating the investment risks associated with demonstrating them at scale. This should lead to at least two or three commercial demonstration projects for each technology in different regions, and to market deployment by the mid-2020s. International co-ordination and co-operation would facilitate better use of resources and help prevent gaps in funding.

Governments also need to take early decisions on large-scale deployment of near-zero emissions technologies. By 2024 in advanced economies and 2026 in emerging market and developing economies, governments should have in place a strategy for incorporating near-zero emissions technologies into the next series of capacity additions and replacements for steel and chemical plants, which should include decisions about whether to pursue CCUS, hydrogen or a combination of both. If they are to succeed, those strategies need to include concrete plans for developing and financing the necessary infrastructure for CCUS and/or hydrogen, together with clean electricity generation for hydrogen production. The construction of the required infrastructure should begin as soon as possible given the long lead-times involved.

Within a similar timeframe, governments of countries that produce cement should decide how to develop the necessary CCUS infrastructure for that sub-sector, including the necessary legal and regulatory frameworks. Importing countries should make plans to move progressively to exclusive use of low-emissions cement, which may involve the need to support the development of CCUS-equipped facilities elsewhere in order to ensure supplies and to avoid a disproportionate burden being placed on other countries.

Strategies must be underpinned by specific policies. By 2025, all countries should have a long-term CO_2 emissions reduction policy framework in place to provide certainty that the next wave of investment in capacity additions will feature near-zero emissions technologies. Successful strategies are likely to require initial measures such as carbon contracts for difference, public procurement and incentives to encourage private sector procurement. As new technologies are deployed and costs decline, there is likely to be a strong case by about 2030 for replacing these initial measures with others such as CO_2 taxes, emissions trading systems and emissions performance standards. Financing support for near-zero emissions capacity additions may also have an important role to play through measures such as low interest and concessional loans and blended finance, as well as through contributions by

advanced economies to funds that support projects in emerging market and developing economies. Strategies should also include measures to reduce industrial emissions through material efficiency, for example by revising design regulations, adopting incentives to promote longer product and building lifetimes, and improving systems for collecting and sorting materials for recycling.

There is a strong case for an international agreement on the transition to near-zero emissions for globally traded products by the mid-2020s so as to establish a level playing field. Alternatively, countries may need to resort to measures to shield domestic near-zero emissions production from competition from products that create emissions. Any such policy would need to be designed to respect the regulatory frameworks governing international trade, such as those of the World Trade Organization.

Even with accelerated innovation timelines and strong policies in place, some high-emitting capacity additions will be needed to meet demand in the next decade before near-zero emissions technologies are available. It would make sense for governments to require any new capacity to incorporate retrofit-ready designs so that unabated capacity added in the next few years has the technical capacity and space requirement to integrate near-zero emissions technologies in coming years. Beyond 2030, investment in the NZE is confined to innovative near-zero emissions process routes.

Governments should not overlook the need for measures to spur deployment of already available near-zero emissions technologies in light manufacturing industries. Adopting a carbon price and then sufficiently increasing the price over time – through carbon taxes or emissions trading systems for larger manufacturers – may be the simplest way to achieve that objective. Other regulatory measures such as tradeable low-carbon fuel and emissions standards could yield the same outcome, but may involve greater administrative complexity. Technology mandates are likely to be needed to achieve the energy efficiency savings in the NZE, such as minimum energy performance standards for new motors and boilers. Tailored programmes and incentives for small and medium enterprises could also play a helpful role.

3.6 Transport

3.6.1 Energy and emission trends in the Net-Zero Emissions Scenario

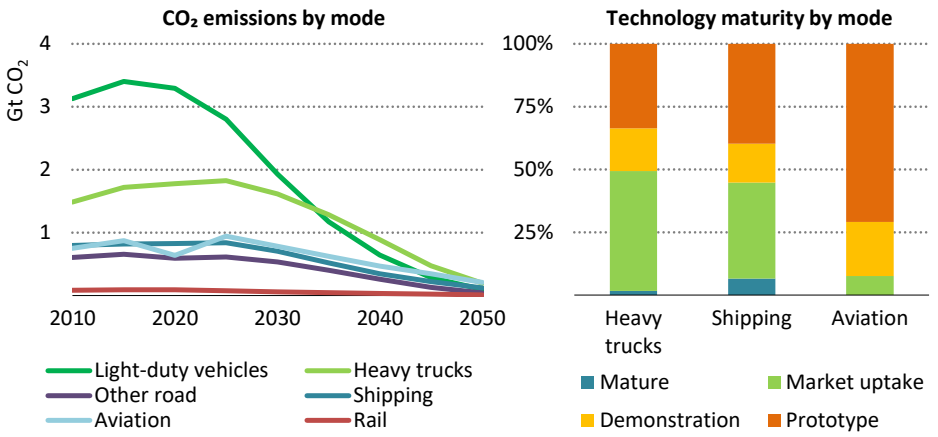
The global transport sector emitted over 7 Gt CO_2 in 2020, and nearly 8.5 Gt in 2019 before the Covid-19 pandemic.[7] In the NZE, transport sector CO_2 emissions are slightly over 5.5 Gt in 2030. By 2050 they are around 0.7 Gt – a 90% drop relative to 2020 levels. CO_2 emissions decline even with rapidly rising passenger travel, which nearly doubles by 2050, and rising freight activity, which increases by two-and-a-half-times from current levels, and an increase in the global passenger car fleet from 1.2 billion vehicles in 2020 to close to 2 billion in 2050.

[7] Unless otherwise noted, CO_2 emissions reported here are direct emissions from fossil fuel combusted during the operation of vehicles.

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The transport modes do not decarbonise at the same rate because technology maturity varies markedly between them (Figure 3.21). CO_2 emissions from two/three-wheelers almost cease by 2040, followed by cars, vans and rail in the late 2040s. Emissions from heavy trucks, shipping and aviation fall by an annual average of 6% between 2020 and 2050, but still collectively amount to more than 0.5 Gt CO_2 in 2050. This reflects projected activity growth and that many of the technologies needed to reduce CO_2 emissions in long distance transport are currently under development and do not start to make substantial inroads into the market in the coming decade.

Figure 3.21 ▷ Global CO_2 transport emissions by mode and share of emissions reductions to 2050 by technology maturity in the NZE



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Passenger cars can make use of low-emissions technologies on the market, but major advances are needed for heavy trucks, shipping and aviation to reduce their emissions

Notes: Other road = two/three wheelers and buses. Shipping and aviation include both domestic and international operations. See Box 2.4 for details on the maturity categories.

Decarbonisation of the transport sector in the NZE relies on policies to promote modal shifts and more efficient operations across passenger transport modes (see sections 2.5.7 and 4.4.3),[8] as well as improvements in energy efficiency. It also depends on two major technology transitions: shifts towards electric mobility (electric vehicles [EVs] and fuel cell electric vehicles [FCEVs])[9] and shifts towards higher fuel blending ratios and direct use of

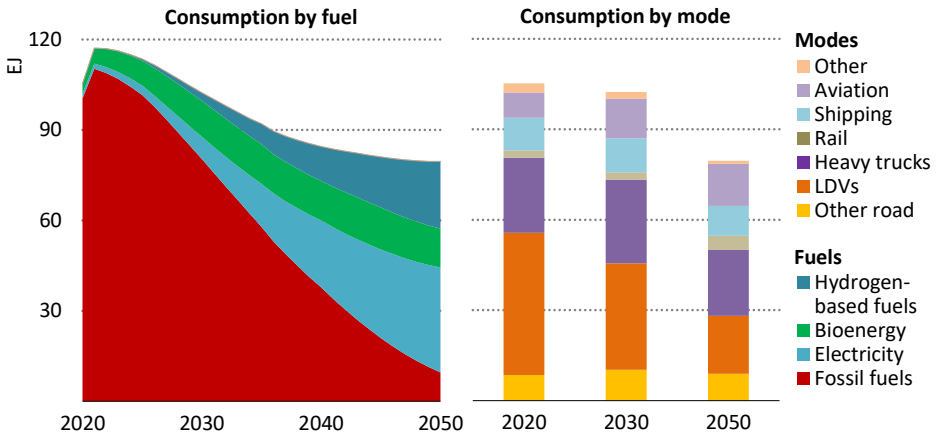
[8] Examples of efficient operations include: seamless integration of various modes (inter-modality) and "Mobility as a Service" in passenger transport; logistics measures in road freight, e.g. backhauling, night-time deliveries, real-time routing; slow steaming in shipping; and air traffic management, e.g. landing and take-off scheduling in aviation.

[9] EVs include battery electric vehicles, plug-in hybrid electric-gasoline vehicles and plug-in hybrid electric-diesel vehicles. FCEVs contain a battery and electric motor and are capable of operating without tailpipe emissions.

low-carbon fuels (biofuels and hydrogen-based fuels). These shifts are likely to require interventions to stimulate investment in supply infrastructure and to incentivise consumer uptake.

Transport has traditionally been heavily reliant on oil products, which accounted for more than 90% of transport sector energy needs in 2020 despite inroads from biofuels and electricity (Figure 3.22). In the NZE, the share of oil drops to less than 75% in 2030 and slightly over 10% by 2050. By the early 2040s, electricity becomes the dominant fuel in the transport sector worldwide in the NZE: it accounts for nearly 45% of total final consumption in 2050, followed by hydrogen-based fuels (28%) and bioenergy (16%). Biofuels almost reach a 15% blending share in oil products by 2030 in road transport, which reduces oil needs by around 4.5 million barrels of oil equivalent per day (mboe/d). Beyond 2030, biofuels are increasingly used for aviation and shipping, where the scope for using electricity and hydrogen is more limited. Hydrogen carriers (such as ammonia) and low-emissions synthetic fuels also supply increasing shares of energy demand in these modes.

Figure 3.22 ▷ Global transport final consumption by fuel type and mode in the NZE



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Electricity and hydrogen-based fuels account for more than 70% of transport energy demand by 2050

Note: LDVs = Light-duty vehicles; Other road = two/three wheelers and buses.

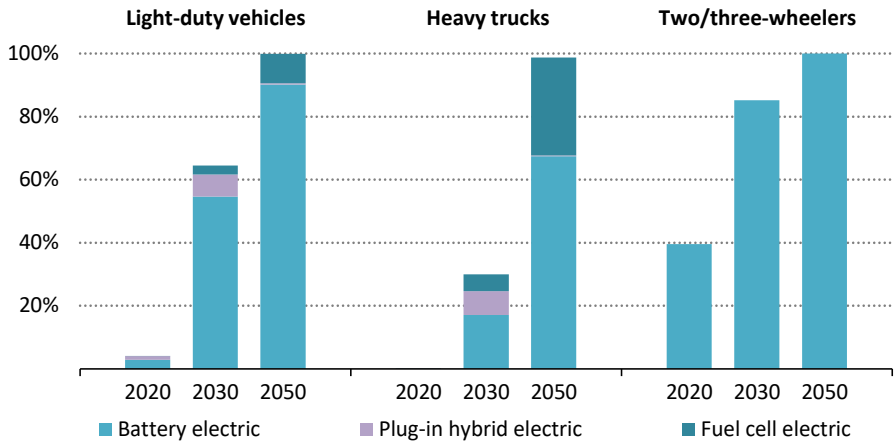
Road vehicles

Electrification plays a central role in decarbonising road vehicles in the NZE. Battery cost declines of almost 90% in a decade have boosted sales of electric passenger cars by 40% on average over the past five years. Battery technology is already relatively commercially competitive. FCEVs start to make inroads in the 2020s in the NZE. The electrification of heavy trucks moves more slowly due to the weight of the batteries, high energy and power

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requirements required for charging, and limits on driving ranges. But fuel cell heavy trucks make significant progress, mainly after 2030 (Figure 3.23). The number of battery electric, plug-in hybrid and fuel cell electric light-duty vehicles (cars and vans) on the world's roads reaches 350 million in 2030 and almost 2 billion in 2050, up from 11 million in 2020. The number of electric two/three-wheelers also rises rapidly, from just under 300 million today to 600 million in 2030 and 1.2 billion in 2050. The electric bus fleet expands from 0.5 million in 2020 to 8 million in 2030 and 50 million in 2050.

Figure 3.23 ▷ Global share of battery electric, plug-in hybrid and fuel cell electric vehicles in total sales by vehicle type in the NZE



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Sales of battery electric, plug-in hybrid and fuel cell electric vehicles soar globally

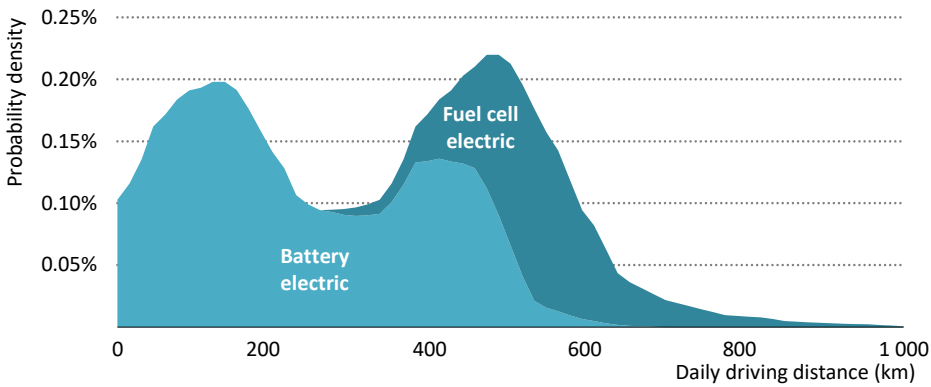
Note: Light-duty vehicles = passenger cars and vans; Heavy trucks = medium- and heavy-freight trucks.

Light-duty vehicles are electrified faster in advanced economies over the medium term and account for around 75% of sales by 2030. In emerging and developing economies, they account for about 50% of sales. Almost all light-duty vehicle sales in advanced economies are battery electric, plug-in hybrid or fuel cell electric by the early 2030s and in emerging and developing economies by the mid-2030s.

For heavy trucks that operate over long distances, currently biofuels are the main viable commercial alternative to diesel, and they play an important role in lowering emissions from heavy-duty trucks over the 2020s. Beyond 2030, the number of electric and hydrogen-powered heavy trucks increases in the NZE as supporting infrastructure is built and as costs decline (lower battery costs, energy density improvements and lower costs to produce and deliver hydrogen) (IEA, 2020b). This coincides with a reduction in the availability of sustainable bioenergy, as limited supplies increasingly go to hard-to-abate segments such as aviation and shipping, though biofuels still meet about 10% of fuel needs for heavy-duty trucks in 2050 (see Chapter 2). Advanced economies have a higher market share of battery

electric and fuel cell electric heavy-duty trucks sales in 2030, more than twice the level in emerging market and developing economies, although this gap closes towards 2050.

Figure 3.24 ▷ Heavy trucks distribution by daily driving distance, 2050



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Driving distance is the key factor affecting powertrain choice for trucks

Realising the objectives of the NZE depends on rapid scaling up of battery manufacturing (current announced production capacity for 2030 would cover only 50% of required demand in that year), and on the rapid introduction on the market of next generation battery technology (solid state batteries) between 2025 and 2030. Electrified road systems using conductive or inductive power transfer to provide electricity to trucks offer an alternative for battery electric and fuel cell electric trucks on long-distance operations, but these systems too would need rapid development and deployment.

Aviation[10]

The NZE assumes that air travel, measured in revenue-passenger kilometres, increases by only around 3% per year to 2050 relative to 2020. This compares with about around 6% over the 2010-19 period. The NZE assumes that aviation growth is constrained by comprehensive government policies that promote a shift towards high-speed rail and rein in expansion of long-haul business travel, e.g. through taxes on commercial passenger flights (see section 2.5.2).

Global CO_2 emissions from aviation rise in the NZE from about 640 Mt in 2020 (down from around 1 Gt in 2019) to a peak of 950 Mt by around 2025. Emissions then fall to 210 Mt in 2050 as the use of low-emissions fuels grows. Emissions are hard to abate because aviation

[10] Aviation considered here includes both domestic and international flights. While the focus here is on commercial passenger aviation, dedicated freight and general (military and private) aviation, which collectively account for more than 10% of fuel use and emissions, are also included in the energy and emissions accounting.

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requires fuel with a high energy density. Emissions in aviation comprise just over 10% of unabated CO_2 emissions from fossil fuels and industrial processes in 2050.

In the NZE, the global use of jet kerosene declines to about 3 EJ in 2050 from 9 EJ in 2020 (and around 14.5 EJ in 2019 before the Covid-19 crisis), and its share of total energy use falls from almost 100% to just over 20%. The use of sustainable aviation fuel (SAF) starts to increase significantly in the late-2020s. In 2030, around 15% of total fuel consumption in aviation is SAF, most of which is biojet kerosene (a type of liquid biofuel). This is estimated to increase the ticket price for a mid-haul flight (1 200 km) by about USD 3 per passenger. By 2050, biojet kerosene meets 45% of total fuel consumption in aviation and synthetic hydrogen-based fuels meet about 30%. This is estimated to increase the ticket price for a mid-haul flight in 2050 by about USD 10 per passenger. The NZE also sees the adoption of commercial battery electric and hydrogen aircraft from 2035, but they account for less than 2% of fuel consumption in 2050.

Operational improvements, together with fuel efficiency technologies for airframes and engines, also help to reduce CO_2 emissions by curbing the pace of fuel demand growth in the NZE. These improvements are incremental, but revolutionary technologies such as open rotors, blended wing-body airframes and hybridisation could bring further gains and enable the industry to meet the International Civil Aviation Organization's (ICAO) ambitious 2050 efficiency targets (IEA, 2020b).

Maritime shipping[11]

Maritime shipping was responsible for around 830 Mt CO_2 emissions worldwide in 2020 (880 Mt CO_2 in 2019), which is around 2.5% of total energy sector emissions. Due to a lack of available low-carbon options on the market and the long lifetime of vessels (typically 25-35 years), shipping is one of the few transport modes that does not achieve zero emissions by 2050 in the NZE. Nevertheless, emissions from shipping decline by 6% annually to 120 Mt CO_2 in 2050.

In the short term, there is considerable potential for curbing fuel consumption in shipping through measures to optimise operational efficiency and improve energy efficiency. Such approaches include slow steaming and the use of wind-assistance technologies (IEA, 2020b). In the medium to long term, significant emissions reductions are achieved in the NZE by switching to low-carbon fuels such as biofuels, hydrogen and ammonia. Ammonia looks likely to be a particularly good candidate for scaling up, and a critical fuel for long-range transoceanic journeys that need fuel with high energy density.

Ammonia and hydrogen are the main low-carbon fuels for shipping adopted over the next three decades in the NZE, their combined share of total energy consumption in shipping reaching around 60% in 2050. The 20 largest ports in the world account for more than half of global cargo (UNCTAD, 2018); they could become industrial hubs to produce hydrogen and

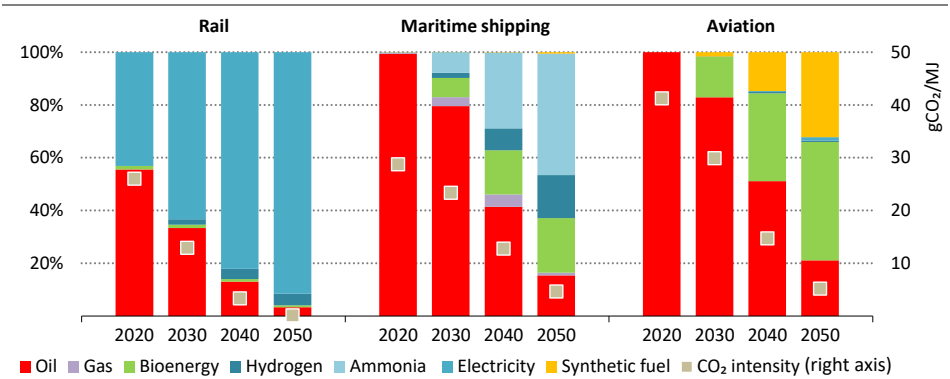
[11] Maritime shipping here includes both domestic and international operations.

ammonia for use in both chemical and refining industries, as well as for refuelling ships. Internal combustion engines for ammonia-fuelled vessels are currently being developed by two of the largest manufacturers of maritime engines and are expected to become available on the market by 2024. Sustainable biofuels provide almost 20% of total shipping energy needs in 2050. Electricity plays a very minor role, as the relatively low energy density of batteries compared with liquid fuels makes it suitable only for shipping routes of up to 200 km. Even with an 85% increase in battery energy density in the NZE as solid state batteries come to market, only short-distance shipping routes can be electrified.

Rail

Rail transport is the most energy-efficient and least carbon-intensive way to move people and second only to shipping for carrying goods. Passenger rail almost doubles its share of total transport activity to 20% by 2050 in the NZE, with particularly rapid growth in urban and high-speed rail (HSR), the latter of which contributes to curbing growth in air travel. Global CO_2 emissions from the rail sector fall from 95 Mt CO_2 in 2020 (100 Mt CO_2 in 2019) to almost zero by 2050 in the NZE, driven primarily by rapid electrification.

Figure 3.25 ▷ Global energy consumption by fuel and CO_2 intensity in non-road sectors in the NZE



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Railways rely heavily on electricity to decarbonise, while shipping and aviation curb emissions mainly by switching to low-emissions fuels

Note: Synthetic fuel = low-emissions synthetic hydrogen-based fuels.

In the NZE, all new tracks on high-throughput corridors are electrified from now on, while hydrogen and battery electric trains, which have recently been demonstrated in Europe, are adopted on rail lines where throughput is too low to make electrification economically viable. Oil use, which accounted for 55% of total energy consumption in the rail sector in 2020, falls to almost zero in 2050: it is replaced by electricity, which provides over 90% of rail energy needs and by hydrogen which provides another 5%.

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3.6.2 Key milestones and decision points

Table 3.4 ▷ Key milestones in transforming the global transport sector

Category	
Road transport	• 2035: no new passenger internal combustion engine car sales globally
Aviation and shipping	• Implementation of strict carbon emissions intensity reduction targets as soon as possible.

Category		2020	2030	2050
Road transport				
Share of PHEV, BEV and FCEV in sales:	cars	5%	64%	100%
	two/three-wheelers	40%	85%	100%
	bus	3%	60%	100%
	vans	0%	72%	100%
	heavy trucks	0%	30%	99%
Biofuel blending in oil products		5%	13%	41%
Rail				
Share of electricity and hydrogen in total energy consumption		43%	65%	96%
Activity increase due to modal shift (index 2020=100)		100	100	130
Aviation				
Synthetic hydrogen-based fuels share in total aviation energy consumption		0%	2%	33%
Biofuels share in total aviation energy consumption		0%	16%	45%
Avoided demand from behaviour measures (index 2020=100)		0	20	38
Shipping				
Share in total shipping energy consumption:	Ammonia	0%	8%	46%
	Hydrogen	0%	2%	17%
	Bioenergy	0%	7%	21%
Infrastructure				
EV public charging (million units)		1.3	40	200
Hydrogen refuelling units		540	18 000	90 000
Share of electrified rail lines		34%	47%	65%

Note: PHEV = plug-in hybrid electric vehicles; BEV = battery electric vehicles; FCEV = fuel cell electric vehicles.

Electrification is the main option to reduce CO_2 emissions from road and rail modes, the technologies are already on the market and should be accelerated immediately, together with the roll-out of recharging infrastructure for EVs. Deep emission reductions in the hard-to-abate sectors (heavy trucks, shipping and aviation) require a massive scale up of the required technologies over the next decade, which today are largely at the prototype and demonstration stages, together with plans for the development of associated infrastructure, including hydrogen refuelling stations.

The transformation of transport required to be on track to reduce emissions in line with the NZE calls for a range of government decisions over the next decade. In the next few years, all governments need to eliminate fossil fuel subsidies and encourage switching to low-carbon technologies and fuels across the entire transport sector. Before 2025, governments need to define clear R&D priorities for all the technologies that can contribute to decarbonise transport in line with their strategic priorities and needs. Ideally this would be informed by international dialogue and collaboration. R&D is critical in particular for battery technology, which should be an immediate priority.

To achieve the emissions reductions required by the NZE, governments also need to move quickly to signal the end of sales of new internal combustion engine cars. Early commitments would help the private sector to make the necessary investment in new powertrains, relative supply chains and refuelling infrastructure (see section 4.3.4). This is particularly important for the supply of battery metals, which require long-term planning (IEA, 2021a).

By 2025, the large-scale deployment of EV public charging infrastructure in urban areas needs to be sufficiently advanced to allow households without access to private chargers to opt for EVs. Governments should ensure sustainable business models for companies installing chargers, remove barriers to planning and construction, and put in place regulatory, fiscal and technological measures to enable and encourage smart charging, and to ensure that EVs support electricity grid stability and stimulate the adoption of variable renewables (IEA, 2021b).

For heavy trucks, battery electric trucks are just beginning to become available on the market, and fuel cell electric technologies are expected to come to market in the next few years. Working in collaboration with truck manufacturers, governments should take steps in the near term to prioritise the rapid commercial adoption of battery electric and fuel cell electric trucks. By 2030, they should take stock of the competitive prospects for these technologies, so as to focus R&D on the most important challenges and allow adequate time for strategic infrastructure deployment, thus paving the way for large-scale adoption during the 2030s.

Governments need to define their strategies for low-carbon fuels in shipping and aviation by 2025 at the latest, given the slow turnover rate of the fleets, after which they should rapidly implement them. International co-operation and collaboration will be crucial to success. Priority action should target the most heavily used ports and airports so as to maximise the impact of initial investment. Harbours near industrial areas are ideally placed to become low-carbon fuel hubs.

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Box 3.3 ▷ What would be the implications of an all-electric approach to emissions reductions in the road transport sector?

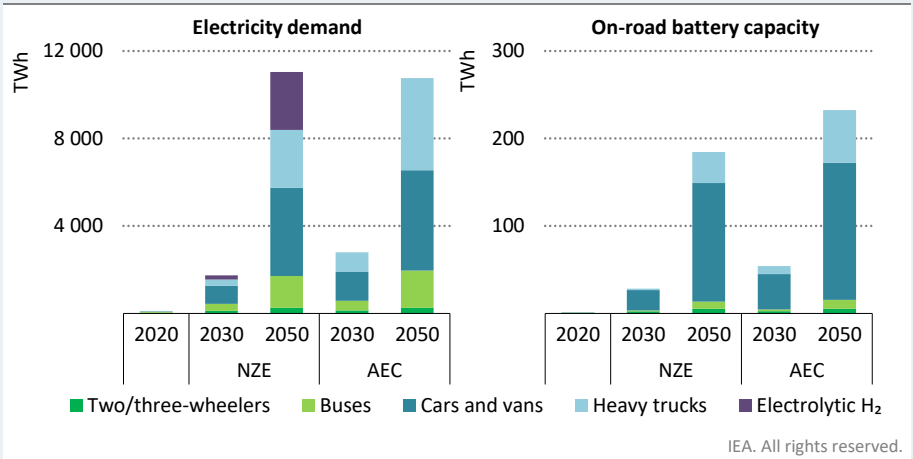
The use of a variety of fuels in road transport is a core component of the NZE. However, governments might want to consider an all-electric route to eliminate CO_2 emissions from transport, especially if other technologies such as FCEVs and advanced biofuels fail to develop as projected. We have therefore developed an *All-Electric Case* which looks at the implications of electrifying all road vehicle modes. In the NZE, decarbonisation of road transport occurs primarily via the adoption of plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs) and advanced biofuels. The All-Electric Case assumes the same rate of road transport decarbonisation as the NZE, but achieved via battery electric vehicles alone.

The All-Electric Case depends on even further advances in battery technologies than the NZE that lead to energy densities of at least 400 Watt hours per kilogramme (Wh/kg) by the 2030s at costs that would make BEV trucks preferable to FCEV trucks in long-haul operations. This would mean 30% more BEVs (an additional 350 million) on the road in 2030 than in the NZE. Over sixty five million public chargers would be needed to support the vehicles, requiring a cumulative investment of around USD 300 billion, 35% higher than the NZE. This would require faster expansion of battery manufacturing. The annual global battery capacity additions for BEVs in 2030 would be almost 9 TWh, requiring 80 giga-factories (assuming 35 GWh per year output) more than in the NZE, or an average of over two per month from now to 2030.

The increased use of electricity for road transport would also create additional challenges for the electricity sector. The total electricity demand for road transport (11 000 TWh or 15% of total electricity consumption in 2050), would be roughly the same in both cases, when account is taken of demand for electrolytic hydrogen. However, the electrolytic hydrogen in the NZE can be produced flexibly, in regions and at times with surplus renewables-based capacity and from dedicated (off-grid) renewable power. Peak power demand in the All-Electric Case, taking into consideration the flexibility that enables smart charging of cars, is about one-third (2 000 GW) higher than in the NZE, mainly due to the additional evening/overnight charging of buses and trucks. If not coupled with energy storage devices, ultra-fast chargers for heavy-duty vehicles could cause additional spikes in demand, putting even more strain on electricity grids.

While full electrification of road transport is possible, it could involve additional challenges and undesirable side effects. For example, it could increase pressure on electricity grids, requiring significant additional investment, and increasing the vulnerability of the transport system to power disruptions. Fuel diversification could bring benefits in terms of resilience and energy security.

Figure 3.26 ▷ Global electricity demand and battery capacity for road transport in the NZE and the All-Electric Case



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Both direct electricity consumption and vehicle battery capacity in 2050 increase by about a quarter in the All-Electric Case relative to the NZE

Note: AEC = All-Electric Case.

3.7 Buildings

3.7.1 Energy and emission trends in the Net-Zero Emissions Scenario

Floor area in the buildings sector worldwide is expected to increase 75% between 2020 and 2050, of which 80% is in emerging market and developing economies. Globally, floor area equivalent to the surface of the city of Paris is added every week through to 2050. Moreover, buildings in many advanced economies have long lifetimes and around half of the existing buildings stock will still be standing in 2050. Demand for appliances and cooling equipment continues to grow, especially in emerging market and developing economies where 650 million air conditioners are added by 2030 and another 2 billion by 2050 in the NZE. Despite this demand growth, total CO_2 emissions from the buildings sector decline by more than 95% from almost 3 Gt in 2020 to around 120 Mt in 2050 in the NZE.[12]

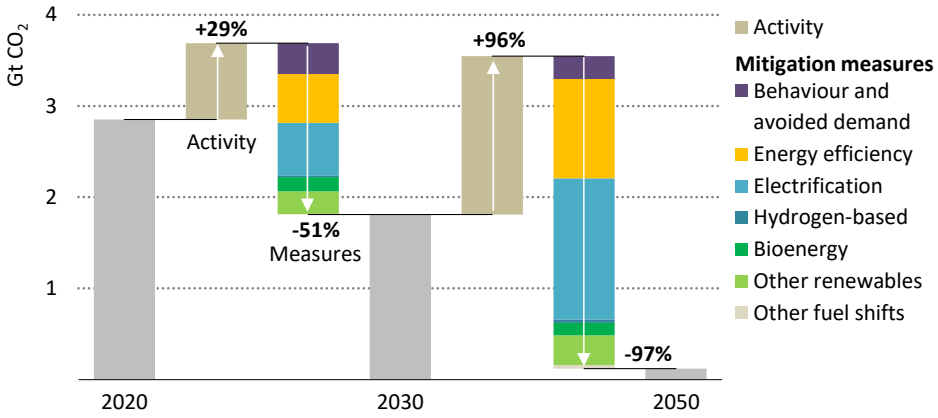
Energy efficiency and electrification are the two main drivers of decarbonisation of the buildings sector in the NZE (Figure 3.27). That transformation relies primarily on technologies

[12] All CO_2 emissions in this section refer to direct CO_2 emissions unless otherwise specified. The NZE also pursues reductions in emissions linked to construction materials used in buildings. These embodied emissions are cut by 40% per square metre of new floor area by 2030, with material efficiency strategies cutting cement and steel use by 50% by 2050 relative to today through measures at the design, construction, use and end-of-life phases.

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already available on the market, including improved envelopes for new and existing buildings, heat pumps, energy-efficient appliances, and bioclimatic and material-efficient building design. Digitalisation and smart controls enable efficiency gains that reduce emissions from the buildings sector by 350 Mt CO_2 by 2050. Behaviour changes are also important in the NZE, with a reduction of almost 250 Mt CO_2 in 2030 reflecting changes in temperature settings for space heating or reducing excessive hot water temperatures. Additional behaviour changes such as greater use of cold temperature clothes washing and line drying, facilitate the decarbonisation of electricity supply. There is scope for these reductions to be achieved rapidly and at no cost.

Figure 3.27 ▷ Global direct CO_2 emissions reductions by mitigation measure in buildings in the NZE



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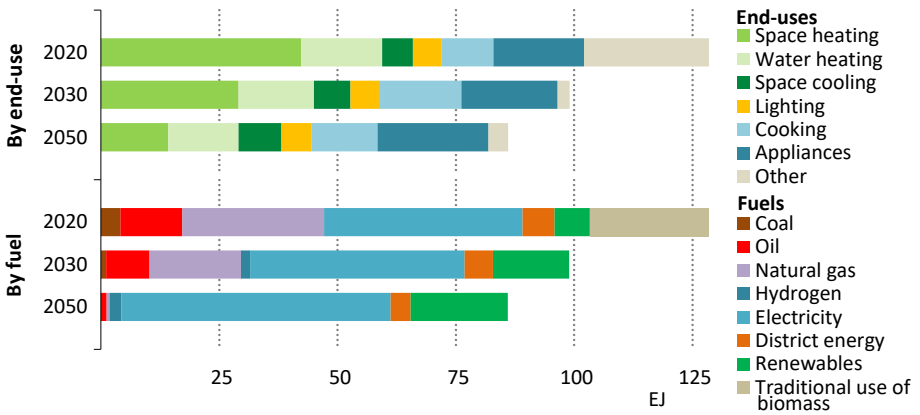
Electrification and energy efficiency account for nearly 70% of buildings-related emissions reductions through to 2050, followed by solar thermal, bioenergy and behaviour

Notes: Activity = change in energy service demand related to rising population, increased floor area and income per capita. Behaviour = change in energy service demand from user decisions, e.g. changing heating temperatures. Avoided demand = change in energy service demand from technology developments, e.g. digitalisation.

Rapid shifts to zero-carbon-ready technologies see the share of fossil fuels in energy demand in the buildings sector drop to 30% by 2030, and to 2% by 2050 in the NZE. The share of electricity in the energy mix reaches almost 50% by 2030 and 66% by 2050, up from 33% in 2020 (Figure 3.28). All end-uses today dominated by fossil fuels are increasingly electrified in the NZE, with the share of electricity in space heating, water heating and cooking increasing from less than 20% today to more than 40% in 2050. District energy networks and low-carbon gases, including hydrogen-based fuels, remain significant in 2050 in regions with high heating needs, dense urban populations and existing gas or district heat networks. Bioenergy meets nearly one-quarter of overall heat demand in the NZE by 2050, over 50% of bioenergy use is for cooking, nearly all in emerging market and developing economies, where 2.7 billion

people gain access to clean cooking by 2030 in the NZE. Space heating demand drops by two-thirds between 2020 and 2050, driven by improvement in energy efficiency and behavioural changes such as the adjustment of temperature set points.

Figure 3.28 ▷ Global final energy consumption by fuel and end-use application in buildings in the NZE



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Fossil fuel use in the buildings sector declines by 96% and space heating energy needs by two-thirds to 2050, thanks mainly to energy efficiency gains

Note: Other includes desalination and traditional use of solid biomass which is not allocated to a specific end-use.

Zero-carbon-ready buildings

The NZE pathway for the buildings sector requires a step change improvement in the energy efficiency and flexibility of the stock and a complete shift away from fossil fuels. To achieve this, more than 85% of buildings need to comply with zero-carbon-ready building energy codes by 2050 (Box 3.4). This means that mandatory zero-carbon-ready building energy codes for all new buildings need to be introduced in all regions by 2030, and that retrofits need to be carried out in most existing buildings by 2050 to enable them to meet zero-carbon-ready building energy codes.

Retrofit rates increase from less than 1% per year today to about 2.5% per year by 2030 in advanced economies: this means that around 10 million dwellings are retrofitted every year. In emerging market and developing economies, building lifetimes are typically lower than in advanced economies, meaning that retrofit rates by 2030 in the NZE are lower, at around 2% per year. This requires the retrofitting of 20 million dwellings per year on average to 2030. To achieve savings at the lowest cost and to minimise disruption, retrofits need to be comprehensive and one-off.

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Box 3.4 ▷ Towards zero-carbon-ready buildings

Achieving decarbonisation of energy use in the sector requires almost all existing buildings to undergo a single in-depth retrofit by 2050, and new construction to meet stringent efficiency standards. Building energy codes covering new and existing buildings are the fundamental policy instrument to drive such changes. Building energy codes currently exist or are under development in only 75 countries, and codes in around 40 of these countries are mandatory for both the residential and services sub-sectors. In the NZE, comprehensive zero-carbon-ready building codes are implemented in all countries by 2030 at the latest.

What is a zero-carbon-ready building?

A zero-carbon-ready building is highly energy efficient and either uses renewable energy directly, or uses an energy supply that will be fully decarbonised by 2050, such as electricity or district heat. This means that a zero-carbon-ready building will become a zero-carbon building by 2050, without any further changes to the building or its equipment.

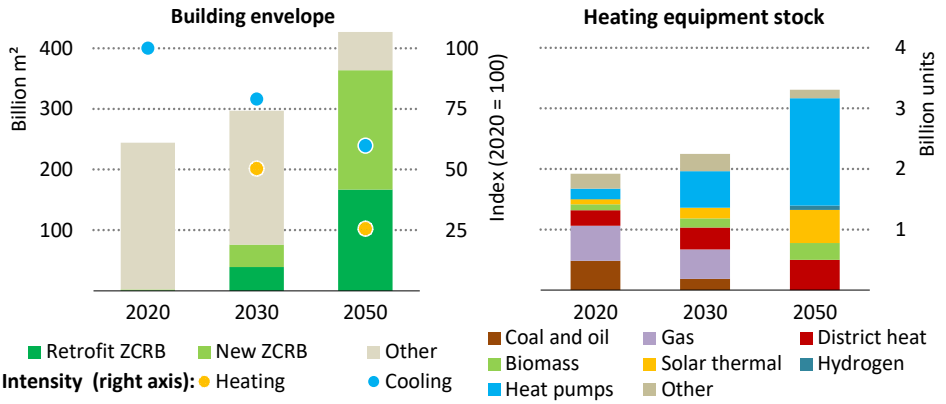
Zero-carbon-ready buildings should adjust to user needs and maximise the efficient and smart use of energy, materials and space to facilitate the decarbonisation of other sectors. Key considerations include:

- **Scope.** Zero-carbon-ready building energy codes should cover building operations (scope 1 and 2) as well as emissions from the manufacturing of building construction materials and components (scope 3 or embodied carbon emissions).
- **Energy use.** Zero-carbon-ready energy codes should recognise the important part that passive design features, building envelope improvements and high energy performance equipment play in lowering energy demand, reducing both the operating cost of buildings and the costs of decarbonising the energy supply.
- **Energy supply.** Whenever possible, new and existing zero-carbon-ready buildings should integrate locally available renewable resources, e.g. solar thermal, solar PV, PV thermal and geothermal, to reduce the need for utility-scale energy supply. Thermal or battery energy storage may be needed to support local energy generation.
- **Integration with power systems.** Zero-carbon-ready building energy codes need buildings to become a flexible resource for the energy system, using connectivity and automation to manage building electricity demand and the operation of energy storage devices, including EVs.
- **Buildings and construction value chain.** Zero-carbon-ready building energy codes should also target net-zero emissions from material use in buildings. Material efficiency strategies can cut cement and steel demand in the buildings sector by more than a third relative to baseline trends, and embodied emissions can be further reduced by more robust uptake of bio-sourced and innovative construction materials.

Heating and cooling

Building envelope improvements in zero-carbon-ready retrofit and new buildings account for the majority of heating and cooling energy intensity reductions in the NZE, but heating and cooling technology also makes a significant contribution. Space heating is transformed in the NZE, with homes heated by natural gas falling from nearly 30% of the total today to less than 0.5% in 2050, while homes using electricity for heating rise from nearly 20% of the total today to 35% in 2030 and about 55% in 2050 (Figure 3.29). High efficiency electric heat pumps become the primary technology choice for space heating in the NZE, with worldwide heat pump installations per month rising from 1.5 million today to around 5 million by 2030 and 10 million by 2050. Hybrid heat pumps are also used in some of the coldest climates, but meet no more than 5% of heating demand in 2050.

Figure 3.29 ▷ Global building and heating equipment stock by type and useful space heating and cooling demand intensity changes in the NZE



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By 2050, over 85% of buildings are zero-carbon-ready, reducing average useful heating intensity by 75%, with heat pumps meeting over half of heating needs

Notes: ZCRB refers to buildings meeting zero-carbon-ready building energy codes. Other for building envelope refers to envelopes that do not meet zero-carbon-ready building energy codes. Other for heating equipment stock includes resistive heaters, and hybrid and gas heat pumps.

Not all buildings are best decarbonised with heat pumps, however, and bioenergy boilers, solar thermal, district heat, low-carbon gases in gas networks and hydrogen fuel cells all play a role in making the global building stock zero-carbon-ready by 2050. Bioenergy meets 10% of space heating needs by 2030 and more than 20% by 2050. Solar thermal is the preferred renewable technology for water heating, especially where heat demand is low; in the NZE it meets 35% of demand by 2050, up from 7% today. District heat networks remain an attractive option for many compact urban centres where heat pump installation is impractical, in the NZE they provide more than 20% of final energy demand for space heating in 2050, up from a little over 10% today.

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There are no new coal and oil boilers sold globally from 2025 in the NZE. Sales of gas boilers fall by more than 40% from current levels by 2030 and by 90% by 2050. By 2025 in the NZE, any gas boilers that are sold are capable of burning 100% hydrogen and therefore are zero-carbon-ready. The share of low-carbon gases (hydrogen, biomethane, synthetic methane) in gas distributed to buildings rises from almost zero to 10% by 2030 to above 75% by 2050.

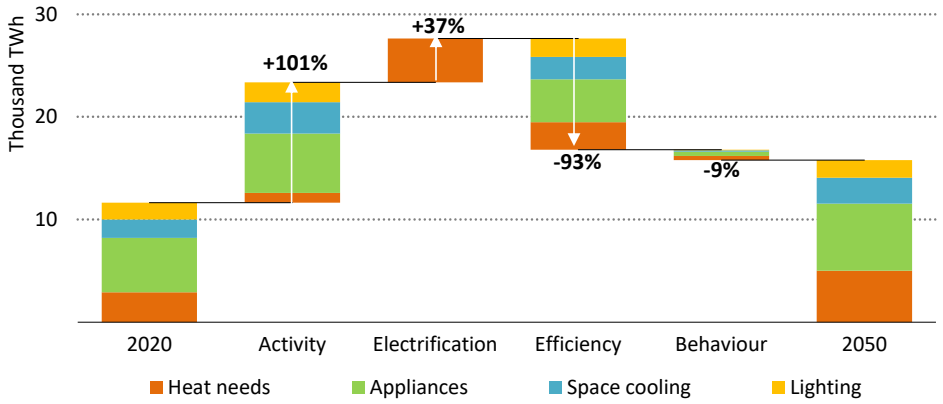
Buildings that meet the standards of zero-carbon-ready building energy codes drive down the need not only for space heating but also for space cooling – the fastest growing end-use in buildings since 2000. Space cooling represented only 5% of total buildings energy consumption worldwide in 2020, but demand for cooling is likely to grow strongly in the coming decades with rising incomes and a hotter climate. In the NZE, 60% of households have an air conditioner in 2050, up from 35% in 2020. High-performance building envelopes, including bioclimatic designs and insulation, can reduce the demand for space cooling by 30-50%, while providing greater resilience during extreme heat events. In the NZE, electricity demand for space cooling grows annually by 1% to reach 2 500 TWh in 2050. Without 2 000 TWh of savings from residential building envelope improvements and higher efficiency equipment, space cooling demand would be almost twice as high.

Appliances and lighting

Electric appliances and lighting become much more efficient over the next three decades in the NZE thanks to policy measures and technical advances. By 2025 in the NZE, over 80% of all appliances and air conditioners sold in advanced economies are the best available technologies today in these markets, and this share increases to 100% by the mid-2030s. In emerging market and developing economies, which account for over half of appliances and air conditioners by 2050, the NZE assumes a wave of policy action over the next decade which leads to 80% of equipment sold in these markets in 2030 being as efficient as the best available technologies in advanced economies today, increasing to close to 100% by 2050 (Figure 3.30). The share of light-emitting diode (LED) lamps in total lightbulb sales reaches 100% by 2025 in all regions. Minimum energy performance standards are complemented by requirements for smart control of appliances to facilitate demand-side response in all regions.

Energy use in buildings will be increasingly focused on electric, electronic and connected equipment and appliances. The share of electricity in energy consumption in buildings rises from 33% in 2020 to around two-thirds in 2050 in the NZE, with many buildings incorporating decentralised electricity generation using local solar PV panels, battery storage and EV chargers. The number of residential buildings with solar PV panels increases from 25 million to 240 million over the same period. In the NZE, smart control systems shift flexible uses of electricity in time to correspond with generation from local renewables, or to provide flexibility services to the power system, while optimised home battery and EV charging allow households to interact with the grid. These developments help improve electricity supply security and lower the cost of the energy transition by making it easier and cheaper to integrate renewables into the system.

Figure 3.30 ▷ Global change in electricity demand by end-use in the buildings sector



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Energy efficiency is critical to mitigate electricity demand growth for appliances and air conditioning, with savings more than offsetting the impact of electrifying heat

3.7.2 Key milestones and decision points

Table 3.5 ▷ Key milestones in transforming global buildings sector

Category	
New buildings	• From 2030: all new buildings are zero-carbon-ready.
Existing buildings	• From 2030: 2.5% of buildings are retrofitted to be zero-carbon-ready each year.

Category	2020	2030	2050
Buildings			
Share of existing buildings retrofitted to the zero-carbon-ready level	<1%	20%	>85%
Share of zero-carbon-ready new buildings construction	5%	100%	100%
Heating and cooling			
Stock of heat pumps (million units)	180	600	1 800
Million dwellings using solar thermal	250	400	1 200
Avoided residential energy demand from behaviour	n.a.	12%	14%
Appliances and lighting			
Appliances: unit energy consumption (index 2020=100)	100	75	60
Lighting: share of LED in sales	50%	100%	100%
Energy access			
Population with access to electricity (billion people)	7.0	8.5	9.7
Population with access to clean cooking (billion people)	5.1	8.5	9.7
Energy infrastructure in buildings			
Distributed solar PV generation (TWh)	320	2 200	7 500
EV private chargers (million units)	270	1 400	3 500

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Near-term government decisions are required for energy codes and standards for buildings, fossil fuel phase out, use of low-carbon gases, acceleration of retrofits and financial incentives to encourage investment in building sector energy transitions. Decisions will be most effective if they focus on decarbonising the entire value chain, taking into account not only buildings but also the energy and infrastructure networks that supply them, as well as wider considerations including the role of the construction sector and urban planning. Such decisions are likely to bring wider benefits, notably in reducing fuel poverty.

Near-term government action is needed to ensure that zero-carbon-ready buildings become the new norm across the world before 2030 for both new construction and retrofits. This requires governments to act before 2025 to ensure that zero-carbon-ready compliant building energy codes are implemented by 2030 at the latest. While this goal applies to all regions, ways to achieve zero-carbon-ready buildings vary significantly across regions and climate zones, and the same is true for heating and cooling technology strategies. Governments should consider paving the way by making public buildings zero-carbon-ready in the coming decade.

Governments will need to find ways to make new zero-carbon-ready buildings and retrofits affordable and attractive to owners and occupants by overcoming financial barriers, addressing split incentive barriers and minimising disruption to building use. Building energy performance certificates, green lease agreements, green bond financing and pay-as-you save models could all play a part.

Making zero-carbon-ready building retrofits a central pillar of economic recovery strategies in the early 2020s is a no-regrets action to jumpstart progress towards a zero-emissions building sector. Foregoing the opportunity to make energy use in buildings more efficient would drive up electricity demand linked to electrification of energy use in the buildings sector and make decarbonising the energy system significantly more difficult and more costly (Box 3.5).

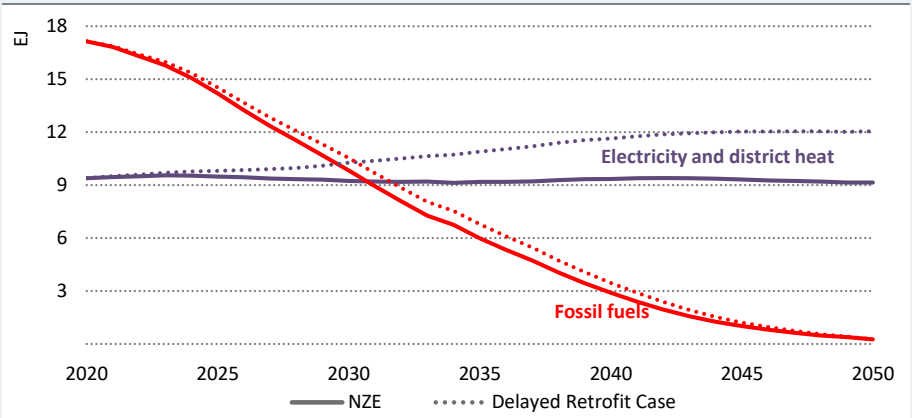
Box 3.5 ▷ What would be the impact of global retrofit rates not rising to 2.5%?

Decarbonising heating in existing buildings in the NZE rests upon a deep retrofit of the majority of the existing building stock. Having almost all buildings meet zero-carbon-ready building energy codes by 2050 would require retrofit rates of 2.5% each year by 2030, up from less than 1% today. Retrofits can be disruptive for occupants, require high upfront investment and may face permitting difficulties. These issues make achieving the required pace and depth of retrofits in the coming years the biggest challenge facing the buildings sector.

Any delay in reaching 2.5% of annual retrofits by 2030 would require such a steep subsequent ramp up as to make retrofitting the vast majority of buildings by 2050 virtually impossible. Modelling indicates that a delay of ten years in the acceleration of retrofitting, would increase residential space heating energy demand by 25% and space

cooling demand by more than 20%, translating to a 20% increase in electricity demand in 2050 relative to the NZE (Figure 3.31). This would put more strain on the power sector, which would need to install more low-carbon generation capacity. Policies and fuel switching would still drive down fossil fuel demand in the *Delayed Retrofit Case*, but an additional 15 EJ of fossil fuels would be burned by 2050, emitting 1 Gt of CO_2.

Figure 3.31 ▷ Global residential space heating and cooling energy demand in the NZE and Delayed Retrofit Case



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Delays in the ramp up of retrofit rates and depth would be almost impossible to catch up, placing further strain on the power sector and pushing up fossil fuel demand

Governments need to establish policies for coal and oil boilers and furnaces for space and water heating, which in the NZE are no longer available for sale from 2025. They also need to take action to ensure that new gas boilers are able to operate with low-carbon gases (hydrogen ready) in decarbonised gas networks. This puts a premium on the availability of compelling alternatives to the types of boilers being phased out, including the use of heat pumps, efficient wood stoves (using sustainable supplies of wood), district energy, solar PV, solar thermal and other renewable energy technologies. Which alternatives are best will depend to some extent on local conditions, but electrification will be the most energy-efficient and cost-effective low-carbon option in most cases, and decarbonising and expanding district energy networks is likely to make sense where densities allow. The use of biomethane or hydrogen in existing or upgraded gas networks may be the best option in areas where more efficient alternatives are not possible.

Governments also face decisions on minimum energy performance standards (MEPS). The NZE sees all countries introduce MEPS for all main appliance categories set at the most stringent levels prevailing in advanced economies by 2025 at the latest. Among others, this would mean ending the sale of incandescent, halogen and compact fluorescent lamps by that

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time. Setting MEPS at the right level will require careful planning; international collaboration to align standards and objectives could play a helpful role in keeping costs down.

The systemic nature of the NZE means that strategies and policies for buildings will work best if they are aligned with those being adopted for power systems, urban planning and mobility. This would help to ensure the successful scaling up of building-integrated PV technologies, battery storage and smart controls to make buildings active service providers to grids. It would also help to foster the deployment of smart EV charging infrastructure. Policies incentivising dense and mixed-use urban planning coupled with easy access to local services and public transport could reduce reliance on personal vehicles (see Chapter 2). There are also links between buildings strategies and measures to reduce the embodied carbon emissions of new construction, which falls by 95% by 2050 in the NZE.

Wider implications of achieving net-zero emissions

SUMMARY

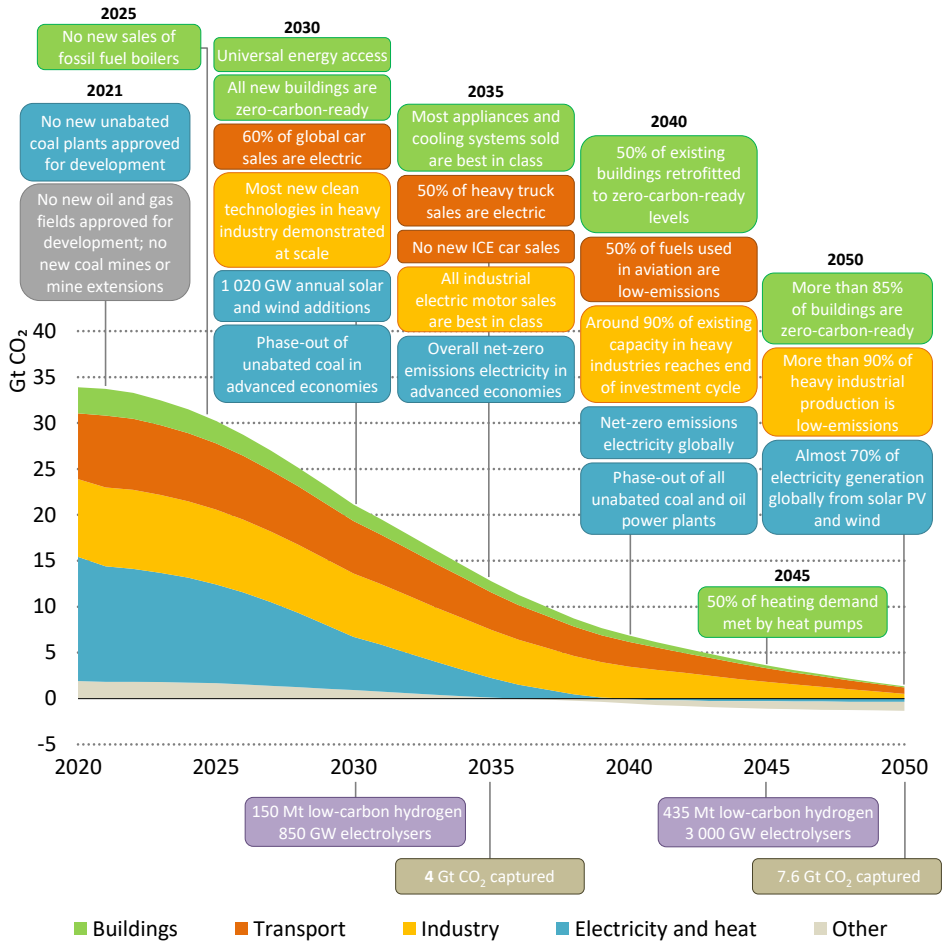
- **Economy:** In our Net-Zero Emissions by 2050 Scenario (NZE), global CO_2 emissions reach net zero by 2050 and investment rises across electricity, low-emissions fuels, infrastructure and end-use sectors. Clean energy employment increases by 14 million to 2030, but employment in oil, gas and coal declines by around 5 million. There are varying results for different regions, with job gains not always occurring in the same place, or matching the same skill set, as job losses. The increase in jobs and investment stimulates economic output, resulting in a net increase in global GDP to 2030. But oil and gas revenues in producer economies are 80% lower in 2050 than in recent years and tax revenues from retail oil and gas sales in importing countries are 90% lower.
- **Energy industry:** There is a major contraction in fossil fuel production, but companies that produce these fuels have skills and resources that could play a key role in developing new low-emissions fuels and technologies. The electricity industry scales up to meet demand rising over two-and-a-half-fold to 2050 and becomes more capital intensive, focusing on renewables, sources of flexibility and grids. Large energy-consuming companies, vehicle manufacturers and their suppliers adjust designs and retool factories while improving efficiency and switching to alternative fuel supplies.
- For **citizens** who lack access to electricity and clean cooking, the NZE delivers universal access by 2030. This costs around USD 40 billion a year over the next decade and adds less than 0.2% to CO_2 emissions. For citizens the world over, the NZE brings profound changes, and their active support is essential if it is to succeed. Around three-quarters of behavioural changes in the NZE can be directly influenced or mandated by government policies. The cost of energy is also an important issue for citizens, and the proportion of disposable household income spent on energy over the period to 2050 remains stable in emerging market and developing economies, despite a large increase in demand for modern energy services.
- **Government** action is central to achieve net-zero emissions globally by 2050; it underpins the decisions made by all other actors. Four particular points are worth stressing. First, the NZE depends on actions that go far beyond the remit of energy ministers, and requires a co-ordinated cross-government approach. Second, the fall in oil and gas demand in the NZE may reduce some traditional energy security risks, but they do not disappear, while potential new vulnerabilities emerge from increasing reliance on electricity systems and critical minerals. Third, accelerated innovation is needed. The emissions cuts to 2030 in the NZE can be mostly achieved with technologies on the market today, but almost half of the reductions in 2050 depend on technologies that are currently under development. Fourth, an unprecedented level of international co-operation is needed. This helps to accelerate innovation, develop international standards and facilitate new infrastructure to link national markets. Without the co-operation assumed in the NZE, the transition to net-zero emissions would be delayed by decades.

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4.1 Introduction

Achieving net-zero emissions by 2050 is a monumental task, especially against a backdrop of increasing economic and population growth. It calls for an unwavering focus from all governments, working together with industries and citizens, to ensure that the transition to global net-zero emissions proceeds in a co-ordinated way without delay. In this chapter, we look at what the changes that deliver net-zero emissions globally by 2050 in the NZE would mean for the economy, the energy industry, citizens and governments.

Figure 4.1 ▷ Selected global milestones for policies, infrastructure and technology deployment in the NZE



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There are multiple milestones on the way to global net-zero emissions by 2050. If any sector lags, it may prove impossible to make up the difference elsewhere.

Wide-ranging measures and regulations in the NZE help to influence or change the purchases that individuals make, the way they heat and cool their homes, and their means of transport. Many industries, especially those that are currently involved in the production of energy or are large-scale users of energy, also face change. Some of the shifts for individuals and industries may be unpopular, underscoring the fact that it is essential to ensure that the energy transition is transparent, just and cost-effective, and to persuade citizens of the need for reform. These changes deliver significant benefits. There are around 790 million people who do not have access to electricity today and 2.6 billion people who do not have access to clean cooking options. The NZE shows how emissions reductions can go hand-in-hand with efforts to provide universal access to electricity and clean cooking, and to improve air quality. It provides significant opportunities too, with clean energy technologies providing many new business opportunities and jobs, and with innovations that stimulate new industrial capacities.

Underpinning all of these changes are decisions taken by governments. This will require wholehearted buy-in from all levels of government and from all countries. The magnitude of the changes required to reach global net-zero emissions by 2050 are not within the power of government energy or environment departments alone to deliver, nor within the power of individual countries. It will involve an unprecedented level of global collaboration, with recognition of and sensitivity to differences in the stages of development of individual countries, and an appreciation of the difficulties faced by particular communities and members of society, especially those who may be negatively affected by the transition to net-zero emissions. In the NZE, governments start by setting unequivocal long-term targets, ensuring that these are fully supported from the outset by explicit, near-term targets and policy measures that clearly set out the pathway, and that recognise each country's unique starting conditions, to support the deployment of new infrastructure and technologies (Figure 4.1).

4.2 Economy

4.2.1 Investment and financing

The transition to net-zero emissions by 2050 requires a substantial ramp up in the investment of electricity, infrastructure and the end-use sectors. The largest increase over the next decade is in electricity generation: annual investment increases from about USD 0.5 trillion over the past five years to USD 1.6 trillion in 2030 (Figure 4.2). By 2030, annual investment in renewables in the electricity sector is around USD 1.3 trillion, slightly more than the highest level ever spent on fossil fuel supply (USD 1.2 trillion in 2014). Annual investment in clean energy infrastructure increases from around USD 290 billion over the past five years to about USD 880 billion in 2030. This is for electricity networks, public electric vehicle (EV) charging stations, hydrogen refuelling stations and import and export terminals, direct air capture and CO_2 pipelines and storage facilities. Annual investment in low-carbon technologies in end-use sectors rises from USD 530 billion in recent years to USD 1.7 trillion

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in 2030.[1] This includes spending on deep retrofitting of buildings, transformation of industrial processes, and the purchase of new low-emissions vehicles and more efficient appliances.

After 2030, annual electricity generation investment falls by one-third to 2050. A lot of infrastructure for a low-emissions electricity sector is established within the first decade of the NZE, and the cost of renewables continues to decline after 2030. In end-use sectors, there are continued increases in investment in EVs, carbon capture, utilisation and storage (CCUS) and hydrogen use in industry and transport, and more efficient buildings and appliances.

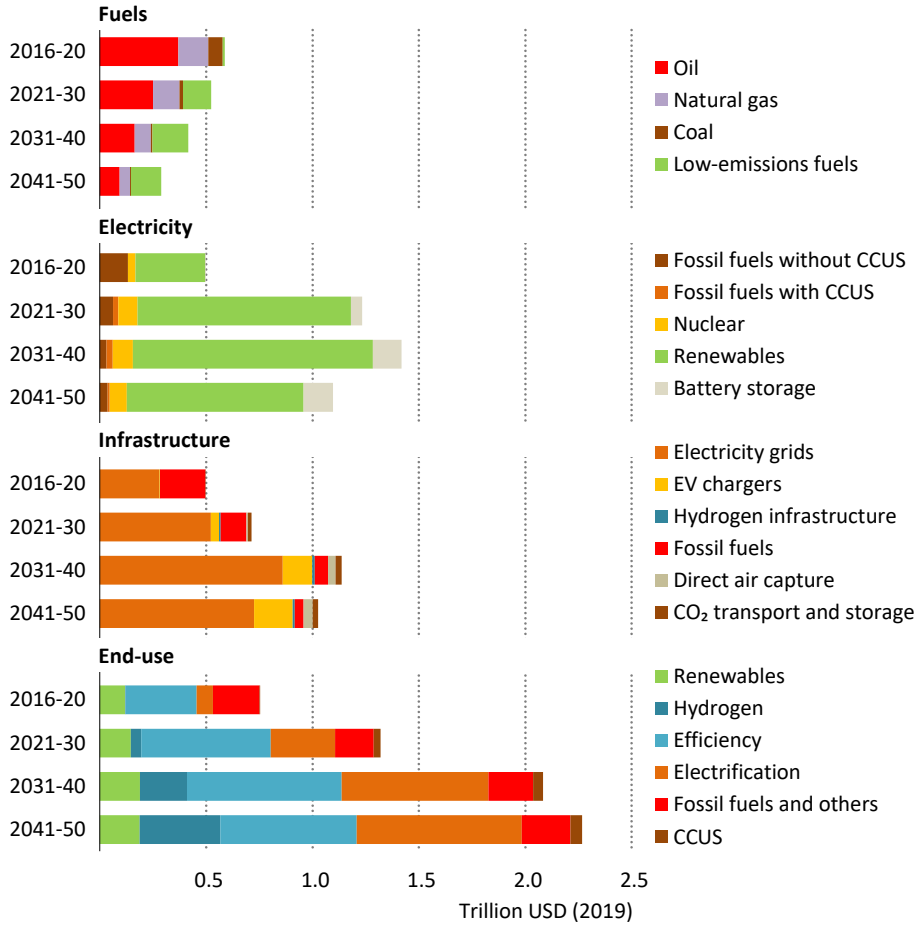
Global investment in fossil fuel supply falls steadily from about USD 575 billion on average over the past five years to USD 110 billion in 2050 in the NZE, with upstream fossil fuel investment restricted to maintaining production at existing oil and natural gas fields. This investment reflects the fact that fossil fuels are still used in 2050 in the NZE in processes where they are paired with CCUS, in non-emitting processes (such as petrochemical manufacturing), and in sectors where emissions reductions are most challenging (with emissions offset by carbon dioxide removal). Investment in low-emissions fuels increases more than thirty-fold between 2020 and 2050, reaching about USD 135 billion in 2050. This is split roughly equally between the production of hydrogen and hydrogen-based fuels, and the production of biofuels.

Over the 2021-50 period in the NZE, annual average total energy sector investment as a share of gross domestic product (GDP) is around 1% higher than over the past five years. The private sector is central to finance higher investment needs. It requires enhanced collaboration between developers, investors, public financial institutions and governments. Collaboration will be especially important over the next five to ten years for the development of large infrastructure projects and for technologies in the demonstration or prototype phase today such as some hydrogen and CCUS applications. Companies and investors have declared strong interest to invest in clean energy technologies, but turning interest into actual investment at the levels required in the NZE also depends on public policies.

Some obstacles to investment need to be tackled. Many emerging market and developing economies are reliant on public sources to finance energy projects and new industrial facilities. In some cases, improvements in regulatory and policy frameworks would facilitate the international flow of long-term capital to support the development of both new and existing clean energy technologies. The rapid growth in investment in transport and buildings in the NZE presents a different kind of challenge for policy makers. In many cases, an increase in capital spending for an efficient appliance or low-emissions vehicle would be more than offset by lower expenditure on fuels and electricity over the product lifetime, but some low-income households and small and medium enterprises may not be able to afford the upfront capital required.

[1] Investment levels presented in this report include a broader accounting of efficiency improvements in buildings and differ from that reported in the IEA World Energy Investment report (IEA, 2020a). End-use efficiency investments are the incremental cost of improving the energy performance of equipment relative to a conventional design.

Figure 4.2 ▷ Global average annual energy investment needs by sector and technology in the NZE



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Investment increases rapidly in electricity generation, infrastructure and end-use sectors. Fossil fuel investment drops sharply, partly offset by a rise in low-emissions fuels.

Notes: CCUS = carbon capture, utilisation and storage; EV = electric vehicle. Infrastructure includes electricity networks, public EV charging, CO_2 pipelines and storage facilities, direct air capture and storage facilities, hydrogen refuelling stations, and import and export terminals for hydrogen and fossil fuels pipelines and terminals. End-use efficiency investments are the incremental cost of improving the energy performance of equipment relative to a conventional design.

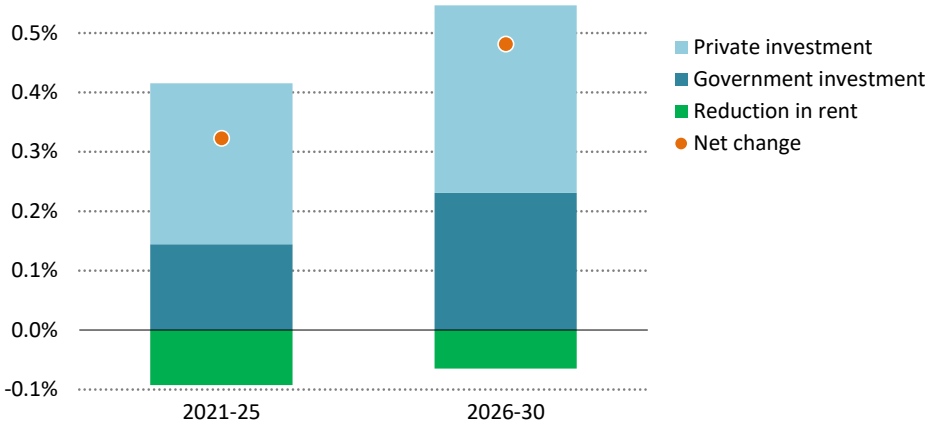
4.2.2 Economic activity

The energy transition required for net-zero emissions by 2050 will affect all economic activities directly or indirectly. In co-ordination with the International Monetary Fund, we have modelled the medium-term global macroeconomic impact of the changes in the energy

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sector that occur in the NZE. This analysis shows that the surge in private and government spending on clean energy technologies in the NZE creates a large number of jobs and stimulates economic output in the engineering, manufacturing and construction industries. This results in annual GDP growth that is nearly 0.5% higher than the levels in the Stated Policies Scenario (STEPS)[2] during latter half of the 2020s (Figure 4.3).[3]

Figure 4.3 ▷ Change in annual growth rate of global GDP in the NZE relative to the STEPS



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The surge in government and private investment in the NZE has a positive impact on global GDP, but there are large differences between regions

Notes: GDP = gross domestic product. Reduction in rents stem mainly from lower fossil fuel income.

Source: IEA analysis based on IMF.

There are large differences in macroeconomic impacts between regions. The decline in fossil fuel use and prices results in a fall in GDP in the producer economies,[4] where revenues from oil and gas sales often cover a large share of public spending on education, health care and other public services. The drop in oil and gas demand, and the consequent fall in international prices for oil and gas, cause net income in producer economies to drop to historic lows (Figure 4.4). Some countries with the lowest cost oil resources (including members of the

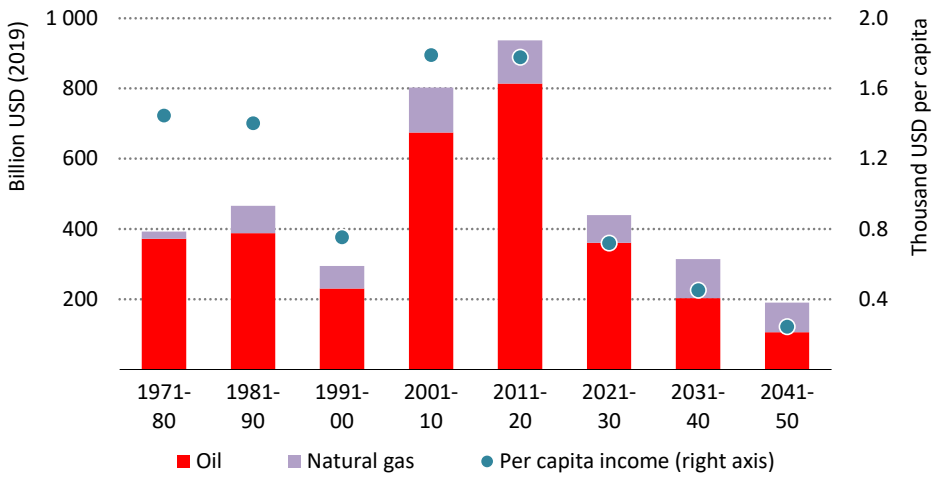
[2] The IEA Stated Policies Scenario is the projection for the global energy system based on the policies and measures that governments around the world have already put in place and on announced policies as expressed in official targets and plans, such as Nationally Determined Contributions put forward under the Paris Agreement (see Chapter 1).

[3] The estimated general equilibrium macroeconomic impact of the increase in public and private investment and the reduction in oil-related revenue contained in the NZE has been provided by the International Monetary Fund using its Global Integrated Monetary and Fiscal Model (GIMF).

[4] Producer economies are large oil and gas exporters that rely on hydrocarbon revenues to finance a significant proportion of their national budgets, including countries in the Middle East, Russia and the Caspian region.

Organization of the Petroleum Exporting Countries [OPEC]) gain market share in these circumstances, but even they would see large falls in revenues. Structural reforms would be needed to address the societal challenges, including those to accelerate the process of reforming inefficient fossil fuel subsidies and to speed up moves to use hydrocarbon resources to produce low-emissions fuels, e.g. hydrogen and hydrogen-based fuels (see section 4.3.1).

Figure 4.4 ▷ Income from oil and gas sales in producer economies in the NZE



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Structural reforms and new sources of revenue are needed in producer economies, but these are unlikely to compensate fully for a large drop in oil and gas income

The macroeconomic effects of the NZE are very uncertain. They depend on a host of factors including: how government expenditure is financed; benefits from improvements to health; changes in consumer bills; broad impact of changes in consumer behaviour; and potential for productivity spill-overs from accelerated energy innovation. Nonetheless, impacts are likely to be lower than assessments of the cost of climate change damages (OECD, 2015). It is also likely that a co-ordinated, orderly transition can be executed without major global systemic financial impacts, but this will require close attention from governments, financial regulators and the corporate sector.

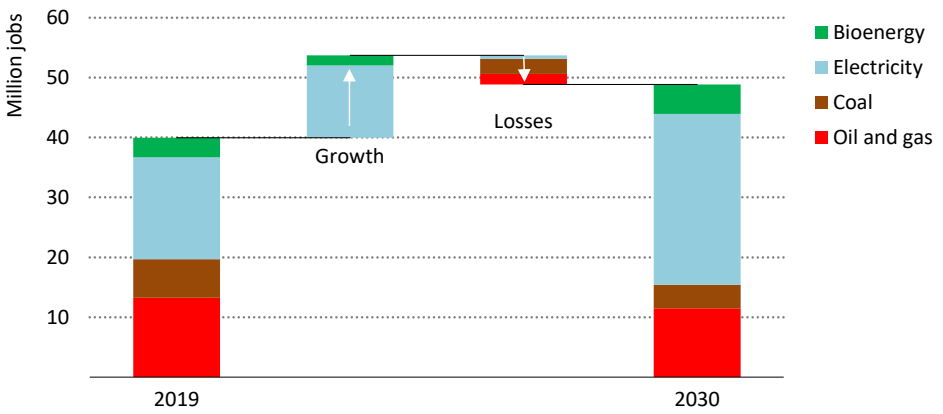
4.2.3 Employment

Employment in the energy sector shifts markedly in the NZE in response to changes in investment and spending on energy. We estimate that today roughly 40 million people around the world work directly in the oil, gas, coal, renewables, bioenergy and energy network industries (IEA, 2020b). In the NZE, clean energy employment increases by 14 million

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to 2030, while employment in oil, gas and coal fuel supply and power plants declines by around 5 million, leading to a net increase of nearly 9 million jobs (Figure 4.5).

Figure 4.5 ▷ Global energy sector employment in the NZE, 2019-2030



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Overall employment in the energy sector increases by almost 9 million to 2030 as jobs created in clean energy sectors outpace losses in fossil fuels

Jobs created would not necessarily be in the same area where jobs are lost, plus the skill sets required for the clean energy jobs may not be directly transferable. Job losses would be most pronounced in communities that are heavily dependent on fossil energy production or transformation activities. Even where the number of direct energy jobs lost is small, the impact on the local economy may be significant. Government support would almost certainly be needed to manage these transitions in a just, people-centred way. In preparation, a better understanding of current energy industry employment is needed. A useful action would be for governments to adopt more detailed surveying approaches for energy industry employment, such as those used in the *US Energy & Employment Report* (NASEO and Energy Futures Initiative, 2021).

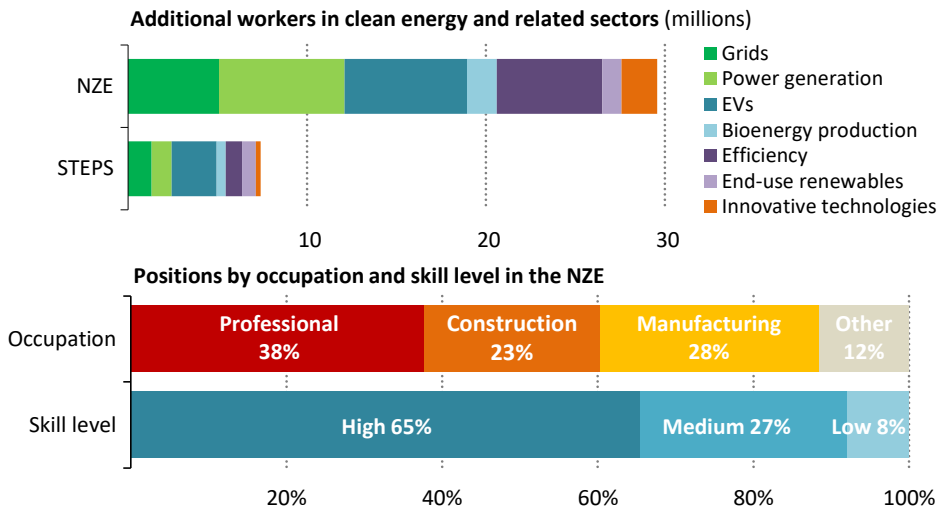
In addition to the 14 million new clean energy jobs created in the NZE, other new jobs are created by changes in spending on more efficient appliances, electric and fuel cell vehicles, and building retrofits and energy-efficient construction. These changes would require a further 16 million workers, meaning that there would be 30 million more people working in clean energy, efficiency and low-emissions technologies by 2030 in the NZE (Figure 4.6).[5] Investment in electricity generation, electricity networks, EV manufacturing and energy efficiency are among the areas that will open up new employment opportunities. For example, jobs in solar and wind more than quadruple in the NZE over current levels. Nearly two-thirds of workers in these sectors by 2030 in the NZE would be highly skilled and the

[5] This includes new jobs and jobs filled by moving current employment from one type of production to another.

majority require substantial training. In addition, with the more than doubling of total energy investment, new employment opportunities will arise in associated areas such as wholesale trading, financial and legal services.

In many cases it may be possible to shift workers to new product lines within the same company, for example in vehicle manufacturing as production reconfigures to EVs. However, there would be larger risks for specialised supply chain companies that provide products and services, e.g. internal combustion engines that are replaced by new components such as batteries.

Figure 4.6 ▷ New workers in clean energy and related sectors and shares by skill level and occupation in the NZE and the STEPS in 2030



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About 30 million new workers are needed by 2030 to meet increased demand for clean energy, efficiency, and low-emissions technologies; over half are highly skilled positions

Note: EVs = electric vehicles.

The new jobs created in the NZE tend to have more geographic flexibility and a wider distribution than is the case today. Around 40% are jobs located close to where the work is being done, e.g. building efficiency improvements or wind turbine installation, and the remaining are jobs tied to manufacturing sites. Today the manufacturing capacity for a number of clean energy technologies, such as batteries and solar photovoltaic panels, is concentrated in particular areas, notably China. The rapid increase in demand for clean energy technologies in the NZE requires new production capacity to come online that could be located in any region. Those countries and companies that move first may enjoy strategic advantages in capturing burgeoning demand.

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4.3 Energy industry

4.3.1 Oil and gas

The energy transition envisioned in the NZE involves a major contraction of oil and gas production with far-reaching implications for all the companies that produce these fuels. Oil demand falls from around 90 million barrels per day (mb/d) in 2020 to 24 mb/d in 2050, while natural gas demand falls from 3 900 billion cubic metres (bcm) to around 1 700 bcm. No fossil fuel exploration is required in the NZE as no new oil and natural gas fields are required beyond those that have already been approved for development. This represents a clear threat to company earnings, but there are also opportunities. The resources and skills of the oil and gas industry are a good match with some of the new technologies needed to tackle emissions in sectors where reductions are likely to be most challenging, and to produce some of the low-emissions liquids and gases for which there is a rapid increase in demand in the NZE (see Chapter 2). By partnering with governments and other stakeholders, the oil and gas industry could play a leading role in developing these fuels and technologies at scale, and in establishing new business models.

The oil and gas industry is highly diverse, and various companies could pursue very different strategies in the transition to net-zero emissions. Minimising emissions from core oil and gas operations however should be a first-order priority for all oil and gas companies. This includes tackling methane emissions that occur during operations (they fall by 75% between 2020 and 2030 in the NZE) and eliminating flaring. Companies should also electrify operations using renewable electricity wherever possible, either by purchasing electricity from the grid or by integrating off-grid renewable energy sources into upstream facilities or transport infrastructure. Producers that can demonstrate strong and effective action to reduce emissions can credibly argue that their oil and gas resources should be preferred over higher emissions options.

Some oil and gas companies may choose to become "energy companies" focused on low-emissions technologies and fuels, including renewable electricity, electricity distribution, EV charging and batteries. Several technologies that are critical to the achievement of net-zero emissions, such as CCUS, hydrogen, bioenergy and offshore wind, look especially well-suited to some of the existing skills, competencies and resources of oil and gas companies.

- **Carbon capture, utilisation and storage**. The oil and gas industry is already the global leader in developing and deploying CCUS. Of the 40 million tonnes (Mt) of CO_2 captured today at large-scale facilities, around three-quarters is captured from oil and gas operations, which often produce concentrated streams of CO_2 that are relatively easy and cost effective to capture (IEA, 2020c). The oil and gas industry also has the large-scale engineering, pipeline, sub-surface and project management skills and capabilities to handle large volumes of CO_2 and to help scale up the deployment of CCUS.

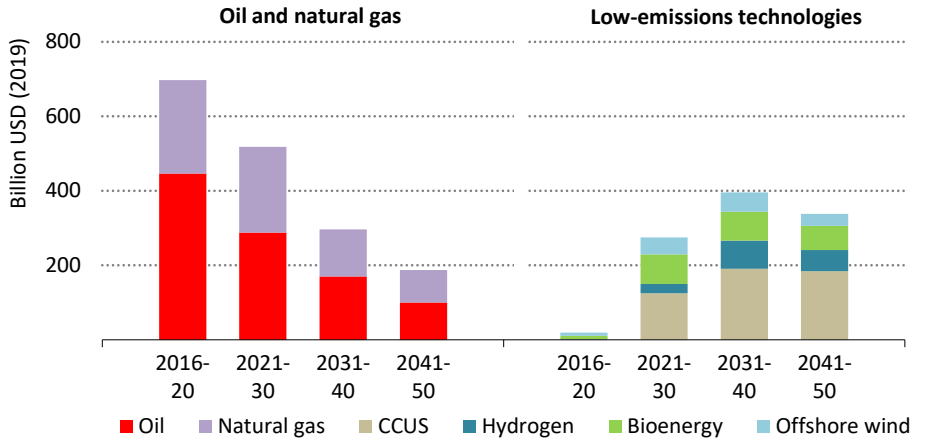
- **Low-emissions hydrogen and hydrogen-based fuels**. Oil and gas companies could contribute to developing and deploying low-emissions hydrogen in several ways (IEA, 2019a). Nearly 40% of hydrogen production in 2050 in the NZE is from natural gas in facilities equipped with CCUS, providing an important opportunity for companies and countries to utilise their natural gas resources in a way that is consistent with net-zero emissions. Of the total output of 530 Mt of hydrogen in 2050, about 30% is processed into ammonia and synthetic fuels (equivalent to around 7.5 mboe/d). The transformation processes involved have many potential synergies with the skills and equipment used in oil and gas processing and refining. Oil and gas companies also have long experience of transporting liquids and gases by pipeline and ships.
- **Advanced biofuels and biomethane**. The production of advanced biofuels grows substantially in the NZE, but this depends critically on continued technological innovation. Many oil and gas companies have active R&D programmes in these areas and could become leading producers. Biomethane – a low-emissions alternative to natural gas – can be produced in large centralised facilities, which could be a good fit with the knowledge and technical expertise of existing gas producers (IEA, 2020d).
- **Offshore wind**. About 40% of the lifetime costs of a standard offshore wind project involve significant synergies with the offshore oil and gas sector (IEA, 2019b). The oil and gas industry has considerable experience of working in offshore locations, which could be of value in the construction of foundations and subsea structures for offshore wind farms, especially when using vessels during installation and operation. The experience of maintaining safety standards in oil and gas companies could also be helpful during maintenance and inspection of offshore wind farms once they are in operation.

Oil and gas companies are well-placed to accelerate the pace of development and deployment of these technologies, and to gain a commercial edge over other companies. In the NZE, investment in low-emissions technologies suited to the skills and expertise of oil and gas companies exceeds that in traditional oil and gas operations by 2030. Total capital spending on these technologies and on traditional oil and gas operations averages USD 650 billion per year over 2021-50, just less than annual investment in oil and gas projects between 2016 and 2020 (Figure 4.7).

Not all oil and gas companies will choose to follow a strategy of diversifying into other types of energy. For example, it is far from certain that national oil companies will be charged by their state owners to diversify and develop low-emissions energy sources outside their core area of activity; other companies may decide simply to concentrate on supplying oil and natural gas as cleanly and efficiently as possible, and to return income to shareholders. What is clear, however, is that no oil and gas company would be unaffected by the NZE and that all parts of the industry need to decide how to respond (IEA, 2020e).

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Figure 4.7 ▷ Annual average investment in oil and gas and low-emissions technologies with synergies for the oil and gas industry in the NZE



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Investment in low-emissions technologies suited to the skills and expertise of oil and gas companies exceeds investment in traditional operations by 2030

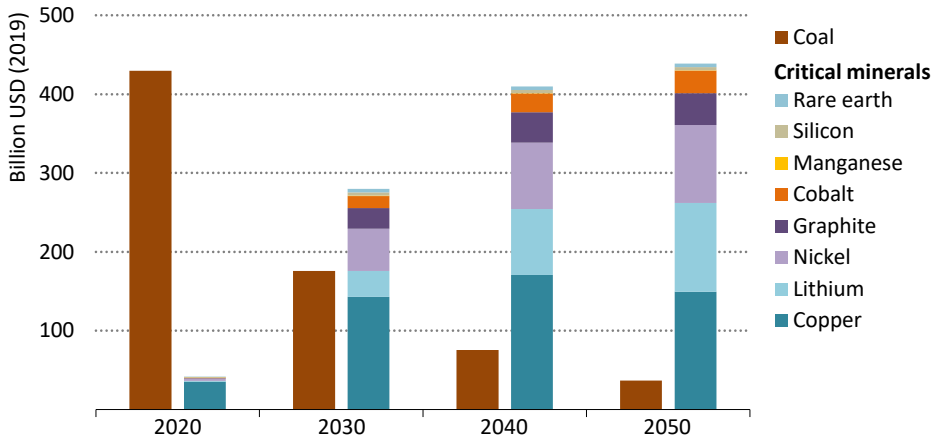
Note: CCUS = carbon capture, utilisation and storage.

4.3.2 Coal

The precipitous decline in coal use projected in the NZE would have major implications for the future of mining companies and countries with large existing production capacities. Around 470 million tonnes of coal equivalent (Mtce) of coal used in the NZE in 2050 is in facilities equipped with CCUS (80% of global coal demand in 2050), which prevents an even sharper decline in demand. But no new coal mines or mine extensions are needed in the NZE. Retraining and regional revitalisation programmes would be essential to reduce the social impact of job losses at the local level and to enable workers and communities to find alternative livelihoods. There could also be opportunities to locate new clean energy facilities, including the new processing facilities that are needed for critical minerals, in the areas most affected by mine closures.

For mining companies, however, the contraction in coal demand in the NZE could be offset by the need to increase mining of other raw minerals, including those vital to many clean energy technologies, such as copper, lithium and nickel (IEA, 2021a). Global demand for these critical minerals rises rapidly in the NZE (Figure 4.8). For example, demand for lithium for use in batteries expands by a factor of 30 by 2030, while demand for rare earths, primarily used for making EV motors and wind turbines, increases by a factor of ten by 2030. Critical mineral resources are not always located in the same locations or countries as existing coal mines, but the skills and experience of mining companies will be essential to ensure that the supply of these minerals is able to match demand at reasonable prices. By the 2040s, the size of the global market for these minerals approaches that for coal today.

Figure 4.8 ▷ Global value of coal and selected critical minerals in the NZE



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The market for critical minerals approaches that of coal today in the 2040s

Notes: Includes total revenue for coal and for selected critical minerals used in clean energy technologies. The prices of critical minerals are based on conservative assumptions about cost increases (around a 10%-20% increase from current levels to 2050).

4.3.3 Electricity

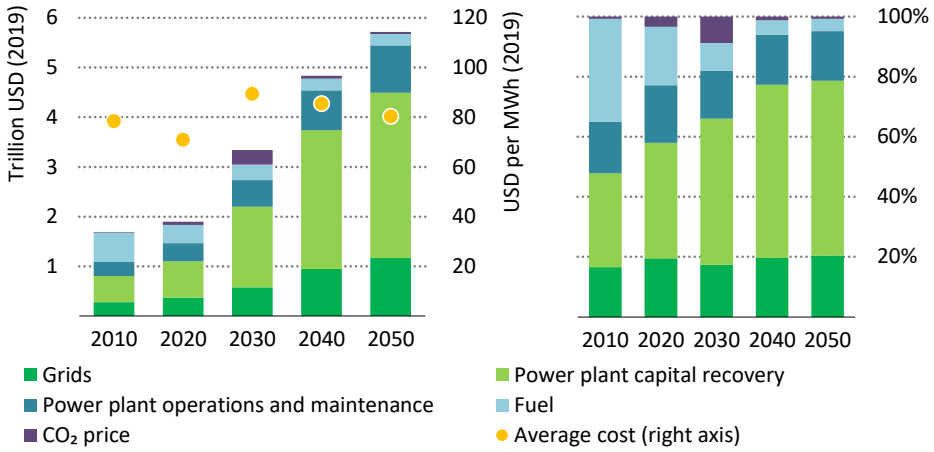
Getting to net-zero emissions calls for a massive expansion of the electricity sector to power the needs of a growing global economy, the electrification of end-uses that previously used fossil fuels, and the production of hydrogen from electrolysis. While electricity demand increases more than two-and-a-half times, the rapid transformation of the industry means that total electricity supply costs triple from 2020 to 2050 in the NZE, raising average costs per unit of electricity generation modestly (Figure 4.9).

The electricity supply industry also becomes much more capital intensive, accelerating a recent trend. The share of capital in total costs rises from less than 60% in 2020 (already ten percentage points higher than in 2010) to about 80% in 2050. This is largely due to a massive increase in renewable energy and the corresponding need for more network capacity and sources of flexibility, including battery storage. In the late 2020s and 2030s, the upgrading and replacement of existing solar and wind capacity as they come to the end of their operating lives also boosts capital needs.[6] New nuclear power capacity additions add further capital spending in the NZE. The rising capital intensity of the electricity industry increases the importance of limiting risk for new investment and ensuring sufficient revenues in all years for grid operators to fund rising investment needs – a point underlined by the financial difficulties experienced by some network companies in 2020 due to depressed electricity demand resulting from the Covid-19 crisis (IEA, 2020f).

[6] They typically need replacing after 25-30 years of operation, whereas many conventional hydropower, nuclear and coal plants operate far longer albeit with periodic additional investment.

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Figure 4.9 ▷ Global electricity supply costs by component in the NZE



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Electricity system costs triple to 2050, raising average supply costs modestly; the massive growth of renewables makes the industry more capital intensive

Notes: Electricity supply costs include all the direct costs to produce and transmit electricity to consumers. Battery storage systems are included in power plant capital recovery.

The rising share of renewables in the electricity generation mix has important implications for the design of electricity markets. When the shares of solar, wind, other variable renewables and nuclear power reach high levels, available electricity supply at no marginal cost is often above electricity demand, resulting in a wholesale price of electricity that is zero or even negative. By 2050, without changes in electricity market design, about 7% of wind and solar output in the NZE would be above and beyond what can be integrated (and so curtailed), and the share of zero-price hours in the year would increase to around 30% in major markets from close to zero today, despite the active use of demand response. If the share of renewables in the electricity generation mix is to rise as envisioned in the NZE, it would therefore be highly desirable to effect significant changes in the design of electricity markets so as to provide signals for investment, including investment in sources of flexibility such as battery storage and dispatchable power plants.

The increase in electricity use inevitably raises associated costs. Operating and maintaining power plants worldwide costs close to USD 1 trillion in 2050 in the NZE, two-and-a-half times the level in 2020. In 2020, upkeep at fossil fuel power plants accounted for USD 150 billion, and renewables required nearly as much, mostly for hydropower. By 2050, the cost of operating and maintaining renewables reaches USD 780 billion, most it needed for wind and solar photovoltaics (PV) as a result of their massive scaling up: offshore wind alone accounts for USD 90 billion.

The sharp reduction of fossil fuel use in the electricity industry and lower fuel prices mean that costs related to fuel and CO_2 prices are significantly reduced. This continues a recent trend driven by near record-low natural gas prices in many markets. Even with rising CO_2 prices over time, the rapid decarbonisation of electricity means that fuel and CO_2 make up a declining share of total costs, falling from about one-quarter in 2020 to 5% in 2050. The balance of fuel costs shifts towards low-emissions sources, mainly nuclear power and bioenergy (including with CCUS), though some still remains related to natural gas and coal used in power plants equipped with CCUS.

One challenge in this context is what to do about the coal-fired power plants in operation. In 2020, over 2 100 gigawatts (GW) of power plants worldwide used coal to produce electricity and heat, and they emitted nearly 30% of all energy-related CO_2 emissions. Options include retrofitting coal-fired power plants with CCUS technologies, co-firing with biomass or ammonia; repurposing coal plants to focus on providing flexibility; and, where feasible, phasing them out. In the NZE, all unabated coal-fired power plants are phased out in advanced economies by 2030 and in emerging market and developing economies by 2040. As a result, emissions from coal-fired power plants fall from 9.8 gigatonnes (Gt) in 2020 to 3.0 Gt in 2030 and to just 0.1 Gt by 2040 (residual emissions from coal with CCUS plants).[7]

Another challenge is related to the scale of capacity retirements envisaged and associated site rehabilitation, starting with coal. The pace of retirement of coal-fired power plants over 2020-50 is nearly triple that of the past decade. Decommissioning at each site can often last a decade and entail significant cost, and may involve closing a mine as well. In some cases, it may be financially attractive to build a renewable energy project on the same site, taking advantage of the grid connection and limiting the cost of rehabilitation. Thousands of natural gas-fired and oil-fired power plants are also retired by 2050, though these sites are often strategically located on the grid and many are likely to be replaced directly with battery storage systems.

The large fleet of ageing nuclear reactors in advanced economies means their decommissioning increases, despite many reactor lifetime extensions. In the NZE, annual average nuclear retirements globally are 60% higher over the next 30 years than in the last decade. Each nuclear decommissioning project can span decades, with costs ranging from several hundred million dollars to well over USD 1 billion for large reactors (NEA, 2016).

4.3.4 Energy-consuming industries

The changes in the NZE would have an enormous impact on industries that manufacture vehicles and their material and component suppliers. Around 95% of all the cars and nearly all of the trucks sold worldwide in 2020 were conventional vehicles with an internal combustion engine. In the NZE, about 60% of global car sales in 2030 are EVs, and 85% of

[7] A CO_2 capture rate of 90% is assumed, though higher rates are technically possible with reduced efficiencies and additional costs (IEA, 2020g).

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heavy-duty trucks sold in 2040 are EVs or fuel cell vehicles. In the NZE, vehicle component suppliers and vehicle manufacturers alike retool factories, change designs to incorporate batteries and fuel cells, and adjust supply chains to minimise the lifecycle emissions intensities of vehicles. This provides opportunities to redesign existing parts and manufacturing processes to improve efficiency and lower costs.

The rapid increase in EV sales in the NZE requires an immediate scale up of new supply chains for batteries as well as recharging and low-emissions refuelling infrastructure. In the NZE, battery production capacity increases to more than 6.5 terawatt-hours (TWh) by 2030, compared with less than 0.2 TWh in 2020. Any delay in expanding battery manufacturing capacity would have a detrimental impact on the roll-out of EVs and slow cost reductions for other clean energy technologies that benefit in the NZE from having similar manufacturing processes and know-how (such as fuel cell vehicles and electrolysers).

In aviation and shipping, liquid low-emissions fuels are central to cut emissions. Switching to some of these would have little impact on vessel design: the use of hydrogen-based fuels or biofuels in shipping would only require changes to the motor and fuel system, and bio-kerosene or synthetic kerosene can operate with existing aircraft. New bunkering and refuelling infrastructure are needed in the NZE, however, and the use of these low-emissions fuels also requires new safety and standardisation standards, protocols for permitting, construction and design, as well as international regulation, monitoring, reporting and verification of their production and use.

In heavy industrial sectors – steel, cement and chemicals – most deep emissions reduction technologies are not available on the market today. In the NZE, material producers soon demonstrate near-zero emission processes, aided by government risk-sharing mechanisms, and start to adapt their existing production assets. For multinational companies, this includes developing technology transfer strategies to roll-out processes across plants. International co-operation would help to ensure a level playing field for all. Within countries, efforts focus on industrial hubs in order to accelerate emissions reductions across multiple industrial sectors by promoting economies of scale for new infrastructure (such as CO_2 transport and storage) and supplies of low-emissions energy.

Materials producers work with governments in the NZE to create an international certification system for near-zero emission materials to differentiate them from conventional ones. This would enable buyers of materials such as vehicle manufacturers and construction companies to enter into commercial agreements to purchase near-zero emissions materials at a price premium. In most cases, the premium would result in only a modest impact on the final price of the product price given that materials generally account for a small portion of manufacturing costs (Material Economics, 2019).

4.4 Citizens

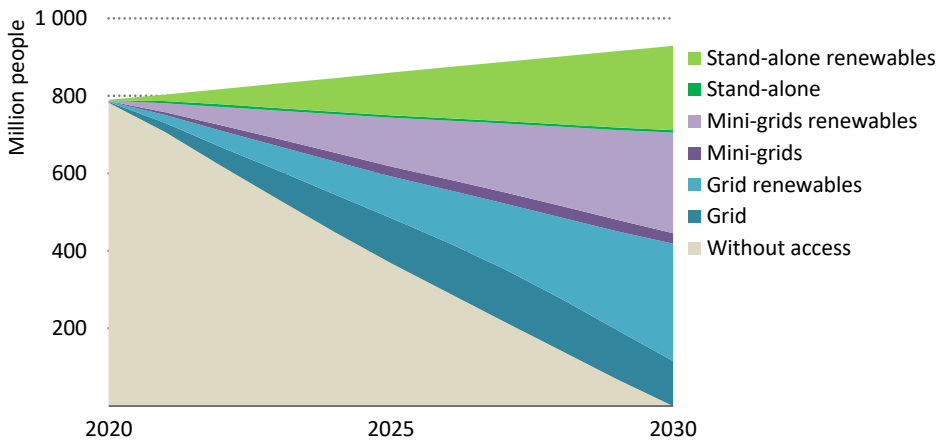
4.4.1 Energy-related Sustainable Development Goals

An inclusive and people-centred transition is key to the world moving rapidly, collectively and consistently toward net-zero emissions by mid-century. The NZE achieves the United Nations energy-related Sustainable Development Goals (SDGs) of universal access to clean modern energy by 2030 (SDG 7.1) and reducing premature deaths caused by air pollution (SDG 3.9). The technologies, options and measures used to achieve full access to low-emissions electricity and clean cooking solutions by 2030 in the NZE also help to reduce greenhouse gas (GHG) emissions from household energy use.

Energy access

About 790 million people worldwide did not have access to electricity in 2020, most of them living in sub-Saharan Africa and developing Asia. Around 2.6 billion people did not have access to clean cooking options: 35% of them were in sub-Saharan Africa, 25% in India and 15% in China. A lack of access to energy not only impedes economic development, but also causes serious harm to health and is a barrier to progress on gender equality and education.[8]

Figure 4.10 ▷ People gaining access to electricity by type of connection in emerging market and developing economies in the NZE



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More than 80% of people gaining access to electricity by 2030 are supplied renewable power and just over half via off-grid systems

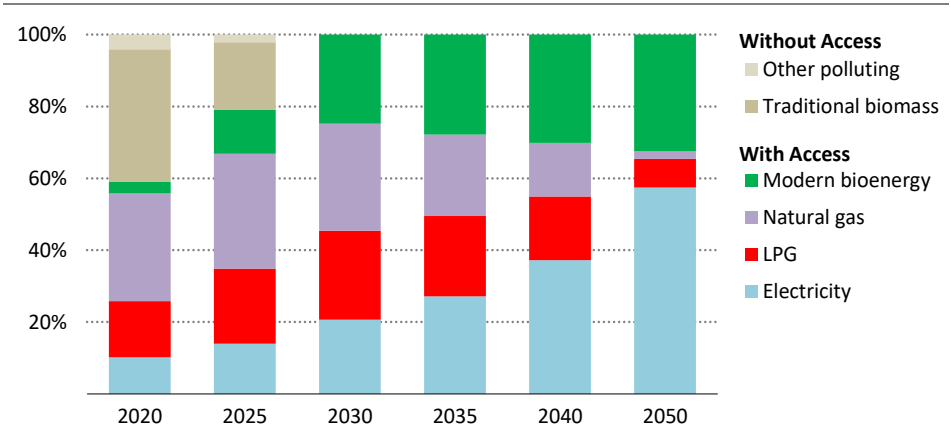
[8] Households relying on the traditional use of biomass for cooking dedicate around 1.4 hours each day collecting firewood and several hours cooking with inefficient stoves, a burden largely borne by women (IEA, 2017).

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Around 45% of those who lack access to electricity by 2030 gain it via a connection to a main grid, while the rest are served by mini-grids (30%) and stand-alone solutions (25%) (Figure 4.10). Almost all off-grid or mini-grid solutions are 100% renewable. Decentralised systems that rely on diesel generators, which are also deployed in some grid-connected systems to compensate for low reliability, are phased out later and replaced with solar storage systems. Achieving full access does not lead to a significant increase in global emissions: in 2030 it adds less than 0.2% to CO_2 emissions. Achieving full access to electricity also brings efficiency gains and accelerates the electrification of appliances, which become critical to emissions reductions in buildings after 2030 in emerging market and developing economies.

For clean cooking, 55% of those gaining access by 2030 in the NZE do so through improved biomass cookstoves (ICS) fuelled by modern biomass, biogas or ethanol, 25% through the use of liquefied petroleum gas (LPG) and 20% via electric cooking solutions (Figure 4.11). LPG is the main fuel adopted in urban areas and ICS is the main option in rural areas. The use of LPG results in a slight increase in CO_2 emissions in 2030 but a net reduction in overall GHG emissions due to reduced methane, nitrous oxides and black carbon emissions from the traditional use of biomass. In addition, LPG is increasingly decarbonised after 2030 using bio-sourced butane and propane (bioLPG) produced sustainably from municipal solid waste (MSW) and other renewable feedstocks. The technical potential of bioLPG production from MSW in 2050 in Africa could be enough to satisfy the cooking needs of more than 750 million people (GLPGP, 2020; Liquid Gas Europe, 2021).

Figure 4.11 ▷ Primary cooking fuel by share of population in emerging market and developing economies in the NZE



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Traditional biomass is entirely replaced with modern energy by 2030, mainly in the form of bioenergy and LPG; by 2050, electricity, bioenergy and bioLPG meet most cooking needs

Notes: Modern bioenergy includes improved cook stoves, biogas and ethanol. Liquefied petroleum gas (LPG) includes fossil and renewable fuel.

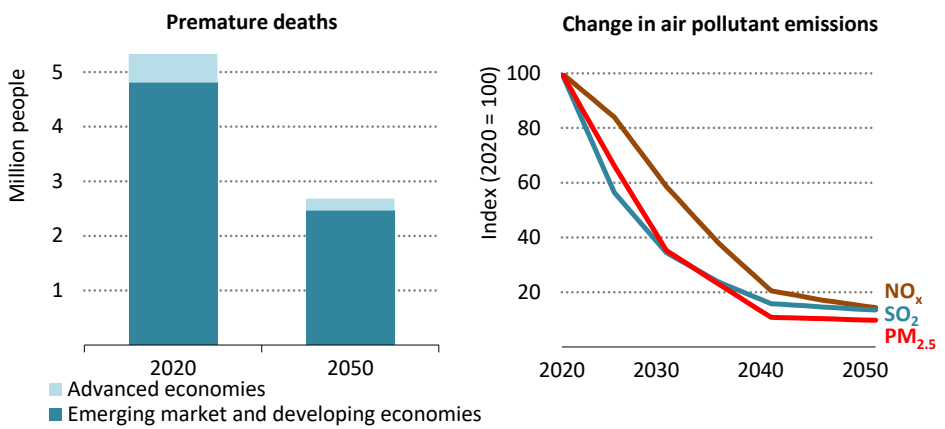
The achievement of universal access to clean energy by 2030 requires governments and donors to put expanding access at the heart of recovery plans and programmes. There would be multiple benefits: investing heavily in energy access would provide an immediate economic boost, create local jobs and bring durable improvements to social well-being by modernising health services and food chains. In the NZE, around USD 35 billion is spent each year improving access to electricity and almost USD 7 billion each year on clean cooking solutions for people in low-income countries from now to 2030.

Air pollution and health

More than 90% of people around the world are exposed to polluted air today. Such pollution led to around 5.4 million premature deaths in 2020, undermining economic productivity and placing extra stress on healthcare systems. Most of these deaths were in emerging market and developing economies. Just over half were caused by exposure to outdoor air pollution; the remainder resulted from breathing polluted air indoors, caused mainly by the traditional use of biomass for cooking and heating.

Energy-related emissions of the three major air pollutants – sulphur dioxide (SO_2), nitrogen oxides (NO_X) and fine particulate matter ($PM_{2.5}$) – fall rapidly in the NZE. SO_2 emissions fall by 85% between 2020 and 2050, mainly as a result of the large-scale phase-out of coal-fired power plants and industrial facilities. NO_X emissions also drop by around 85% as a result of the increased use of electricity, hydrogen and ammonia in the transport sector. The increased uptake of clean cooking fuels in developing countries, together with air pollution control measures in industry and transport, results in a 90% drop in $PM_{2.5}$ emissions (Figure 4.12). The reduction in air pollution in the NZE leads to roughly a halving in premature deaths in 2050 compared with 2020, saving the lives of about 2 million people per year, around 85% of them in emerging market and developing economies.

Figure 4.12 ▷ Global premature deaths and air pollutant emissions in the NZE



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Reductions in major air pollutants mean 2 million fewer premature deaths per year

Sources: IEA analysis based on IIASA.

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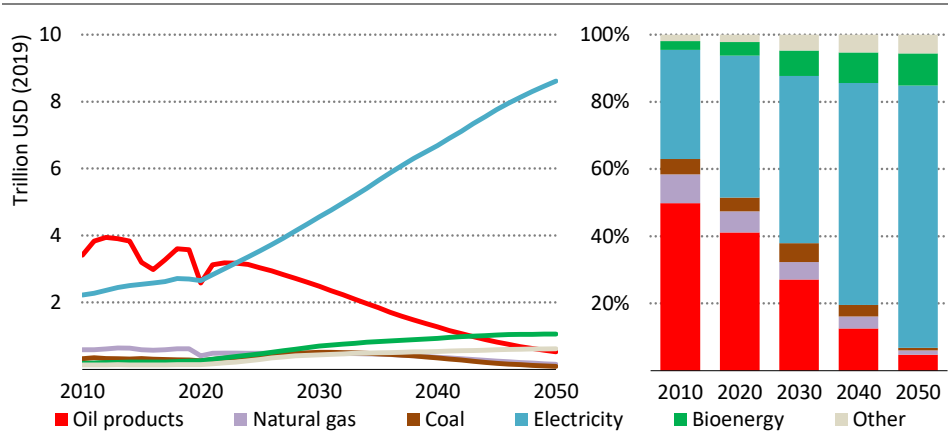
4.4.2 Affordability

Total spending on energy

Energy affordability is a key concern for governments, businesses and households. Global direct spending on energy, i.e. the total fuel bills paid by all end users, which totalled USD 6.3 trillion in 2020, increases by 45% to 2030 and 75% to 2050, in large part reflecting population and GDP growth over this period. As a share of global GDP, the figures look rather different: total direct spending on energy holds steady at around 8% out to 2030 (similar to the average over the last five years), but then declines to 6% in 2050. This decline offsets a significant share of the higher cost of buying new, more efficient energy-consuming equipment.

A portion of the increase in energy spending in the NZE is related to rising CO_2 prices and the removal of consumption subsidies for fossil fuels and electricity. CO_2 pricing (taxes and trading schemes) paid by end users at its peak generates global revenues in the NZE of close to USD 700 billion each year between 2030 and 2035, before declining steadily due to declining overall emissions: these revenues could be recycled into economies or otherwise used to improve consumer welfare, particularly for low-income households. The NZE also sees the progressive removal of consumption subsidies for fossil fuels, many of which disproportionally benefit wealthier segments of the population that use more of the subsidised fuel. Phasing out the subsidies would provide more efficient price signals for consumers, and spur more energy conservation and measures to improve energy efficiency. The impact of phasing out subsidies on lower income households could be offset through direct payment schemes or other means at lower overall costs to the economy.

Figure 4.13 ▷ Global energy spending by fuel in the NZE



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Total energy spending increases by 75% to 2050, mainly on electricity

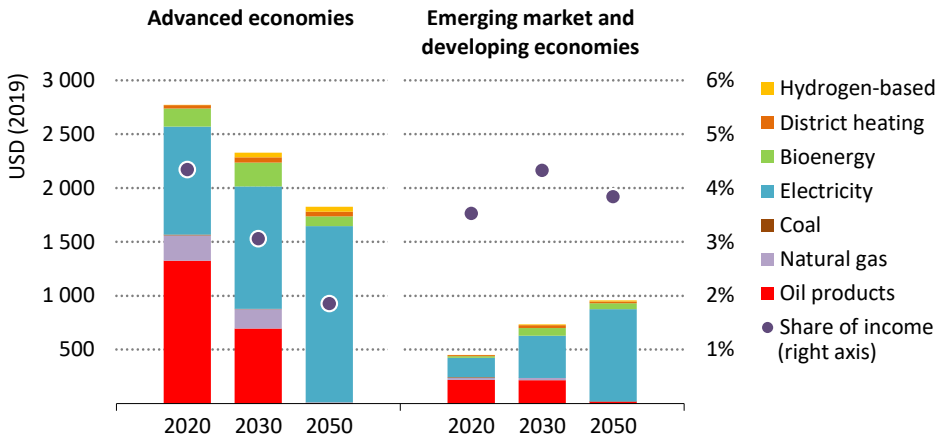
Note: Other = hydrogen-based and synthetic fuels, and district heating.

The transformation of the global energy system in the NZE drives a major shift in the composition of energy spending. Spending on electricity at USD 2.7 trillion in 2020 (45% of total energy spending) exceeded spending on oil products for the first time and it rises to over USD 8.5 trillion in 2050 (80% of total energy spending) (Figure 4.13). Retail electricity prices increase by 50% on average, contributing to the total increase. Spending on oil, which has dominated overall energy spending for decades, goes into long-term decline in the 2020s, its share of spending falling from 40% in 2020 to just 5% in 2050. Spending on natural gas and coal also declines in the long term, offset by higher spending on low-emissions fuels. Spending on bioenergy reaches about USD 900 billion per year by 2040, while other low-emissions fuels, including hydrogen-based products, gain a foothold and establish a market worth of around USD 600 billion per year by 2050.

Household spending on energy

Direct spending by households on energy, including for heating, cooling, electricity and fuel for passenger cars, falls as a share of disposable income in the NZE, though there are large differences between countries (Figure 4.14).

Figure 4.14 ▷ Average annual household energy bill in the NZE



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The proportion of disposable household income spent on energy is stable in emerging market and developing economies, and drops substantially in advanced economies

Note: Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

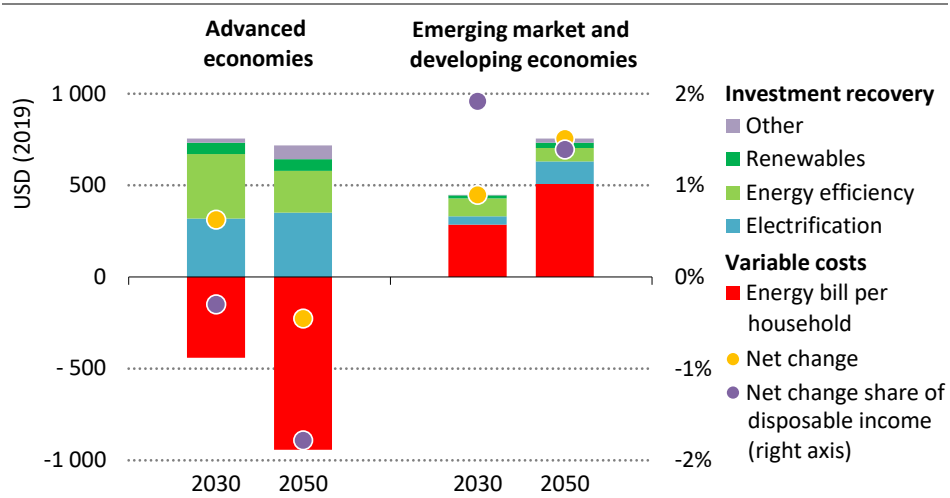
In advanced economies, the average annual bill declines from about USD 2 800 in 2020 to USD 2 300 in 2030, thanks to a strong push on energy efficiency and cost-effective electrification. Oil products make up close to half of household energy bills in 2020, but this falls to 30% in 2030 and almost zero in 2050, due to a rapid shift to EVs and to downward pressure on oil prices. Natural gas bills, which make up almost 10% of the total today, also

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fall to almost zero in 2050 with the electrification of heating and cooking. Electricity rises from about 35% of household fuel bills in 2020 to 90% in 2050, increasing the sensitivity of households to electricity prices and consumption. Increasing incomes mean that household spending on energy as a share of disposable income drops from 4% in 2020 to 2% in 2050.

In emerging market and developing economies, there is a huge increase in demand for modern energy services linked to expanding populations, economic growth, rising incomes and universal access to electricity and clean cooking options. As in advanced economies, electricity accounts for the vast majority of energy bills in 2050. The use of more efficient appliances and equipment curbs some of the increase in demand, but household bills still increase in the NZE by over 60% to 2030 and more than double by 2050. As a percentage of disposable income, however, bills in emerging market and developing economies remain around 4%, and there are large social and economic benefits from increased energy use.

Figure 4.15 ▷ Change in household spending on energy plus energy-related investment in the NZE relative to 2020



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Total household spending on energy increases modestly in emerging market and developing economies, leaving over 90% of additional income available for other uses

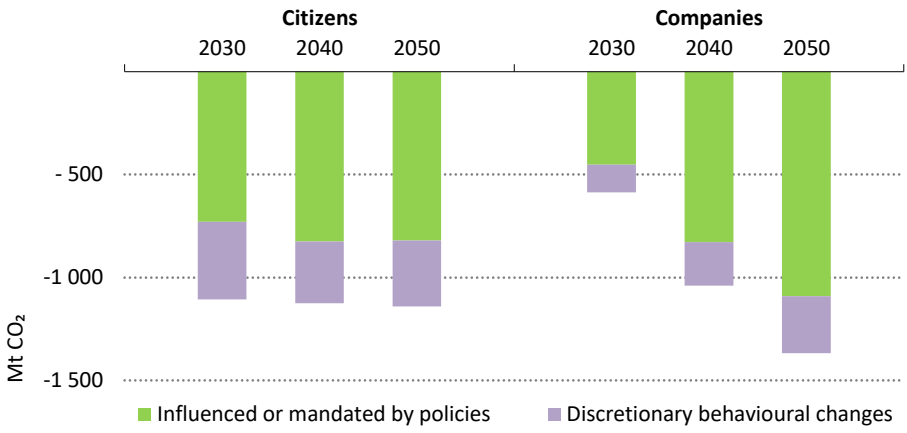
Taking into account additional investment in electricity-consuming equipment such as efficient appliances and electric vehicles, spending on energy plus related investment is USD 1.30 higher per day per household globally in 2050 than in 2020 in the NZE. This modest increase means that expenditure on energy makes up a smaller share of disposable income in 2050 than it does today, though the impacts vary by country. In advanced economies, additional investment in electrification, energy efficiency and renewable energy costs about USD 750 per household by 2030 and USD 720 in 2050, which is fully offset by reductions in the level of energy bills (Figure 4.15). In emerging market and developing economies, a

growing basket of energy services means increased use of energy, and total energy-related household spending increases. Additional investment moderates the change in energy bills, with the result that total energy-related spending takes 2 percentage points more of household disposable income in 2030 and 1 percentage point more in 2050 than today.

4.4.3 Behavioural changes

Behavioural changes play an important part in reducing energy demand and emissions in the NZE, especially in sectors where technical options for cutting emissions are limited in 2050. While it is citizens and companies that modify their behaviour, the changes are mostly enabled by the policies and investments made by governments, and in some instances, they are required by laws or regulations. The Covid-19 pandemic has increased general awareness of the potential effectiveness of behavioural changes, such as mask-wearing, and working and schooling at home. The crisis demonstrated that people can make behavioural changes at significant speed and scale if they understand the changes to be justified, and that it is necessary for governments to explain convincingly and to provide clear guidance about what changes are needed and why they are needed.

Figure 4.16 ▷ Emissions reductions from policy-driven and discretionary behavioural changes by citizens and companies in the NZE



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Three-quarters of the emissions saved by behavioural changes could be directly influenced or mandated by government policies

Around three-quarters of the emissions saved by behavioural changes between 2020 and 2050 in the NZE could be directly influenced or mandated by government policy (Figure 4.16). They include mitigation measures such as phasing out polluting cars from large cities and reducing speed limits on motorways. The other one-quarter involves more discretionary behavioural changes, such as reducing wasteful energy use in homes and

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offices, though even these types of changes could be promoted through awareness campaigns and other means. Around 10% of emissions savings directly influenced or mandated by government policy would require new or redirected investment in infrastructure. For example, the shift in the NZE from regional flights to high-speed rail would necessitate building around 170 000 kilometres of new track globally by 2050 (a tripling of 2020 levels).

Behavioural changes made by citizens and companies play a roughly equal role in reducing emissions in the NZE. Most changes in road transport and energy-saving in homes would depend on individuals, whereas the private sector has the primary role in reducing energy demand in commercial buildings and pursuing materials efficiency in manufacturing. Companies can also influence behavioural changes indirectly, for example, by promoting the use of public transport by employees that commute or encouraging working from home. However, a simple distinction between the role for individuals and companies masks a complex underlying dynamic: it is ultimately citizens as consumers of energy-related goods and services who shape corporate strategies, but at the same time companies do much to influence and generate consumer demand through marketing and advertising. In the NZE, consumers and companies move together in adopting behavioural changes, with governments setting the direction of those changes and facilitating them via effective and sustained policy support.

The behavioural changes in the NZE happen to different extents in different regions, and reflect a range of geographical and infrastructure constraints, as well as existing behavioural norms and cultural preferences. In countries with low rates of car ownership or energy service demand in buildings, many of the behavioural changes in advanced economies in NZE would not be relevant or appropriate. As a result, around half of the emissions savings from behavioural changes are in emerging market and developing economies, despite around 95% of activity growth in buildings and road transport between 2020 and 2050 occurring there. Nevertheless, there are significant opportunities in emerging market and developing economies for materials efficiency and urban design to decouple growth in economic prosperity and energy services from increases in emissions. For example, around 85% of CO_2 emissions reductions from cement and steel making in 2050 are due to gains in materials efficiency in emerging market and developing economies.

Cities are important to the behavioural changes in the NZE. Urban design can reduce the average city dweller's carbon footprint by up to 60% by shaping lifestyle choices and influencing day-to-day behaviour. For example, compact cities with clustered amenities can shorten average trip lengths; digitalisation can help shared private mobility to become the de facto option to accommodate much of the growth in service demand; and urban green infrastructure can reduce cooling demand (Feyisa, Dons & Meilby, 2014).

4.5 Governments

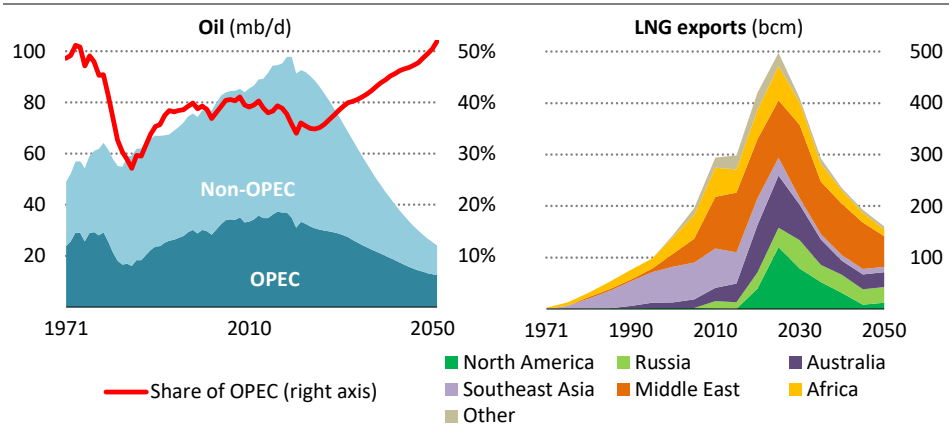
4.5.1 Energy security

Energy security is an important consideration for governments and those they serve, and the pathway to net-zero emissions must take account of it. Concerns about energy security have traditionally been associated with oil and natural gas supplies. The drop in oil and gas demand and the increased diversity of the energy sources used in the NZE may reduce some risks, but they do not disappear. There are also new potential vulnerabilities associated with the need to maintain reliable, flexible and secure electricity systems, and with the increase in demand for raw minerals for clean energy technologies. Improving energy efficiency remains the central measure for increasing energy security – even with rapid growth in low-emissions electricity generation, the safest energy supplies are those that are not needed.

Oil and gas security

No new oil and natural gas fields are required in the NZE beyond those already approved for development, and supplies become increasingly concentrated in a small number of low-cost producers. For oil, OPEC's share of global oil supply grows from around 37% in recent years to 52% in 2050, a level higher than at any point in the history of oil markets (Figure 4.17). For natural gas, inter-regional liquefied natural gas (LNG) trade increases from 420 bcm in 2020 over the next five years but it then falls to around 160 bcm in 2050. Nearly all exports in 2050 come from the lowest cost and lowest emissions producers. This means that the importance of ensuring adequate supplies of oil and natural gas to the smooth functioning of the global energy system would be quantitatively lower in 2050 than today, but it does not suggest that the risk of a shortfall in supply or sudden price rise is necessarily going to diminish, and a shortfall or sudden price rise would still have large repercussions for a number of sectors.

Figure 4.17 ▷ Global oil supply and LNG exports by region in the NZE



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Increased reliance on OPEC and other producer economies suffering from falling oil and gas revenues could pose a risk to supply security in consuming countries

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Even if the timing and ambition of emission reduction policies are clear, the changes in the NZE clearly have implications for producers and consumers alike. Many producer economies would see oil and gas revenues drop to some of the lowest ever levels (see section 4.2.2). Even if these producers increase their market share, and diversify their economies and sources of tax revenue, they are likely to struggle to finance essential spending at current levels. This could have knock-on effects for social stability, and that in turn could potentially threaten the smooth delivery of oil and gas to consuming countries. Moves on the part of producer economies to gain market share or a failure to maintain upstream operations while managing the extreme strains that would be placed on their fiscal balances could lead to turbulent and volatile markets, greatly complicating the task facing policy makers.

Electricity security

The rapid electrification of all sectors in the NZE, and the associated increase in electricity's share of total final consumption from 20% in 2020 to nearly 50% in 2050, puts electricity even more at the heart of energy security across the world than it already is (IEA, 2020h). Greater reliance on electricity has both positive and negative implications for overall energy security. One advantage for energy-importing countries is that they become more self-sufficient, since a much higher share of electricity supply is based on domestic sources in the NZE than is the case for other fuels. However the increased importance of electricity means that any electricity system disruption would have larger impacts. Electricity infrastructure is often more vulnerable to physical shocks such as extreme weather events than pipelines and underground storage facilities, and climate change is likely to put increasing pressure on electricity systems, for example through more frequent droughts that might decrease the availability of water for hydropower and for cooling at thermal power plants. The resilience of electricity systems needs to be enhanced to mitigate these risks and maintain electricity security, including through more robust contingency planning, with solutions based on digital technologies and physical system hardening (IEA, 2021b).

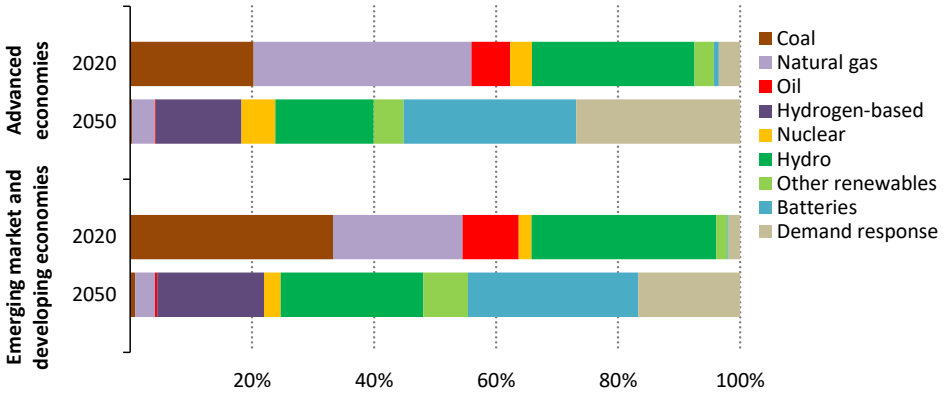
Cybersecurity could pose an even greater risk to electricity security as systems incorporate more digitalised monitoring and controls in a growing number of power plants, electricity network assets and storage facilities. Policy makers have a central part to play in ensuring that the cyber resilience of electricity is enhanced, and there are a number of ways in which they can pursue this (IEA, 2021c).

Maintaining electricity security also requires a range of measures to ensure flexibility, adequacy and reliability at all times. Enhanced electricity system flexibility is of particular importance as the share of variable renewables in the generation mix rises. As a consequence, electricity system flexibility quadruples globally in the NZE in parallel with a more than two-and-a half-fold increase in electricity supply.[9] A portfolio of flexibility sources – including power plants, energy storage and demand response supported by electricity

[9] Electricity system flexibility is quantified here based on hour-to-hour ramping needs, which is only one aspect of flexibility that also includes actions on much shorter time scales to maintain frequency and other ancillary services.

networks – is used to match supply and demand at all times of the year, under varying weather conditions and levels of demand. There is a significant shift in the NZE from using coal- and gas-fired power plants for the provision of flexibility to the use of renewables, hydrogen, battery storage, and demand-side response (Figure 4.18).

Figure 4.18 ▷ Electricity system flexibility by source in the NZE



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To meet four-times the amount of hour-to-hour flexibility needs, batteries and demand response step up to become the primary sources of flexibility

Electricity demand also becomes much more flexible as a result of the use of demand response measures, e.g. to shift consumption to times when renewable energy is plentiful. Conventional sources of demand response such as moderating industry activities remain important, but new areas of demand response such as smart charging of EVs unlock valuable new ways of supplementing them.[10] As the EV fleet expands in the NZE, EVs provide a significant portion of total electricity system flexibility. Although the technology already exists, the roll-out of smart charging has been slow to date due to institutional and regulatory barriers; these hurdles are overcome in the NZE. Measures are also implemented to ensure that the digitalisation of charging and other sources of flexibility does not compromise cybersecurity, and that potential social acceptance issues are addressed.

Energy storage also plays an important role in the provision of flexibility in the NZE. The deployment of battery storage systems is already starting to accelerate and to contribute to the management of short-duration flexibility needs, but the massive scale up to 3 100 GW of storage in 2050 (with four hour duration on average) envisaged in the NZE hinges on overcoming current regulatory and market design barriers. Pumped hydropower offers an attractive means of providing flexibility over a matter of hours and days, while hydrogen has

[10] Smart chargers share real-time data with a centralised platform to allow system operators to optimise charging profiles based on how much energy the vehicle needs over a specified span of time, how much is available, the price of wholesale electricity, grid congestion and other parameters.

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the potential to play an important part in longer term seasonal storage since it can be stored in converted gas storage facilities that have several orders of magnitude more capacity than battery storage projects.

Dispatchable power is essential to the secure transition of electricity systems, and in the NZE this comes increasingly from low-emissions sources. Hydropower provides a significant part of flexibility in many electricity systems today, and this continues in the future, with particular emphasis on expanding pumped hydro facilities. Nuclear power and geothermal plants, though designed for baseload generation, also provide a degree of flexibility in the NZE, but there are constraints on how much these sources can be expanded. This leaves an important role for thermal power plants that are equipped with carbon capture or use low-emissions fuels. For example, the use of sustainable biomass or low-emissions ammonia in existing coal plants offers a way of allowing these facilities to continue to contribute to flexibility and capacity adequacy, while at the same time reducing CO_2 emissions. Additional measures will also be necessary to maintain power system stability (Box 4.1).

Box 4.1 ▷ Power system stability with high shares of variable renewables

Stability is a key feature of electricity security, allowing systems to remain in balance and withstand disturbances such as sudden generator or grid outages. Historically, conventional generators such as nuclear, hydro and fossil fuels have been central to electricity system stability, providing inertia with rotating machines that allow stored kinetic energy to be instantly converted into power in case of a system disturbance, and generating a voltage signal that helps all generators remain synchronous.

In contrast, newer technologies such as solar PV, wind and batteries are connected to the system through converters. They generally do not contribute to system inertia and are configured as "grid-following" units, synchronising to conventional generators. Maintaining system stability will call for new approaches as the share of converter based resources, and in particular variable renewables, rises much higher in electricity systems.

There is a growing body of knowledge and studies on stability in systems with high shares of variable renewables. For example, a recent joint study by the IEA and RTE, the transmission system operator in France, analyses the conditions under which it would be technically feasible to integrate high shares of variable renewables in France (IEA, 2021d). Based on the findings of this study:

- One option to ensure stability for a net zero power system is to maintain a minimum amount of conventional generation from low-carbon technologies during hours of high shares VRE output. This approach to maintain stability comes at the cost of solar and wind curtailment at high shares.
- Updated grid codes can be used to call for variable renewables and batteries to provide fast frequency response services, which can help reduce the amount of conventional generation needed for stability.

- Synchronous condensers are able to provide inertia without generating electricity. The technology is already proven at GW-scale in Denmark and also in South Australia, but experience needs to be expanded at larger scale.
- Grid-forming converters can allow variable renewables and batteries to generate a voltage signal, though experience with this approach needs to move beyond micro-grids and small islands to large interconnected systems.

Demonstration projects, stakeholder consultations and international collaboration will be critical to fully understand the merits of each of these four approaches and the scope for a portfolio of options that would most cost-effectively achieve net zero emissions while maintaining electricity security.

Electricity networks support and enable the use of all sources of flexibility, balancing demand and supply over large areas. Timely investment in grids to minimise congestion and expand the size of the areas where supply and demand are balanced will be critical to making the best use of solar PV and wind projects, and ensuring affordable and reliable supplies of electricity. Expanding long-distance transmission also makes a key contribution in the NZE, since a lack of available land near demand centres and other factors mean new sources of generation are often located in remote areas. It is important that new transmission systems are built with variable, bidirectional operation in mind in order to maximise the use of available flexibility sources, and that regulatory and market arrangements support flexible connections between systems. The key value of interconnections comes from complementary electricity demand and wind patterns: solar PV output is more highly correlated than wind over large areas.

The NZE sees a major increase in demand for critical minerals such as copper, lithium, nickel, cobalt and rare earth elements that are essential for many clean energy technologies. There are several potential vulnerabilities that could hinder the adequate supply of these minerals and lead to price volatility (IEA, 2021a). Today's production and processing operations for many minerals are highly concentrated in a small number of countries, making supplies vulnerable to political instability, geopolitical risks and possible export restrictions. In many cases, there are also concerns about land-use changes, competition for scarce water resources, corruption and misuse of government resources, fatalities and injuries to workers, and human rights abuses, including the use of child labour. New critical mineral projects can have long lead times, so the rapid increase in demand in the NZE could lead to a mismatch in timing between supply and demand. The international trade and investment regime is key to maintaining reliable mineral supplies, but policy support and international co-ordination will be needed to ensure the application of rigorous environmental and social regulations.

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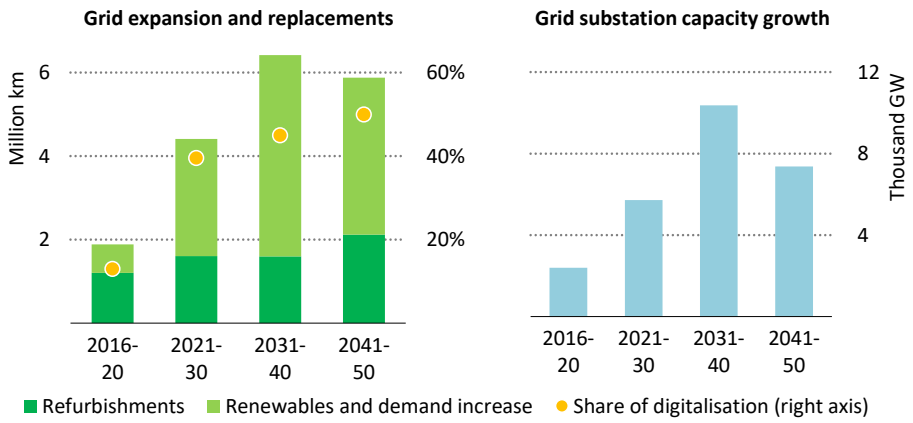
4.5.2 Infrastructure

Getting to net-zero emissions will require huge amounts of new infrastructure and lots of modifications to existing assets. Energy infrastructure is transformed in the NZE as all countries and regions move from systems supporting the use of fossil fuels and the distribution of conventionally generated electricity to systems based largely on renewable electricity and low-emissions fuels. In many emerging market and developing economies, the provision of large amounts of infrastructure would be necessary in the coming decades in any case, creating a window of opportunity to support the transition to a net-zero emissions economy. In all countries, governments will play a central role in planning, financing and regulating the development of infrastructure. Some of the main infrastructure components – electricity networks and EV charging, pipelines systems for low-emissions fuels and CO_2, and transport infrastructure – are discussed below.

The rapid increase in electricity demand in the NZE and the transition to renewable energy call for an expansion and modernisation of electricity networks (Figure 4.19). This would require a sharp reversal in the recent trend of declining investment: failure to achieve this would almost certainly make the energy transition for net-zero emissions impossible. Tariff design and permitting procedures also need to be revised to reflect fundamental changes in the provision and uses of electricity. Some of the main considerations include:

- **Long-distance transmission**. Most of the growth in renewables in the NZE comes from centralised sources. Yet the best solar and wind resources are often in remote regions, requiring new transmission connections. Ultra high-voltage direct current systems are likely to play an important role in supporting transmission over long distances.
- **Local distribution**. Energy efficiency gains in households and wider use of rooftop solar PV mean surplus electricity will be available more often, while electric heat pumps and residential EV charging points will require electricity to be more widely available. Together these developments point to the need for substantial increases in distribution network capacity.
- **Grid substations**. The massive expansion of solar PV and wind requires new grid substations: their capacity expands by more than 57 000 GW in the NZE by 2030, doubling current capacity globally.
- **EV charging**. Major new public charging networks are built in the NZE, including in work places, highway service stations and residential complexes, to support EV expansion and long-distance driving on highways.
- **Digitalisation of networks**. With a large increase in the use of connected devices, the digitalisation of grid assets supports more flexible grid operations, better management of variable renewables and more efficient demand response.

Figure 4.19 ▷ Annual average electricity grid expansion, replacement and substation capacity growth in the NZE



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Grid and substation expansion is driven largely by the massive deployment of renewables and electrification of end-uses, with a rising digital share of infrastructure

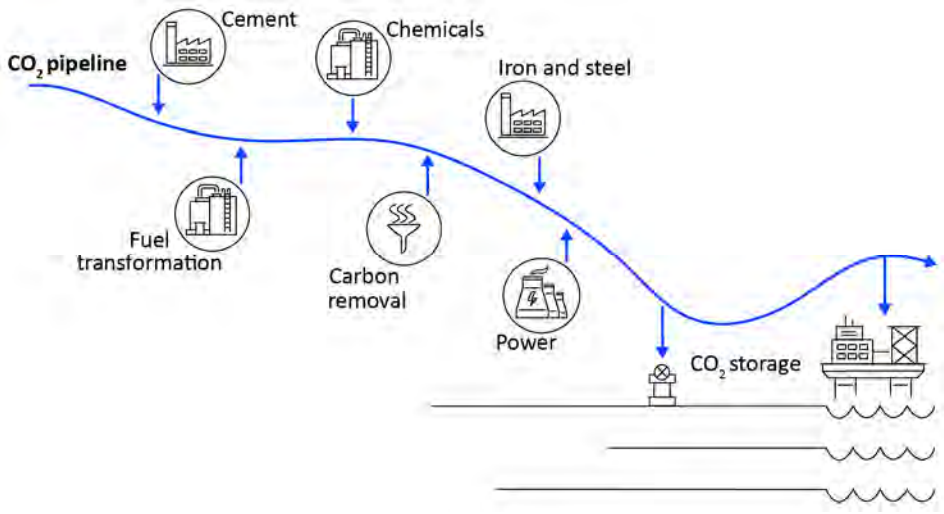
Note: Substation capacity here assumes active electricity is equal to apparent electricity.

Pipelines continue to play a key role in the transmission and distribution of energy in the NZE:

- Given the rapid decline of fossil fuels, significant investment in new oil and gas pipelines are not needed in the NZE. However investment is needed to link the production of low-emissions liquids and gases with consumption centres, and to convert existing pipelines and associated distribution infrastructure for the use of these low-emissions fuels. Some low-emissions fuels, such as biomethane and synthetic hydrogen-based fuels, can make use of existing infrastructure without any modifications, but pure hydrogen requires a retrofit of existing pipelines. New dedicated hydrogen infrastructure is also needed in the NZE, for example to move hydrogen produced in remote areas with excellent renewable resources to demand centres.
- The expansion of CCUS in the NZE requires investment in CO_2 transport and storage capacity. By 2050, 7.6 Gt of CO_2 is captured worldwide, requiring a large amount of pipeline and shipping infrastructure linking the facilities where CO_2 is captured with storage sites. Industrial clusters, including ports, may offer the best near-term opportunities to build CO_2 pipeline and hydrogen infrastructure, as the various industries in those clusters using the new infrastructure would be able to share the upfront investment needs (Figure 4.20).

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Figure 4.20 ▷ Illustrative example of a shared CO_2 pipeline in an industrial cluster



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Deployment of technologies like CCUS and hydrogen and their enabling infrastructure would benefit strongly from a cross-sectoral approach in industrial clusters

Transforming transport infrastructure represents both a challenge and an opportunity. The challenge arises from the potential increase in the energy and carbon intensity of economic growth during the infrastructure development phase.[11] Steel and cement are the two main components of virtually all infrastructure projects, but they are also among the most challenging sectors to decarbonise. The opportunity comes from the scope that exists in some countries to develop infrastructure from scratch in a way that is compatible with the net zero goal. Countries undergoing rapid urbanisation today can design and steer new infrastructure development towards higher urban density and high-capacity mass transit in tandem with EV charging and low-emissions fuelling systems.

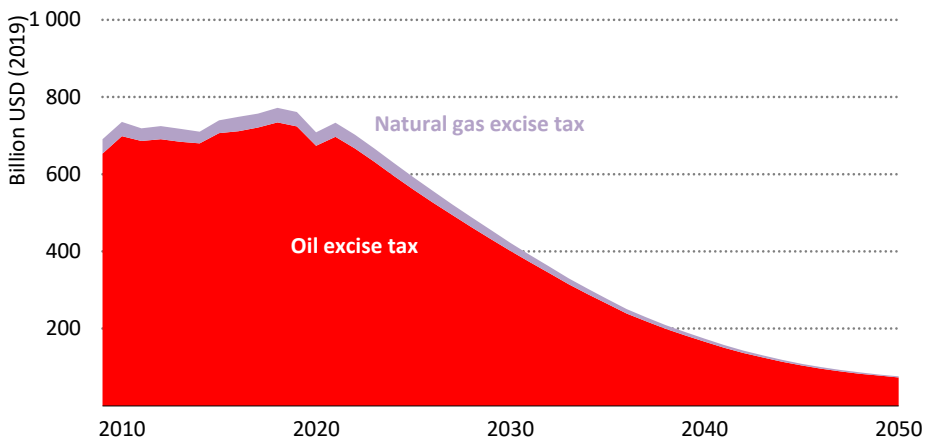
Rail has an important part to play as transport infrastructure is developed. The NZE sees large-scale investment in all regions in high-speed trains to replace both long-distance car driving and short-haul aviation. It also sees large-scale investment in all regions in track, control systems, rolling stock modernisation and combined freight facilities to improve speed and flexibility for just-in-time logistical operations and thus support a shift of freight from road to rail, especially for container traffic.

[11] The modelling for the NZE incorporates the increase in steel and cement that is required to build additional transport infrastructure (roads, cars and trucks) and energy infrastructure, e.g. power plants and wind turbines.

4.5.3 Tax revenues from retail energy sales

The slump in the consumption of fossil fuels required to get to net-zero emissions would result in the loss of a large amount of tax revenue in many countries, given that fuels such as oil-based transport fuels and natural gas are often subject to high excise or other special taxes. In recent years, energy-related taxes accounted for around 4% of total government tax revenues in advanced economies on average and 3.5% in emerging market and developing economies, but they provided as much as 10% in some countries (OECD, 2020).

Figure 4.21 ▷ Global revenues from taxes on retail sales of oil and gas in the NZE



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Tax revenues slump from retail sales of oil and gas

Tax revenue from oil and natural gas retail sales falls by close to 90% between 2020 and 2050 in the NZE (Figure 4.21). Governments are likely to need to rely on some combination of other tax revenues and public spending reforms to compensate. Some taxation measures focused on the energy sector could be useful. However, any such taxes would need to be carefully designed to minimise their impact on low-income households, as poorer households spend a higher percentage of their disposable income on electricity and heating. Options for energy-related taxes include:

- **CO_2 prices**. These are introduced in all regions in the NZE, albeit at different levels for countries and sectors, which provide additional revenue streams. The reduction in oil and natural gas excise taxes is more than compensated over the next 15 years by higher revenues from CO_2 prices related to these fuels paid by end users and other sectors, but these too fall as the global energy system moves towards net-zero emissions.
- **Road fees and congestion charges**. These would have the added benefit of discouraging driving and encouraging switching to other less carbon-intensive modes of transport.

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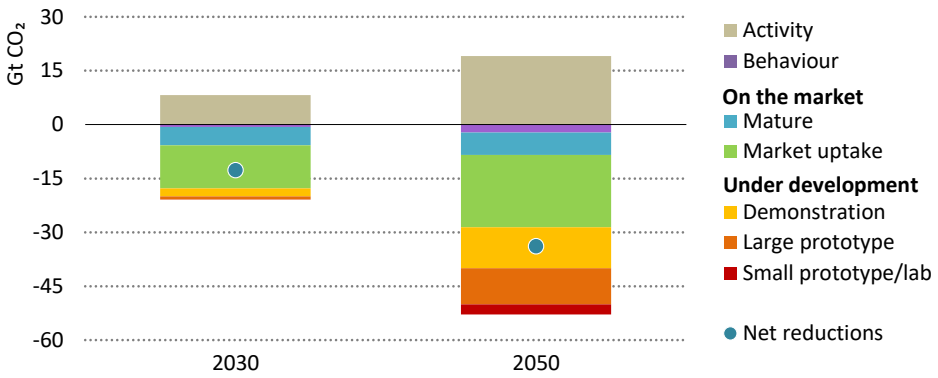
- **Increasing taxation on electricity**. Higher taxes on all electricity sales could generate substantial revenues, especially since large increases in price often have little effect on consumption. This might be counterproductive, however, as it would reduce the cost-effectiveness of both EVs and heat pumps, which could slow their adoption, although this risk could be mitigated by the introduction of CO_2 prices.

Natural gas is currently less taxed than transport fuels in most countries. Introducing and raising CO_2 prices for natural gas used in buildings, mostly for heating, would accelerate energy efficiency improvements and boost government revenues, although care would be needed to avoid disproportionately impacting low-income households. Taxing natural gas used in industry would improve the competitiveness of less carbon-intensive fuels and technologies such as hydrogen, but would run the risk of undermining the international competitiveness of energy-intensive sectors and carbon leakage in the absence of co-ordinated global action or border carbon-tax adjustments.

4.5.4 Innovation

Without a major acceleration in clean energy innovation, reaching net-zero emissions by 2050 will not be achievable. Technologies that are available on the market today provide nearly all of the emissions reductions required to 2030 in the NZE to put the world on track for net-zero emissions by 2050. However, reaching net-zero emissions will require the widespread use after 2030 of technologies that are still under development today. In 2050, almost 50% of CO_2 emissions reductions in the NZE come from technologies currently at demonstration or prototype stage (Figure 4.22). This share is even higher in sectors such as heavy industry and long-distance transport. Major innovation efforts are vital in this decade so that the technologies necessary for net-zero emissions reach markets as soon as possible.

Figure 4.22 ▷ Global CO_2 emissions changes by technology maturity category in the NZE

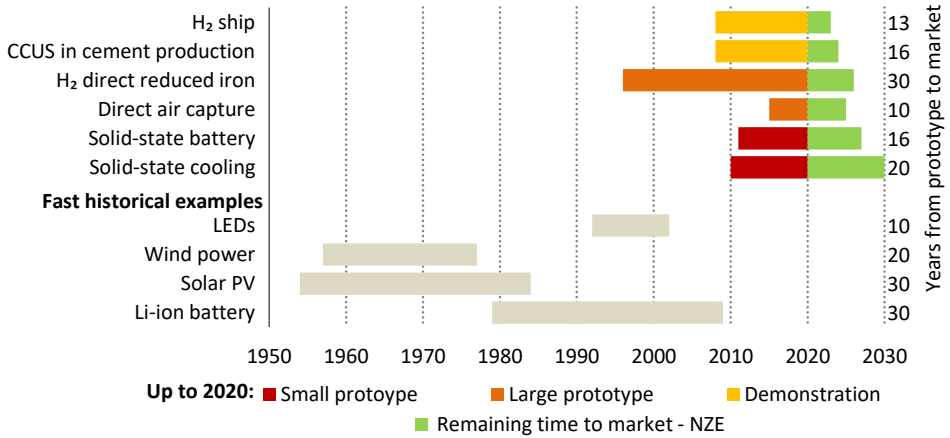


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While the emissions reductions in 2030 mostly rely on technologies on the market, those under development today account for almost half of the emissions reductions in 2050

Innovation cycles for early stage clean energy technologies are much more rapid in the NZE than what has typically been achieved historically, and most clean energy technologies that have not been demonstrated at scale today reach markets by 2030 at the latest. This means the time from first prototype to market introduction is on average 20% faster than the fastest energy technology developments in the past, and around 40% faster than was the case for solar PV (Figure 4.23). Technologies at the demonstration stage, such as CCUS in cement production or low-emissions ammonia-fuelled ships, are brought into the market in the next three to four years. Hydrogen-based steel production, direct air capture (DAC) and other technologies at the large prototype stage reach the market in about six years, while most technologies at small prototype stage – such as solid state refrigerant-free cooling or solid state batteries – do so within the coming nine years.

Figure 4.23 ▷ Time from first prototype to market introduction for selected technologies in the NZE and historical examples



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Technology development cycles are cut by around 20% from the fastest developments seen in the past

Note: H_2 = hydrogen; CCUS = carbon capture, utilisation and storage; LED = light-emitting diode; Li-ion = lithium-ion.

Sources: IEA analysis based on Carbon Engineering, 2021; Greco, 2019; Tenova, 2018; Gross, 2018; European Cement Research Academy, 2012; Kamaya, 2011; Zemships, 2008.

An acceleration of this magnitude is clearly ambitious. It requires technologies that are not yet available on the market to be demonstrated very quickly at scale in multiple configurations and in various regional contexts. In most cases, these demonstrations are run in parallel in the NZE. This is in stark contrast with typical practice in technology development: learning is usually transferred across consecutive demonstration projects in different contexts to build confidence before widespread deployment commences.

The acceleration that is needed also requires a large increase in investment in demonstration projects. In the NZE, USD 90 billion is mobilised as soon as possible to complete a portfolio

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of demonstration projects before 2030: this is much more than the roughly USD 25 billion budgeted by governments to 2030. Most of these projects are concerned with the electrification of end-uses, CCUS, hydrogen and sustainable bioenergy, mainly for long-distance transport and heavy industrial applications.

Increased public funding helps to manage the risks of such first-of-a-kind projects and to leverage private investment in research and development (R&D) in the NZE. This represents a reversal of recent trends: government spending on energy R&D worldwide, including demonstration projects, has fallen as a share of GDP from a peak of almost 0.1% in 1980 to just 0.03% in 2019. Public funding also becomes better aligned with the innovations needed to reach net-zero emissions. In the NZE, electrification, CCUS, hydrogen and sustainable bioenergy account for nearly half of the cumulative emissions reductions to 2050. Just three technologies are critical in enabling around 15% of the cumulative emissions reductions in the NZE between 2030 and 2050: advanced high-energy density batteries, hydrogen electrolysers and DAC.

Governments drive innovation in the NZE

Bringing new energy technologies to market can often take several decades, but the imperative of reaching net-zero emissions globally by 2050 means that progress has to be much faster. Experience has shown that the role of government is crucial in shortening the time needed to bring new technology to market and to diffuse it widely (IEA, 2020i). The government role includes educating people, funding R&D, providing networks for knowledge exchange, protecting intellectual property, using public procurement to boost deployment, helping companies innovate, investing in enabling infrastructure and setting regulatory frameworks for markets and finance.

Knowledge transfer from first-mover countries can also help in the acceleration needed, and is particularly important in the early phases of adoption when new technologies are typically not competitive with incumbent technologies. For example, in the case of solar PV, national laboratories played a key role in the early development phase in the United States, projects supported directly by government in Japan created market niches for initial deployment and government procurement and incentive policies in Germany, Italy, Spain, United States, China, Australia and India fostered a global market. Lithium-ion (Li-ion) batteries were initially developed through public and private research that took place mostly in Japan, their first energy-related commercial operation was made possible in the United States, and mass manufacturing today is primarily in China.

Many of the biggest clean energy technology challenges could benefit from a more targeted approach to speed up progress (Diaz Anadon, 2012; Mazzucato, 2018). In the NZE, concerted government action leverages private sector investment and leads to advances in clean energy technologies that are currently at different stages of development.

- To 2030, the focus of government action is on bringing new zero- or low-emissions technologies to market. For example, in the NZE, steel starts to be produced using low-emissions hydrogen at the scale of a conventional steel plant, large ships start to be

fuelled by low-emissions ammonia and electric trucks begin operating on solid state batteries. In parallel, there is rapid acceleration in the deployment of low-emissions technologies that are already available on the market but that have not yet reached mass market scale, bringing down the costs of manufacturing, construction and operating such technologies due to learning-by-doing and economies of scale.

- From 2030 to 2040, technology advances are consolidated to scale up nascent low-emissions technologies and expand clean energy infrastructure. Clean energy technologies that are in the laboratory or at small prototype stage today become commercial. For example, fuels are replaced by electricity in cement kilns and steam crackers for high value chemicals production.
- From 2040 to 2050, technologies at a very early stage of development today are adopted in promising niche markets. By 2050, clean energy technologies that are at demonstration or large prototype stage today become mainstream for purchases and new installations, and they compete with present conventional technologies in all regions. For example, ultra high-energy density batteries are used in aircraft for short flights.

4.5.5 International co-operation

The pathway to net-zero emissions by 2050 will require an unprecedented level of international co-operation between governments. This is not only a matter of all countries participating in efforts to meet the net zero goal, but also of all countries working together in an effective and mutually beneficial manner. Achieving net-zero emissions will be extremely challenging for all countries, but the challenges are toughest and the solutions least easy to deliver in lower income countries, and technical and financial support will be essential to ensure the early stage deployment of key mitigation technologies and infrastructure in many of these countries. Without international co-operation, emissions will not fall to net zero by 2050.

There are four aspects of international co-operation that are particularly important (Victor, Geels and Sharpe, 2019).

- **International demand signals and economies of scale**. International co-operation has been critical to the cost reductions seen in the past for many key energy technologies. It can accelerate knowledge transfer and promote economies of scale. It can also help align the creation of new demand for clean energy technologies and fuels in one region with the development of supply in other regions. These benefits need to be weighed against the importance of creating domestic jobs and industrial capacities, and of ensuring supply chain resilience.
- **Managing trade and competitiveness**. Industries that operate in a number of countries need standardisation to ensure inter-operability. Progress on innovation and clean energy technology deployment in sectors such as heavy industry has been inhibited in the past by uncoordinated national policies and a lack of internationally agreed

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standards. The development of such standards could accelerate energy technology development and deployment.

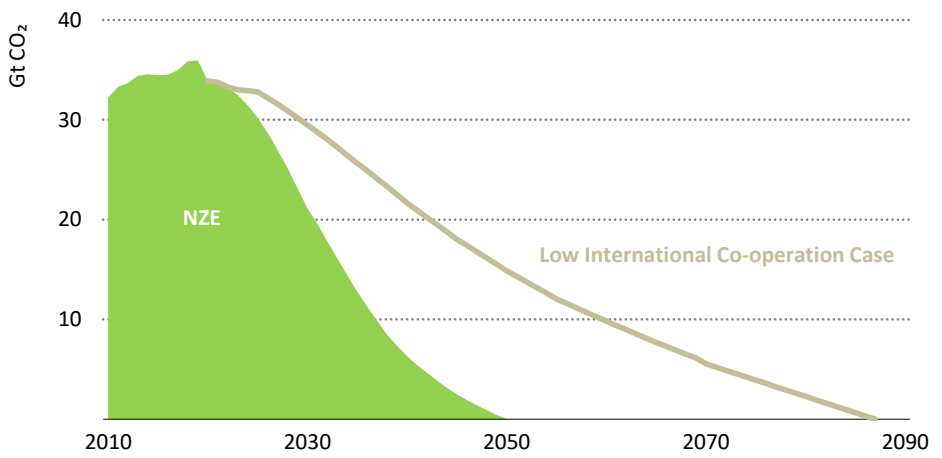
- **Innovation, demonstration and diffusion**. Clean energy R&D and patenting is currently concentrated in a handful of places: United States, Europe, Japan, Korea and China accounted for more than 90% of clean energy patents in 2014-18. Progress towards net-zero emissions would be increased by moving swiftly to extend experience and knowledge of clean energy technologies in countries that are not involved in their initial development, and by funding first-of-a-kind demonstration projects in emerging market and developing economies. International programmes to fund demonstration projects, especially in sectors where technologies are large and complex, would accelerate the innovation process (IEA, 2020i).
- **Carbon dioxide removal (CDR) programmes**. CDR technologies such as bioenergy and DAC equipped with CCUS are essential to provide emissions reductions at a global level. International co-operation is needed to fund and certify these programmes, so as to make the most of suitable land, renewable energy potential and storage resources, wherever they may be. International emissions trading mechanisms could play a role in offsetting emissions in some sectors or areas with negative emissions, though any such mechanisms would require a high degree of co-ordination to ensure market functioning and integrity.

The NZE assumes that international co-operation policies, measures and efforts are introduced to overcome these hurdles. To explore the potential implications of a failure to do so, we have devised a *Low International Co-operation Case* (Box 4.2). This examines what would happen if national efforts to mitigate climate change ramp up in line with the level of effort in the NZE but co-operation frameworks are not developed at the same speed. It shows that the lack of international co-operation has a major impact on innovation, technology demonstration, market co-ordination and ultimately on the emissions pathway.

Box 4.2 ▻ Framing the Low International Co-operation Case

To develop the *Low International Co-operation Case*, technologies and mitigation options were assessed and grouped based on their current degree of maturity and the importance of international co-operation to their deployment. Mature technologies in markets that are firmly established and that have a low exposure to international co-operation are assumed to have the same deployment pathways as in the NZE. Technologies and mitigation options where co-operation is needed to achieve scale and avoid duplication, that have a large exposure to international trade and competitiveness, that depend on large and very capital-intensive demonstration programmes, or that require support to create market pull and standardisation to ensure inter-operability, are assumed to be deployed more slowly (Malhotra and Schmidt, 2020). Compared with the NZE, these technologies are delayed by 5-10 years in their initial deployment in advanced economies and by 10-15 years in emerging market and developing economies.

Figure 4.24 ▷ CO_2 emissions in the Low International Co-operation Case and the NZE



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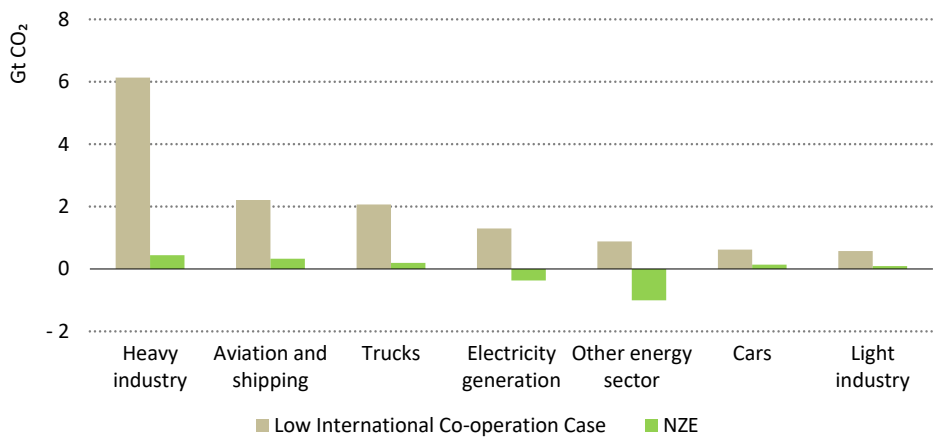
Without international co-operation, the transition to net zero would be delayed by decades

Weak international co-operation slows the deployment of mitigation options that are currently in the demonstration phase (Figure 4.24). This includes emissions reductions in heavy industry, trucks, aviation, shipping and CDR. The energy transition proceeds unevenly as a result. Over the next 20 years in the Low International Co-operation Case, emissions decline at a rapid but still slower pace than in the NZE in electricity generation, cars, light industry and buildings. However, emissions reductions are much slower in other areas. After the mid-2030s, the pace of emissions reductions worldwide slows markedly relative to the NZE, and the transition to net zero is delayed by decades. Just over 40% of the 15 Gt CO_2 of emissions remaining in 2050 are in heavy industry, where the slower pace of demonstration and diffusion of mitigation technologies is particularly significant (Figure 4.25). A further one-third of the residual emissions in 2050 are from aviation, shipping and trucks. Here the slower scale up and diffusion of advanced biofuels, hydrogen-based fuels and high-energy density batteries hinders progress. The absence of co-operation to support the deployment of new projects in emerging market and developing economies means that emissions reductions there are much slower than in the NZE.

These results highlight the importance for governments of strengthening international co-operation. A strong push is needed to accelerate innovation and the demonstration of key technologies, especially for complex technologies in emerging market and developing economies where costs for first-of-a-kind projects are generally higher, and to address concerns about international trade and competitiveness so as to ensure a just transition for all.

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Figure 4.25 ▷ CO_2 emissions in the Low International Co-operation Case and the NZE in selected sectors in 2050



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CO_2 emissions in 2050 in the Low International Co-operation Case are concentrated in the industry and transport sectors

Note: Other energy sector = fuel production and direct air capture.



ANNEXES

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Tables for scenario projections

General note to the tables

This annex includes global historical and projected data for the Net-Zero Emissions by 2050 scenario for the following data sets: energy supply, energy demand, gross electricity generation and electrical capacity, carbon dioxide (CO_2) emissions from fossil fuel combustion and industrial processes, and selected economic and activity indicators.

The definitions for fuels and sectors are in Annex C. Common abbreviations used in the tables include: EJ = exajoules; CAAGR = compound average annual growth rate; CCUS = carbon capture, utilisation and storage. Consumption of fossil fuels in facilities without CCUS are classified as "unabated".

Both in the text of this report and in the tables, rounding may lead to minor differences between totals and the sum of their individual components. Growth rates are calculated on a compound average annual basis and are marked "n.a." when the base year is zero or the value exceeds 200%. Nil values are marked "-".

To download the tables in Excel format go to: **iea.li/nzedata**.

Data sources

The formal base year for the scenario projections is 2019, as this is the last year for which a complete picture of energy demand and production is available. However, we have used more recent data when available, and we include our 2020 estimates for energy production and demand in this annex. Estimates for the year 2020 are based on updates of the IEA's Global Energy Review reports which are derived from a number of sources, including the latest monthly data submissions to the IEA's Energy Data Centre, other statistical releases from national administrations, and recent market data from the IEA Market Report Series that cover coal, oil, natural gas, renewables and power.

Historical data for gross electrical capacity are drawn from the S&P Global Market Intelligence World Electric Power Plants Database (March 2020 version) and the International Atomic Energy Agency PRIS database.

Definitional note: A.1. Energy supply and transformation table

Total energy supply (TES) is equivalent to electricity and heat generation plus "other energy sector" excluding electricity and heat, plus total final consumption (TFC) excluding electricity and heat. TES does not include ambient heat from heat pumps or electricity trade. Solar in TES includes solar PV generation, concentrating solar power and final consumption of solar thermal. Other renewables in TES include geothermal, and marine (tide and wave) energy for electricity and heat generation. Hydrogen production and biofuels production in the other energy sector account for the energy input required to produce merchant hydrogen (mainly natural gas and electricity) and for the conversion losses to produce biofuels (mainly primary solid biomass) used in the energy sector. While not itemised separately, non-renewable waste and other sources are included in TES.

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Definitional note: A.2. Energy demand table

Sectors comprising total final consumption (TFC) include industry (energy use and feedstock), transport, buildings (residential, services and non-specified other) and other (agriculture and other non-energy use). Energy demand from international marine and aviation bunkers are included in transport totals.

Definitional note: A.3. Electricity tables

Electricity generation expressed in terawatt-hours (TWh) and installed electrical capacity data expressed in gigawatts (GW) are both provided on a gross basis (i.e. includes own use by the generator). Projected gross electrical capacity is the sum of existing capacity and additions, less retirements. While not itemised separately, other sources are included in total electricity generation.

Definitional note: A.4. CO_2 emissions table

Total CO_2 includes carbon dioxide emissions from the combustion of fossil fuels and non-renewable wastes, from industrial and fuel transformation processes (process emissions) as well as CO_2 removals. Three types of CO_2 removals are presented:

- Captured and stored emissions from the combustion of bioenergy and renewable wastes (typically electricity generation).
- Captured and stored process emissions from biofuels production.
- Captured and stored carbon dioxide from the atmosphere, which is reported as direct air carbon capture and storage (DACCS).

The first two entries are often reported as bioenergy with carbon capture and storage (BECCS). Note that some of the CO_2 captured from biofuels production and direct air capture is used to produce synthetic fuels, which is not included as CO_2 removal.

Total CO_2 captured includes the carbon dioxide captured from CCUS facilities (such as electricity generation or industry) and atmospheric CO_2 captured through direct air capture but excludes that captured and used for urea production.

Definitional note: A.5. Economic and activity indicators

The emission intensity expressed in kilogrammes of carbon dioxide per kilowatt-hour (kg CO_2/kWh) is calculated based on electricity-only plants and the electricity component of combined heat and power (CHP) plants. [1]

Other abbreviations used include: PPP = purchasing power parity; GJ = gigajoules; Mt = million tonnes; pkm = passenger-kilometres; tkm = tonnes-kilometres; m^2 = square metres.

[1] To derive the associated electricity-only emissions from CHP plants, we assume that the heat production of a CHP plant is 90% efficient and the remainder of the fuel input is allocated to electricity generation.

Table A.1: Energy supply and transformation

	Energy supply (EJ)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Total energy supply	**612**	**587**	**547**	**535**	**543**	**100**	**100**	**100**	**-0.7**	**-0.3**
Renewables	67	69	167	295	362	12	30	67	9.3	5.7
Solar	4	5	32	78	109	1	6	20	21	11
Wind	5	6	29	67	89	1	5	16	17	9.6
Hydro	15	16	21	27	30	3	4	6	2.9	2.2
Modern solid bioenergy	31	32	54	73	73	5	10	14	5.3	2.8
Modern liquid bioenergy	4	3	12	14	15	1	2	3	14	4.9
Modern gaseous bioenergy	2	2	5	10	14	0	1	3	10	6.4
Other renewables	4	5	13	24	32	1	2	6	11	6.7
Traditional use of biomass	25	25	-	-	-	4	-	-	n.a.	n.a.
Nuclear	30	29	41	54	61	5	8	11	3.5	2.4
Unabated natural gas	139	136	116	44	17	23	21	3	-1.6	-6.6
Natural gas with CCUS	0	1	13	31	43	0	2	8	37	16
Oil	190	173	137	79	42	29	25	8	-2.3	-4.6
of which non-energy use	28	27	32	31	29	5	6	5	1.4	0.2
Unabated coal	160	154	68	16	3	26	12	1	-7.9	-12
Coal with CCUS	0	0	4	16	14	0	1	3	60	22
Electricity and heat sectors	**233**	**230**	**240**	**308**	**371**	**100**	**100**	**100**	**0.4**	**1.6**
Renewables	36	38	107	220	284	17	44	77	11	6.9
Solar PV	2	3	25	61	84	1	10	23	24	12
Wind	5	6	29	67	89	2	12	24	17	9.6
Hydro	15	16	21	27	30	7	9	8	2.9	2.2
Bioenergy	9	10	18	35	39	4	8	10	6.3	4.6
Other renewables	4	4	14	30	42	2	6	11	14	8.5
Hydrogen	-	-	5	11	11	-	2	3	n.a.	n.a.
Ammonia	-	-	1	2	2	-	0	0	n.a.	n.a.
Nuclear	30	29	41	54	61	13	17	16	3.5	2.4
Unabated natural gas	56	55	49	4	2	24	21	0	-1.1	-11
Natural gas with CCUS	-	-	1	5	5	-	1	1	n.a.	n.a.
Oil	9	8	2	0	0	4	1	0	-12	-14
Unabated coal	102	100	30	0	0	43	12	0	-11	-34
Coal with CCUS	0	0	3	10	7	0	1	2	55	19
Other energy sector	**57**	**57**	**61**	**76**	**91**	**100**	**100**	**100**	**0.7**	**1.5**
Hydrogen production	-	0	21	49	70	0	35	77	66	23
Biofuels production	5	6	12	15	12	10	20	13	8	2.7

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Table A.2: Energy demand

	Energy demand (EJ)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Total final consumption	**435**	**412**	**394**	**363**	**344**	**100**	**100**	**100**	**-0.4**	**-0.6**
Electricity	82	81	103	140	169	20	26	49	2.4	2.5
Liquid fuels	175	158	143	96	66	38	36	19	-1.0	-2.9
Biofuels	4	3	12	14	15	1	3	4	14	4.9
Ammonia	-	-	1	3	5	-	0	1	n.a.	n.a.
Synthetic oil	-	-	0	2	5	-	0	1	n.a.	n.a.
Oil	171	154	129	77	42	37	33	12	-1.8	-4.2
Gaseous fuels	70	68	68	60	53	16	17	15	0.1	-0.8
Biomethane	0	0	2	5	8	0	1	2	25	13
Hydrogen	0	0	6	12	20	0	2	6	54	20
Synthetic methane	-	-	0	1	4	-	0	1	n.a.	n.a.
Natural gas	70	67	58	40	20	16	15	6	-1.4	-4.0
Solid fuels	92	89	61	46	35	22	16	10	-3.6	-3.0
Biomass	39	39	24	25	25	9	6	7	-4.8	-1.4
Coal	53	50	38	21	10	12	10	3	-2.8	-5.3
Heat	13	13	12	9	6	3	3	2	-1.2	-2.7
Other	3	3	7	11	15	1	2	4	8.2	5.2
Industry	**162**	**157**	**170**	**169**	**160**	**100**	**100**	**100**	**0.8**	**0.1**
Electricity	35	35	47	62	74	22	28	46	3.0	2.5
Liquid fuels	31	31	31	27	23	20	18	15	-0.2	-0.9
Oil	31	31	31	27	23	20	18	15	-0.2	-0.9
Gaseous fuels	32	32	35	34	28	20	21	18	1.0	-0.4
Biomethane	0	0	1	2	4	0	0	3	22	15
Hydrogen	-	0	3	4	5	0	2	3	44	15
Unabated natural gas	32	32	30	22	9	20	18	6	-0.5	-4.0
Natural gas with CCUS	0	0	1	5	7	0	1	4	38	18
Solid fuels	58	52	51	40	30	34	30	18	-0.3	-1.9
Biomass	10	9	15	19	20	6	9	13	5.2	2.8
Unabated coal	48	44	35	15	3	28	20	2	-2.3	-9.0
Coal with CCUS	0	0	1	5	7	0	1	4	91	31
Heat	6	6	6	3	2	4	3	1	-1.2	-4.5
Other	0	0	1	3	4	0	1	2	33	14
Iron and steel	36	33	37	36	32	21	22	20	1.1	-0.2
Chemicals	22	20	26	26	25	13	15	15	2.7	0.7
Cement	12	16	11	11	10	10	7	7	-3.3	-1.3

Table A.2: Energy demand

	Energy demand (EJ)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Transport	**122**	**105**	**102**	**85**	**80**	**100**	**100**	**100**	**-0.3**	**-0.9**
Electricity	1	1	7	22	35	1	7	44	17	11
Liquid fuels	115	99	89	53	30	94	87	38	-1.0	-3.9
Biofuels	4	3	11	12	11	3	11	14	14	4.3
Oil	111	96	76	35	9	91	74	12	-2.2	-7.4
Gaseous fuels	5	5	6	10	15	5	6	18	2.1	3.7
Biomethane	0	0	1	1	2	0	0	2	23	11
Hydrogen	0	0	1	6	13	0	1	16	92	34
Natural gas	5	5	4	2	0	5	4	0	-1.5	-11
Road	90	81	73	57	50	77	72	63	-0.9	-1.6
Passenger cars	47	41	30	19	17	39	29	21	-3.1	-2.9
Trucks	27	25	28	24	22	24	27	28	1.1	-0.4
Aviation	14	8	13	13	14	8	13	18	4.6	1.7
Shipping	12	11	11	10	10	10	11	12	0.4	-0.3
Buildings	**129**	**127**	**99**	**89**	**86**	**100**	**100**	**100**	**-2.4**	**-1.3**
Electricity	43	42	45	51	57	33	46	66	0.7	1.0
Liquid fuels	13	13	9	4	2	10	10	2	-3.2	-6.0
Biofuels	0	0	0	1	1	0	0	1	26	12
Oil	13	13	9	4	1	10	9	1	-3.4	-7.7
Gaseous fuels	30	28	23	13	6	22	23	7	-2.1	-4.9
Biomethane	0	0	1	2	2	0	1	2	29	11
Hydrogen	-	0	2	2	2	0	2	2	103	27
Natural gas	30	28	19	7	1	22	20	1	-3.8	-12
Solid fuels	34	34	10	7	6	27	10	7	-11	-5.5
Modern biomass	5	5	9	7	6	4	9	7	6.9	0.9
Traditional use of biomass	25	25	-	-	-	20	-	-	n.a.	n.a.
Coal	4	4	1	0	0	3	1	0	-12	-21
Heat	7	7	6	5	4	5	6	5	-1.2	-1.6
Other	2	3	5	8	11	2	5	12	7.1	4.8
Residential	91	90	67	59	58	71	67	67	-3.0	-1.5
Services	38	36	32	30	28	29	33	33	-1.2	-0.9
Other	**22**	**23**	**22**	**20**	**18**	**100**	**100**	**100**	**-0.5**	**-0.9**

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Table A.3: Electricity

	Electricity Generation (TWh)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Total generation	**26 922**	**26 778**	**37 316**	**56 553**	**71 164**	**100**	**100**	**100**	**3.4**	**3.3**
Renewables	7 153	7 660	22 817	47 521	62 333	29	61	88	12	7.2
Solar PV	665	821	6 970	17 031	23 469	3	19	33	24	12
Wind	1 423	1 592	8 008	18 787	24 785	6	21	35	18	9.6
Hydro	4 294	4 418	5 870	7 445	8 461	17	16	12	2.9	2.2
Bioenergy	665	718	1 407	2 676	3 279	3	4	5	7.0	5.2
of which BECCS	-	-	*129*	*673*	*842*	-	*0*	*1*	*n.a.*	*n.a.*
CSP	14	14	204	880	1 386	0	1	2	31	17
Geothermal	92	94	330	625	821	0	1	1	13	7.5
Marine	1	2	27	77	132	0	0	0	28	14
Nuclear	2 792	2 698	3 777	4 855	5 497	10	10	8	3.4	2.4
Hydrogen-based	-	-	875	1 857	1 713	-	2	2	n.a.	n.a.
Fossil fuels with CCUS	1	4	459	1 659	1 332	0	1	2	61	21
Coal with CCUS	1	4	289	966	663	0	1	1	54	19
Natural gas with CCUS	-	-	170	694	669	-	0	1	n.a.	n.a.
Unabated fossil fuels	16 941	16 382	9 358	632	259	61	25	0	-5.4	-13
Coal	9 832	9 426	2 947	0	0	35	8	0	-11	-40
Natural gas	6 314	6 200	6 222	626	253	23	17	0	0.0	-10
Oil	795	756	189	6	6	3	1	0	-13	-15

	Electrical Capacity (GW)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Total capacity	**7 484**	**7 795**	**14 933**	**26 384**	**33 415**	**100**	**100**	**100**	**6.7**	**5.0**
Renewables	2 707	2 994	10 293	20 732	26 568	38	69	80	13	7.5
Solar PV	603	737	4 956	10 980	14 458	9	33	43	21	10
Wind	623	737	3 101	6 525	8 265	9	21	25	15	8.4
Hydro	1 306	1 327	1 804	2 282	2 599	17	12	8	3.1	2.3
Bioenergy	153	171	297	534	640	2	2	2	5.7	4.5
of which BECCS	-	-	*28*	*125*	*152*	-	*0*	*0*	*n.a.*	*n.a.*
CSP	6	6	73	281	426	0	0	1	28	15
Geothermal	15	15	52	98	126	0	0	0	13	7.4
Marine	1	1	11	32	55	0	0	0	34	16
Nuclear	415	415	515	730	812	5	3	2	2.2	2.3
Hydrogen-based	-	-	139	1 455	1 867	-	1	6	n.a.	n.a.
Fossil fuels with CCUS	0	1	81	312	394	0	1	1	66	25
Coal with CCUS	0	1	53	182	222	0	0	1	59	22
Natural gas with CCUS	-	-	28	130	171	-	0	1	n.a.	n.a.
Unabated fossil fuels	4 351	4 368	3 320	1 151	677	56	22	2	-2.7	-6.0
Coal	2 124	2 117	1 192	432	158	27	8	0	-5.6	-8.3
Natural gas	1 788	1 829	1 950	679	495	23	13	1	0.6	-4.3
Oil	440	422	178	39	25	5	1	0	-8.3	-9.0
Battery storage	11	18	585	2 005	3 097	0	4	9	42	19

Table A.4: CO_2 emissions

	CO_2 emissions (Mt CO_2)					CAAGR (%)	
	2019	2020	2030	2040	2050	2020-2030	2020-2050
Total CO_2*	**35 926**	**33 903**	**21 147**	**6 316**	**0**	**-4.6**	**n.a.**
Combustion activities (+)	**33 499**	**31 582**	**19 254**	**6 030**	**940**	**-4.8**	**-11**
Coal	14 660	14 110	5 915	1 299	195	-8.3	-13
Oil	11 505	10 264	7 426	3 329	928	-3.2	-7.7
Natural gas	7 259	7 138	5 960	1 929	566	-1.8	-8.1
Bioenergy and waste	75	71	- 48	- 528	- 748	n.a.	n.a.
Industry removals (-)	**1**	**1**	**214**	**914**	**1 186**	**75**	**28**
Biofuels production	1	1	142	385	553	68	24
Direct air capture	-	-	71	528	633	n.a.	n.a.
Electricity and heat sectors	**13 821**	**13 504**	**5 816**	**- 81**	**- 369**	**-8.1**	**n.a.**
Coal	10 035	9 786	2 950	102	69	-11	-15
Oil	655	628	173	6	6	-12	-14
Natural gas	3 131	3 089	2 781	268	128	-1.0	-10
Bioenergy and waste	-	-	- 87	- 457	- 572	n.a.	n.a.
Other energy sector*	**1 457**	**1 472**	**679**	**- 85**	**- 368**	**-7.4**	**n.a.**
Final consumption*	**20 647**	**18 928**	**14 723**	**7 011**	**1 370**	**-2.5**	**-8.4**
Coal	4 486	4 171	2 935	1 186	117	-3.5	-11
Oil	10 272	9 077	6 973	3 242	880	-2.6	-7.5
Natural gas	3 451	3 332	2 668	1 453	303	-2.2	-7.7
Bioenergy and waste	75	71	40	- 70	- 176	-5.6	n.a.
Industry*	8 903	8 478	6 892	3 485	519	-2.0	-8.9
Iron and steel	2 507	2 349	1 778	859	220	-2.7	-7.6
Chemicals	1 344	1 296	1 199	654	66	-0.8	-9.5
Cement	2 461	2 334	1 899	906	133	-2.0	-9.1
Transport	8 290	7 153	5 719	2 686	689	-2.2	-7.5
Road	6 116	5 483	4 077	1 793	340	-2.9	-8.9
Passenger cars	3 121	2 746	1 626	547	85	-5.1	-11
Trucks	1 835	1 721	1 614	890	198	-0.6	-6.9
Aviation	1 019	621	783	469	210	2.4	-3.5
Shipping	883	800	705	348	122	-1.3	-6.1
Buildings	3 007	2 860	1 809	685	122	-4.5	-10
Residential	2 030	1 968	1 377	541	108	-3.5	-9.2
Services	977	892	432	144	14	-7.0	-13
Total CO_2 removals	**1**	**1**	**317**	**1 457**	**1 936**	**79**	**29**
Total CO_2 captured	**40**	**40**	**1 665**	**5 619**	**7 602**	**45**	**19**

**Includes industrial process emissions.*

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Table A.5: Economic and Activity Indicators

	Indicator					CAAGR (%)	
	2019	2020	2030	2040	2050	2020-2030	2020-2050
Population (million)	7 672	7 753	8 505	9 155	9 692	0.9	0.7
GDP (USD 2019 billion, PPP)	134 710	128 276	184 037	246 960	316 411	3.7	3.1
GDP per capita (USD 2019, PPP)	17 558	16 545	21 638	26 975	32 648	2.7	2.3
TES/GDP (GJ per USD 1 000, PPP)	4.543	4.578	2.973	2.164	1.716	-4.2	-3.2
TFC/GDP (GJ per USD 1 000, PPP)	3.231	3.208	2.139	1.468	1.086	-4.0	-3.5
TES per capita (GJ)	79.77	75.74	64.33	58.38	56.03	-1.6	-1.0
CO_2 intensity of electricity generation (kg CO_2 per kWh)	0.468	0.438	0.138	-0.001	-0.005	-11	n.a.

	Activity					CAAGR (%)	
	2019	2020	2030	2040	2050	2020-2030	2020-2050
Industrial production							
Primary chemicals (Mt)	538	529	641	686	688	1.9	0.9
Steel (Mt)	1 869	1 781	1 937	1 958	1 987	0.8	0.4
Cement (Mt)	4 215	4 054	4 258	4 129	4 032	0.5	-0.0
Transport							
Passenger cars (billion vkm)	15 300	14 261	15 775	19 159	24 517	1.0	1.8
Trucks (billion tkm)	26 646	25 761	38 072	49 756	59 990	4.0	2.9
Aviation (billion pkm)	8 506	5 474	10 271	11 573	14 566	6.5	3.3
Shipping (billion tkm)	107 225	109 153	155 621	209 905	291 032	3.6	3.3
Buildings							
Services floor area (million m^2)	49 670	49 825	58 867	68 576	78 157	1.7	1.5
Residential floor area (million m^2)	190 062	192 558	235 745	290 696	345 183	2.0	2.0
Million households	2 095	2 116	2 435	2 765	3 051	1.4	1.2

Electricity generation

Table B.1 ▷ Electricity generation technology costs by selected region in the NZE

	Financing rate (%)	Capital costs ($/kW)			Capacity factor (%)			Fuel, CO_2 and O&M ($/MWh)			LCOE ($/MWh)		
	All	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
United States													
Nuclear	8.0	5 000	4 800	4 500	90	80	75	30	30	30	105	110	110
Coal	8.0	2 100	2 100	2 100	20	*n.a.*	*n.a.*	90	170	235	220	*n.a.*	*n.a.*
Gas CCGT	8.0	1 000	1 000	1 000	55	25	*n.a.*	50	80	105	70	125	*n.a.*
Solar PV	3.7	1 140	620	420	21	22	23	10	10	10	50	30	20
Wind onshore	3.7	1 540	1 420	1 320	42	43	44	10	10	10	35	35	30
Wind offshore	4.5	4 040	2 080	1 480	42	46	48	35	20	15	115	60	40
European Union													
Nuclear	8.0	6 600	5 100	4 500	75	75	70	35	35	35	150	120	115
Coal	8.0	2 000	2 000	2 000	20	*n.a.*	*n.a.*	120	205	275	250	*n.a.*	*n.a.*
Gas CCGT	8.0	1 000	1 000	1 000	40	20	*n.a.*	65	95	120	100	150	*n.a.*
Solar PV	3.2	790	460	340	13	14	14	10	10	10	55	35	25
Wind onshore	3.2	1 540	1 420	1 300	29	30	31	15	15	15	55	45	40
Wind offshore	4.0	3 600	2 020	1 420	51	56	59	15	10	5	75	40	25
China													
Nuclear	7.0	2 800	2 800	2 500	80	80	80	25	25	25	65	65	60
Coal	7.0	800	800	800	60	*n.a.*	*n.a.*	75	135	195	90	*n.a.*	*n.a.*
Gas CCGT	7.0	560	560	560	45	35	*n.a.*	75	100	120	90	115	*n.a.*
Solar PV	3.5	750	400	280	17	18	19	10	5	5	40	25	15
Wind onshore	3.5	1 220	1 120	1 040	26	27	27	15	10	10	45	40	40
Wind offshore	4.3	2 840	1 560	1 000	34	41	43	25	15	10	95	45	30
India													
Nuclear	7.0	2 800	2 800	2 800	70	70	70	30	30	30	75	75	75
Coal	7.0	1 200	1 200	1 200	50	*n.a.*	*n.a.*	35	50	75	65	*n.a.*	*n.a.*
Gas CCGT	7.0	700	700	700	55	50	*n.a.*	45	45	50	55	60	*n.a.*
Solar PV	5.8	580	310	220	20	21	21	5	5	5	35	20	15
Wind onshore	5.8	1 040	980	940	26	28	29	10	10	10	50	45	40
Wind offshore	6.6	2 980	1 680	1 180	32	37	38	25	15	10	130	70	45

Notes: O&M = operation and maintenance; LCOE = levelised cost of electricity; kW = kilowatt; MWh = megawatt-hour; CCGT = combined-cycle gas turbine; n.a. = not applicable. Cost components and LCOE figures are rounded.

Sources: IEA analysis; IRENA Renewable Costing Alliance; IRENA (2020).

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- Major contributors to the LCOE include: overnight capital costs; capacity factor that describes the average output over the year relative to the maximum rated capacity (typical values provided); the cost of fuel inputs; plus operation and maintenance. Economic lifetime assumptions are 25 years for solar PV, onshore and offshore wind.
- Weighted average costs of capital (WACC) reflect analysis for utility-scale solar PV in the *World Energy Outlook 2020* (IEA, 2020) and for offshore wind from the *Offshore Wind Outlook 2019* (IEA, 2019). Onshore wind was assumed to have the same WACC as utility-scale solar PV. A standard WACC was assumed for nuclear power, coal- and gas-fired power plants (7-8% based on the stage of economic development).
- Fuel, CO_2 and O&M costs reflect the average over the ten years following the indicated date in the projections.
- The capital costs for nuclear power represent the "nth-of-a-kind" costs for new reactor designs, with substantial cost reductions from the first-of-a-kind projects.

Batteries and hydrogen

Table B.2 ▷ Capital costs for batteries and hydrogen production technologies in the NZE

	2020	2030	2050
Battery packs for transport applications (USD/kWh)	130 - 155	75 - 90	55 - 80
Low-temperature electrolysers (USD/kW_e)	835 - 1 300	255 - 515	200 - 390
Natural gas with CCUS (USD/kW H_2)	1 155 - 2 010	990 - 1 725	935 - 1 625

Notes: kWh = kilowatt-hour; kW_e = kilowatt electric; CCUS = carbon capture, utilisation and storage; H_2 = hydrogen. Capital costs for electrolysers and hydrogen production from natural gas with CCUS are overnight costs.

Source: IEA analysis.

Definitions

This annex provides general information on terminology used throughout this report including: units and general conversion factors; definitions of fuels, processes and sectors; regional and country groupings; and abbreviations and acronyms.

Units

Area	km^2	square kilometre
	Mha	million hectares
Batteries	Wh/kg	Watt hours per kilogramme
Coal	Mtce	million tonnes of coal equivalent (equals 0.7 Mtoe)
Distance	km	kilometre
Emissions	ppm	parts per million (by volume)
	tCO_2	tonnes of carbon dioxide
	Gt CO_2-eq	gigatonnes of carbon-dioxide equivalent (using 100-year global warming potentials for different greenhouse gases)
	kg CO_2-eq	kilogrammes of carbon-dioxide equivalent
	g CO_2/km	grammes of carbon dioxide per kilometre
	kg CO_2/kWh	kilogrammes of carbon dioxide per kilowatt-hour
Energy	EJ	exajoule
	PJ	petajoule
	TJ	terajoule
	GJ	gigajoule
	MJ	megajoule
	boe	barrel of oil equivalent
	toe	tonne of oil equivalent
	ktoe	thousand tonnes of oil equivalent
	Mtoe	million tonnes of oil equivalent
	MBtu	million British thermal units
	kWh	kilowatt-hour
	MWh	megawatt-hour
	GWh	gigawatt-hour
	TWh	terawatt-hour
Gas	bcm	billion cubic metres
	tcm	trillion cubic metres
Mass	kg	kilogramme (1 000 kg = 1 tonne)
	kt	kilotonnes (1 tonne x 10^3)
	Mt	million tonnes (1 tonne x 10^6)
	Gt	gigatonnes (1 tonne x 10^9)

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Monetary	USD million	1 US dollar x 10^6
	USD billion	1 US dollar x 10^9
	USD trillion	1 US dollar x 10^{12}
	USD/tCO_2	US dollars per tonne of carbon dioxide
Oil	kb/d	thousand barrels per day
	mb/d	million barrels per day
	mboe/d	million barrels of oil equivalent per day
Power	W	watt (1 joule per second)
	kW	kilowatt (1 watt x 10^3)
	MW	megawatt (1 watt x 10^6)
	GW	gigawatt (1 watt x 10^9)
	TW	terawatt (1 watt x 10^{12})

General conversion factors for energy

		Multiplier to convert to:				
		EJ	**Gcal**	**Mtoe**	**MBtu**	**GWh**
Convert from:	**EJ**	1	238.8 x 10^6	23.88	9.47.8 x 10^3	2.778 x 10^5
	Gcal	4.1868 x 10^{-9}	1	10^{-7}	3.968	1.163 x 10^{-3}
	Mtoe	4.1868 x 10^{-2}	10^7	1	3.968 x 10^7	11 630
	MBtu	1.0551 x 10^{-9}	0.252	2.52 x 10^{-8}	1	2.931 x 10^{-4}
	GWh	3.6 x 10^{-6}	860	8.6 x 10^{-5}	3 412	1

Note: There is no generally accepted definition of boe; typically the conversion factors used vary from 7.15 to 7.40 boe per toe.

Currency conversions

Exchange rates *(2019 annual average)*	**1 US dollar (USD) equals:**
British Pound	0.78
Chinese Yuan Renminbi	6.91
Euro	0.89
Indian Rupee	70.42
Indonesian Rupiah	14 147.67
Japanese Yen	109.01
Russian Ruble	64.74
South African Rand	14.45

Source: OECD National Accounts Statistics: purchasing power parities and exchange rates dataset, July 2020.

Definitions

Advanced bioenergy: Sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant lifecycle greenhouse gas emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts. This definition differs from the one used for "advanced biofuels" in US legislation, which is based on a minimum 50% lifecycle greenhouse gas reduction and which, therefore, includes sugar cane ethanol.

Agriculture: Includes all energy used on farms, in forestry and for fishing.

Agriculture, forestry and other land use (AFOLU) **emissions:** Includes greenhouse gas emissions from agriculture, forestry and other land use.

Ammonia (NH_3)**:** Is a compound of nitrogen and hydrogen. It can be used directly as a fuel in direct combustion process, and in fuel cells or as a hydrogen carrier. To be a low-carbon fuel, ammonia must be produced from low-carbon hydrogen, the nitrogen separated via the Haber process, and electricity needs are met by low-carbon electricity.

Aviation: This transport mode includes both domestic and international flights and their use of aviation fuels. Domestic aviation covers flights that depart and land in the same country; flights for military purposes are also included. International aviation includes flights that land in a country other than the departure location.

Back-up generation capacity: Households and businesses connected to a main power grid may also have back-up electricity generation capacity that, in the event of disruption, can provide electricity. Back-up generators are typically fuelled with diesel or gasoline and capacity can be as little as a few kilowatts. Such capacity is distinct from mini-grid and off-grid systems that are not connected to a main power grid.

Biodiesel: Diesel-equivalent, processed fuel made from the transesterification (a chemical process that converts triglycerides in oils) of vegetable oils and animal fats.

Bioenergy: Energy content in solid, liquid and gaseous products derived from biomass feedstocks and biogas. It includes solid biomass, liquid biofuels and biogases.

Biogas: A mixture of methane, carbon dioxide and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment.

Biogases: Include biogas and biomethane.

Biomethane: Biomethane is a near-pure source of methane produced either by upgrading biogas (a process that removes any CO_2 and other contaminants present in the biogas) or through the gasification of solid biomass followed by methanation. It is also known as renewable natural gas.

Buildings: The buildings sector includes energy used in residential, commercial and institutional buildings and non-specified other. Building energy use includes space heating and cooling, water heating, lighting, appliances and cooking equipment.

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Bunkers: Includes both international marine bunkers and international aviation bunkers.

Capacity credit: Proportion of the capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.

Carbon capture, utilisation and storage (CCUS)**:** The process of capturing CO_2 emissions from fuel combustion, industrial processes or directly from the atmosphere. Captured CO_2 emissions can be stored in underground geological formations, onshore or offshore or used as an input or feedstock to create products.

Clean energy: Includes renewables, energy efficiency, low-carbon fuels, nuclear power, battery storage and carbon capture, utilisation and storage.

Clean cooking facilities: Cooking facilities that are considered safer, more efficient and more environmentally sustainable than the traditional facilities that make use of solid biomass (such as a three-stone fire). This refers primarily to improved solid biomass cookstoves, biogas systems, liquefied petroleum gas stoves, ethanol and solar stoves.

Coal: Includes both primary coal (including lignite, coking and steam coal) and derived fuels (including patent fuel, brown-coal briquettes, coke-oven coke, gas coke, gas-works gas, coke-oven gas, blast furnace gas and oxygen steel furnace gas). Peat is also included.

Concentrating solar power (CSP)**:** Solar thermal power/electric generation systems that collect and concentrate sunlight to produce high temperature heat to generate electricity.

Conventional liquid biofuels: Fuels produced from food crop feedstocks. These liquid biofuels are commonly referred to as first generation and include sugar cane ethanol, starch-based ethanol, fatty acid methyl esther (FAME) and straight vegetable oil (SVO).

Decomposition analysis: Statistical approach that decomposes an aggregate indicator to quantify the relative contribution of a set of pre-defined factors leading to a change in the aggregate indicator. This report uses an additive index decomposition of the type Logarithmic Mean Divisia Index (LMDI).

Demand-side integration (DSI)**:** Consists of two types of measures: actions that influence load shape such as energy efficiency and electrification; and actions that manage load such as demand-side response.

Demand-side response (DSR)**:** Describes actions which can influence the load profile such as shifting the load curve in time without affecting the total electricity demand, or load shedding such as interrupting demand for short duration or adjusting the intensity of demand for a certain amount of time.

Dispatchable generation: Refers to technologies whose power output can be readily controlled - increased to maximum rated capacity or decreased to zero - in order to match supply with demand.

Electricity demand: Defined as total gross electricity generation less own use generation, plus net trade (imports less exports), less transmissions and distribution losses.

Electricity generation: Defined as the total amount of electricity generated by power only or combined heat and power plants including generation required for own use. This is also referred to as gross generation.

Energy sector CO_2 emissions: Carbon dioxide emissions from fuel combustion (excluding non-renewable waste). Note that this does not include fugitive emissions from fuels, CO_2 from transport, storage emissions or industrial process emissions.

Energy sector GHG emissions: CO_2 emissions from fuel combustion plus fugitive and vented methane, and nitrous oxide (N_2O) emissions from the energy and industry sectors.

Energy services: See useful energy.

Ethanol: Refers to bio-ethanol only. Ethanol is produced from fermenting any biomass high in carbohydrates. Today, ethanol is made from starches and sugars, but second-generation technologies will allow it to be made from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter.

Fischer-Tropsch synthesis: Catalytic production process for the production of synthetic fuels. Natural gas, coal and biomass feedstocks can be used.

Gases: Includes natural gas, biogases, synthetic methane and hydrogen.

Geothermal: Geothermal energy is heat derived from the sub-surface of the earth. Water and/or steam carry the geothermal energy to the surface. Depending on its characteristics, geothermal energy can be used for heating and cooling purposes or be harnessed to generate clean electricity if the temperature is adequate.

Heat (end-use): Can be obtained from the combustion of fossil or renewable fuels, direct geothermal or solar heat systems, exothermic chemical processes and electricity (through resistance heating or heat pumps which can extract it from ambient air and liquids). This category refers to the wide range of end-uses, including space and water heating, and cooking in buildings, desalination and process applications in industry. It does not include cooling applications.

Heat (supply): Obtained from the combustion of fuels, nuclear reactors, geothermal resources and the capture of sunlight. It may be used for heating or cooling, or converted into mechanical energy for transport or electricity generation. Commercial heat sold is reported under total final consumption with the fuel inputs allocated under electricity and heat sectors.

Hydrogen: Hydrogen is used in the energy system to refine hydrocarbon fuels and as an energy carrier in its own right. It is also produced from other energy products for use in chemicals production. As an energy carrier it can be produced from hydrocarbon fuels or from the electrolysis of water with electricity, and can be burned or used in fuel cells for electricity and heat in a wide variety of applications. To be low-carbon hydrogen, either the emissions associated with fossil-based hydrogen production must be prevented (for example by carbon capture, utilisation and storage) or the electricity input to hydrogen produced from water must be low-carbon electricity. In this report, final consumption of hydrogen

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includes demand for pure hydrogen and excludes hydrogen produced and consumed onsite by the same entity. Demand for hydrogen-based fuels such as ammonia or synthetic hydrocarbons are considered separately.

Hydrogen-based fuels: Include ammonia and synthetic hydrocarbons (gases and liquids). Hydrogen-based is used in figures to refer to hydrogen and hydrogen-based fuels.

Hydropower: The energy content of the electricity produced in hydropower plants, assuming 100% efficiency. It excludes output from pumped storage and marine (tide and wave) plants.

Industry: The sector includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemicals and petrochemicals, cement, and pulp and paper. Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles is reported under industry.

International aviation bunkers: Includes the deliveries of aviation fuels to aircraft for international aviation. Fuels used by airlines for their road vehicles are excluded. The domestic/international split is determined on the basis of departure and landing locations and not by the nationality of the airline. For many countries this incorrectly excludes fuels used by domestically owned carriers for their international departures.

International marine bunkers: Covers fuels delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. Consumption by fishing vessels and by military forces is excluded and included in residential, services and agriculture.

Investment: All investment data and projections reflect spending across the lifecycle of a project, i.e. the capital spent is assigned to the year when it is incurred. Investments for oil, gas and coal include production, transformation and transportation; those for the power sector include refurbishments, uprates, new builds and replacements for all fuels and technologies for on-grid, mini-grid and off-grid generation, as well as investment in transmission and distribution, and battery storage. Investment data are presented in real terms in year-2019 US dollars unless otherwise stated.

Light-duty vehicles (LDV)**:** include passenger cars and light commercial vehicles (gross vehicle weight <3.5 tonnes).

Liquid biofuels: Liquid fuels derived from biomass or waste feedstocks and include ethanol and biodiesel. They can be classified as conventional and advanced liquid biofuels according to the bioenergy feedstocks and technologies used to produce them and their respective maturity. Unless otherwise stated, liquid biofuels are expressed in energy-equivalent volumes of gasoline and diesel.

Liquids: Includes oil, liquid biofuels (expressed in energy-equivalent volumes of gasoline and diesel), synthetic oil and ammonia.

Low-carbon electricity: Includes renewable energy technologies, hydrogen-based generation, nuclear power and fossil fuel power plants equipped with carbon capture, utilisation and storage.

Low-emissions fuels: Include liquid biofuels, biogas and biomethane, hydrogen, and hydrogen-based fuels that do not emit any CO_2 from fossil fuels directly when used and also emit very little when being produced.

Marine: Represents the mechanical energy derived from tidal movement, wave motion or ocean current and exploited for electricity generation.

Merchant hydrogen: Hydrogen produced by one company to sell to others; equivalent to hydrogen reported in total final consumption.

Mini-grids: Small grid systems linking a number of households or other consumers.

Modern bioenergy: Includes modern solid biomass, liquid biofuels and biogases harvested from sustainable sources. It excludes the traditional use of biomass.

Modern energy access: Includes household access to a minimum level of electricity; household access to safer and more sustainable cooking and heating fuels, and stoves; access that enables productive economic activity; and access for public services.

Modern renewables: Includes all uses of renewable energy with the exception of traditional use of solid biomass.

Modern solid biomass: Refers to the use of solid biomass in improved cookstoves and modern technologies using processed biomass such as pellets.

Natural gas: Comprises gases occurring in deposits, whether liquefied or gaseous, consisting mainly of methane. It includes both "non-associated" gas originating from fields producing hydrocarbons only in gaseous form, and "associated" gas produced in association with crude oil as well as methane recovered from coal mines (colliery gas). Natural gas liquids (NGLs), manufactured gas (produced from municipal or industrial waste, or sewage) and quantities vented or flared are not included. Gas data in cubic metres are expressed on a gross calorific value basis and are measured at 15 °C and at 760 mm Hg ("Standard Conditions"). Gas data expressed in tonnes of oil equivalent, mainly for comparison reasons with other fuels, are on a net calorific basis. The difference between the net and the gross calorific value is the latent heat of vaporisation of the water vapour produced during combustion of the fuel (for gas the net calorific value is 10% lower than the gross calorific value).

Natural gas liquids (NGLs)**:** Liquid or liquefied hydrocarbons produced in the manufacture, purification and stabilisation of natural gas. These are those portions of natural gas which are recovered as liquids in separators, field facilities or gas processing plants. NGLs include but are not limited to ethane (when it is removed from the natural gas stream), propane, butane, pentane, natural gasoline and condensates.

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Network gases: Includes natural gas, biomethane, synthetic methane and hydrogen blended in a gas network.

Non-energy use: Fuels used for chemical feedstocks and non-energy products. Examples of non-energy products include lubricants, paraffin waxes, asphalt, bitumen, coal tars and oils as timber preservatives.

Nuclear: Refers to the primary energy equivalent of the electricity produced by a nuclear plant, assuming an average conversion efficiency of 33%.

Off-grid systems: Stand-alone systems for individual households or groups of consumers.

Offshore wind: Refers to electricity produced by wind turbines that are installed in open water, usually in the ocean.

Oil: Oil production includes both conventional and unconventional oil. Petroleum products include refinery gas, ethane, liquid petroleum gas, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin, waxes and petroleum coke.

Other energy sector: Covers the use of energy by transformation industries and the energy losses in converting primary energy into a form that can be used in the final consuming sectors. It includes losses by gas works, petroleum refineries, coal and gas transformation and liquefaction, biofuels production and the production of hydrogen and hydrogen-based fuels. It also includes energy own use in coal mines, in oil and gas extraction, in direct air capture, in biofuels production and in electricity and heat production. Transfers and statistical differences are also included in this category.

Power generation: Refers to fuel use in electricity plants, heat plants and combined heat and power (CHP) plants. Both main activity producer plants and small plants that produce fuel for their own use (auto-producers) are included.

Productive uses: Energy used towards an economic purpose: agriculture, industry, services and non-energy use. Some energy demand from the transport sector, e.g. freight, could also be considered as productive, but is treated separately.

Renewables: Includes bioenergy, geothermal, hydropower, solar photovoltaics (PV), concentrating solar power (CSP), wind and marine (tide and wave) energy for electricity and heat generation.

Residential: Energy used by households including space heating and cooling, water heating, lighting, appliances, electronic devices and cooking equipment.

Services: Energy used in commercial facilities, e.g. hotels, offices, catering, shops, and institutional buildings, e.g. schools, hospitals, offices. Energy use in services includes space heating and cooling, water heating, lighting, equipment, appliances and cooking equipment.

Shale gas: Natural gas contained within a commonly occurring rock classified as shale. Shale formations are characterised by low permeability, with more limited ability of gas to flow through the rock than is the case with a conventional reservoir. Shale gas is generally produced using hydraulic fracturing.

Shipping/navigation: This transport sub-sector includes both domestic and international navigation and their use of marine fuels. Domestic navigation covers the transport of goods or persons on inland waterways and for national sea voyages (starts and ends in the same country without any intermediate foreign port). International navigation includes quantities of fuels delivered to merchant ships (including passenger ships) of any nationality for consumption during international voyages transporting goods or passengers.

Solar photovoltaic (PV)**:** Electricity produced from solar photovoltaic cells.

Solid biomass: Includes charcoal, fuelwood, dung, agricultural residues, wood waste and other solid wastes.

Steam coal: Type of coal that is mainly used for heat production or steam-raising in power plants and, to a lesser extent, in industry. Typically, steam coal is not of sufficient quality for steel making. Coal of this quality is also commonly known as thermal coal.

Synthetic methane: Low-carbon synthetic methane is produced through the methanation of low-carbon hydrogen and carbon dioxide from a biogenic or atmospheric source.

Synthetic oil: Low-carbon synthetic oil produced through Fischer Tropsch conversion or methanol synthesis from syngas, a mixture of hydrogen (H_2) and carbon monoxide (CO).

Total energy supply (TES)**:** Represents domestic demand only and is broken down into electricity and heat generation, other energy sector and total final consumption.

Total final consumption (TFC)**:** Is the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing and mining), transport, buildings (including residential and services) and other (including agriculture and non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.

Total final energy consumption (TFEC)**:** Is a variable defined primarily for tracking progress towards target 7.2 of the UN Sustainable Development Goals. It incorporates total final consumption (TFC) by end-use sectors but excludes non-energy use. It excludes international marine and aviation bunkers, except at world level. Typically this is used in the context of calculating the renewable energy share in total final energy consumption (Indicator 7.2.1 of the Sustainable Development Goals), where TFEC is the denominator.

Total primary energy demand (TPED)**:** See total energy supply

Traditional use of solid biomass: Refers to the use of solid biomass with basic technologies, such as a three-stone fire, often with no or poorly operating chimneys.

Transport: Fuels and electricity used in the transport of goods or people within the national territory irrespective of the economic sector within which the activity occurs. This includes fuel and electricity delivered to vehicles using public roads or for use in rail vehicles; fuel delivered to vessels for domestic navigation; fuel delivered to aircraft for domestic aviation; and energy consumed in the delivery of fuels through pipelines. Fuel delivered to international marine and aviation bunkers is presented only at the world level and is excluded from the transport sector at a domestic level.

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Trucks: Includes medium trucks (gross vehicle weight 3.5-15 tonnes) and heavy trucks (>15 tonnes).

Useful energy: Refers to the energy that is available to end-users to satisfy their needs. This is also referred to as energy services demand. As result of transformation losses at the point of use, the amount of useful energy is lower than the corresponding final energy demand for most technologies. Equipment using electricity often has higher conversion efficiency than equipment using other fuels, meaning that for a unit of energy consumed electricity can provide more energy services.

Wind: electricity produced by wind turbines from the kinetic energy of wind.

Woody energy crops: Short-rotation plantings of woody biomass for bioenergy production, such as coppiced willow and miscanthus.

Variable renewable energy (VRE)**:** Refers to technologies whose maximum output at any time depends on the availability of fluctuating renewable energy resources. VRE includes a broad array of technologies such as wind power, solar PV, run-of-river hydro, concentrating solar power (where no thermal storage is included) and marine (tidal and wave).

Zero-carbon-ready buildings: A zero-carbon-ready building is highly energy efficient and either uses renewable energy directly, or an energy supply that can be fully decarbonised, such as electricity or district heat.

Zero-emissions vehicles (ZEVs)**:** Vehicles which are capable of operating without tailpipe CO_2 emissions (battery electric vehicles and fuel cell vehicles).

Regional and country groupings

Advanced economies: OECD regional grouping and Bulgaria, Croatia, Cyprus[1,2], Malta and Romania.

Africa: North Africa and sub-Saharan Africa regional groupings.

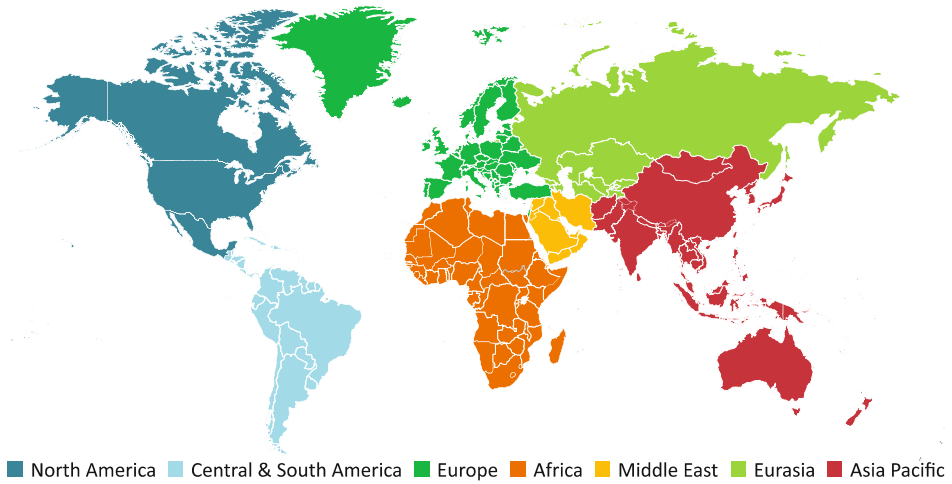
Asia Pacific: Southeast Asia regional grouping and Australia, Bangladesh, China, India, Japan, Korea, Democratic People's Republic of Korea, Mongolia, Nepal, New Zealand, Pakistan, Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[3]

Caspian: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Bolivarian Republic of Venezuela (Venezuela), and other Central and South American countries and territories.[4]

China: Includes the (People's Republic of) China and Hong Kong, China.

Figure C.1 ▷ Main country groupings



Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Developing Asia: Asia Pacific regional grouping excluding Australia, Japan, Korea and New Zealand.

Emerging market and developing economies: All other countries not included in the advanced economies regional grouping.

Eurasia: Caspian regional grouping and the Russian Federation (Russia).

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, North Macedonia, Gibraltar, Iceland, Israel[5], Kosovo, Montenegro, Norway, Serbia, Switzerland, Republic of Moldova, Turkey, Ukraine and United Kingdom.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus[1,2], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

IEA (International Energy Agency)**:** OECD regional grouping excluding Chile, Colombia, Iceland, Israel, Latvia, Lithuania and Slovenia.

Latin America: Central and South America regional grouping and Mexico.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

Non-OECD: All other countries not included in the OECD regional grouping.

Non-OPEC: All other countries not included in the OPEC regional grouping.

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North Africa: Algeria, Egypt, Libya, Morocco and Tunisia.

North America: Canada, Mexico and United States.

OECD (Organisation for Economic Co-operation and Development)**:** Australia, Austria, Belgium, Canada, Chile, Colombia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States.

OPEC (Organisation of the Petroleum Exporting Countries)**:** Algeria, Angola, Republic of the Congo (Congo), Equatorial Guinea, Gabon, the Islamic Republic of Iran (Iran), Iraq, Kuwait, Libya, Nigeria, Saudi Arabia, United Arab Emirates and Bolivarian Republic of Venezuela (Venezuela).

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Sub-Saharan Africa: Angola, Benin, Botswana, Cameroon, Republic of the Congo (Congo), Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Zambia, Zimbabwe and other African countries and territories.[6]

Country notes

[1] Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[2] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste and Tonga and Vanuatu.

[4] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten, Turks and Caicos Islands.

[5] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[6] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Kingdom of Eswatini, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Réunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia and Uganda.

Abbreviations and Acronyms

AFOLU	agriculture forestry and other land use
APC	Announced Pledges Case
ASEAN	Association of Southeast Asian Nations
BECCS	bioenergy equipped with CCUS
BEV	battery electric vehicles
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CFL	compact fluorescent lamp
CH_4	methane
CHP	combined heat and power; the term co-generation is sometimes used
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2-eq	carbon-dioxide equivalent
COP	Conference of Parties (UNFCCC)
CSP	concentrating solar power
DAC	direct air capture
DACCS	direct air capture with carbon capture and storage
DER	distributed energy resources
DSI	demand-side integration
DSO	distribution system operator
DSR	demand-side response
EAF	electric arc furnaces
EHOB	extra-heavy oil and bitumen
ETP	Energy Technology Perspectives
EU	European Union
EV	electric vehicle
FCEV	fuel cell electric vehicle
GDP	gross domestic product
GHG	greenhouse gases
GTL	gas-to-liquids
HEFA	hydrogenated esters and fatty acids
ICE	internal combustion engine
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IOC	international oil company
IPCC	Intergovernmental Panel on Climate Change
LCC	Low CCUS Case
LDVs	light-duty vehicles
LCV	light-commercial vehicle
LED	light-emitting diode

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LNG	liquefied natural gas
LPG	liquefied petroleum gas
MEPS	minimum energy performance standards
NDCs	Nationally Determined Contributions
NEA	Nuclear Energy Agency (an agency within the OECD)
NGLs	natural gas liquids
NGV	natural gas vehicle
NOC	national oil company
NO_X	nitrogen oxides
N_2O	nitrous oxide
NZE	Net-Zero Emissions Scenario
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PHEV	plug-in hybrid electric vehicles
PLDV	passenger light-duty vehicle
PM	particulate matter
$PM_{2.5}$	fine particulate matter
PPP	purchasing power parity
PV	photovoltaics
R&D	research and development
RD&D	research, development and demonstration
SAF	sustainable aviation fuel
SDG	Sustainable Development Goals (United Nations)
SO_2	sulphur dioxide
SR1.5	IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels
STEPS	Stated Policies Scenario
T&D	transmission and distribution
TES	total energy supply
TFC	total final consumption
TFEC	total final energy consumption
TPED	total primary energy demand
UEC	unit energy consumption
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UK	United Kingdom
US	United States
VRE	variable renewable energy
WEO	*World Energy Outlook*
WHO	World Health Organization
ZEV	Zero-emissions vehicle

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DOCUMENT 11

CLIMATE COUNCIL



HITTING HOME: THE COMPOUNDING COSTS OF CLIMATE INACTION



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Authors: Will Steffen and Simon Bradshaw.



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facebook.com/climatecouncil
info@climatecouncil.org.au
twitter.com/climatecouncil
climatecouncil.org.au



Professor Will Steffen
Climate Councillor



Dr Simon Bradshaw
Researcher

Contents

Key findings ii

1. Introduction 1

2. Extreme weather fuelled by climate change 3

2.1 Extreme heat 4
CASE STUDY: Extreme heat in western Sydney 8
CASE STUDY: 2020 Siberian heatwave 9
CASE STUDY: Coral mortality 10

2.2 Intense rainfall 11
CASE STUDY: 2020 Asian monsoon floods 12

2.3 Storms and cyclones 13
CASE STUDY: 2020 North Atlantic hurricane season 16

2.4 Fire 17
CASE STUDY: 2020 US West Coast fires 18

2.5 Drought 19
CASE STUDY: Flash drought 20
BOX 1: Compound disasters 21

3. Abrupt, nonlinear extreme events 22

3.1 Coral reefs 23

3.2 2019-20 bushfire season 24

4. The cost of inaction – Where we are now compared to ten years ago 27
BOX 2: Hitting home – Intensifying disasters and cascading impacts 31

5. By the numbers 33

5.1 2019-20 33

5.2 Long-term trends 35

6. Major events in Australia and around the world 41

7. We must act with more urgency 45

References 49

Image credits 54

Key findings

1

2019-20 was an exceptionally intense period for climate-fuelled extreme weather, with heavy costs felt in Australia and around the world.

- An extraordinary run of events, including unprecedented fire seasons in Australia and the US, a record-breaking North Atlantic hurricane season, and an astonishing series of heat records, paint a sobering portrait of our escalating climate crisis.
- Extreme heat events are rapidly on the rise both here, and overseas. The latest science projects that by 2100, annual deaths from extreme heat worldwide will outstrip all COVID-19 deaths recorded in 2020.
- The cost of extreme weather disasters in Australia has more than doubled since the 1970s, reaching $35 billion for the decade 2010-2019.
- Australians are five times more likely to be displaced by a climate-fuelled disaster than someone living in Europe. In the Pacific, that risk is 100 times higher.
- Australia is surrounded by many countries that are acutely vulnerable to climate impacts. Those unfolding regional impacts may soon become as damaging to Australia as those that strike us directly.

2

Some extreme weather events show 'tipping point' behaviour when a critical level of heat or drought triggers a massive, devastating event.

- In 2019-20, we ushered in a new and dangerous era of megafires that ravaged Australia, Brazil, Siberia and the US West Coast. During the massive Black Summer bushfires, we likely crossed a tipping point for Australia's temperate broadleaf and mixed forests. In any typical fire season, 2-3 percent of these forests burn, but in the Black Summer 21 percent burned.
- Around half of all hard corals along the Great Barrier Reef perished during successive mass bleaching events in the past five years. We are on track to eliminate all of Australia's and the world's tropical coral reefs.

3

Ignoring climate change is deadly. Australians are now paying the price for our own and the world's failure to reduce emissions quickly enough or deeply enough.

- Governments, like the Australian Government, which have failed to substantially reduce emissions over the past decade have sentenced Australians, and communities worldwide, to a far more dangerous future than if they had responded to repeated warnings from scientists.
- Due to this past inaction, gradual, measured steps are not enough to avoid catastrophe. At this point, only truly transformative action is required. That means at least halving global emissions over the coming decade, and reaching net zero emissions globally by 2040 at the latest.

4

No developed country has more to lose from climate change-fuelled extreme weather, or more to gain as the world transforms to a zero-carbon economy, than Australia does.

- We need bold, concerted action across all levels of government, business, industry and community to reduce Australia's emissions to net zero as soon as possible, and prepare for worsening extreme weather events.
- Almost all of Australia's major trading partners and strategic allies, as well as Australian state and territories, are now committed to net zero emissions by around mid-century. This includes countries that buy more than 70% of our coal and gas exports.
- Australia can position itself as a global powerhouse of renewable energy and clean industries, ensuring our prosperity and security in a post-carbon world.

1. Introduction

Many will remember 2020 as the year of the COVID-19 pandemic. Yet for millions of people around the world the virus served as a backdrop to another battle as we lived through the most intense period yet of climate-fuelled extreme weather.

Unprecedented fires, extreme heat, powerful cyclones and devastating floods all occurred in 2019-20, capping off a decade in which the climate crisis hit hard.

This report outlines the latest science on how climate change is driving more destructive heatwaves, downpours, cyclones, droughts, fires and other extreme weather events. It highlights significant events in Australia and around the world from the past two years. Taken alone, any one of the events described in this report – from Australia's Black Summer bushfires to the record-breaking North Atlantic hurricane season, or the remarkable Siberian heatwave – would mark the year as unusual. Taken together, they paint a disturbing portrait of our rapidly escalating climate emergency.

There is no doubt that we have entered an era of consequences arising from decades of climate inaction and delay. We are all paying dearly for the failure of governments to respond adequately to repeated warnings from scientists and those on the frontlines of this unfolding crisis. It is now clear that we must learn to live in a new age of megafires and other climate impacts that are locked in over the coming years. It is equally clear that far greater dangers lie ahead if we fail to act with the urgency and determination that the science demands.

As this report shows, communities here and abroad are already reeling from unprecedented disasters occurring under a temperature rise of around 1.1°C above pre-industrial levels. Every fraction of a degree more will result in even more extreme events.

For Australia, the devastating Black Summer fires, a crippling drought, and yet another mass bleaching of the Great Barrier Reef affirmed our acute vulnerability to climate impacts. Similarly, as the world's third largest exporter of fossil fuels, behind only Russia and Saudi Arabia (Office of the Chief Economist 2020), we are highly exposed to economic losses and job cuts as the world shifts towards a new, clean economy. Yet we could still pivot, and prosper in the emerging renewables-driven economy with natural advantages that are the envy of countries around the globe.

It is no exaggeration to say that decisions made over the coming year, as governments aim to reboot their economies from the COVID-19 crisis and we head toward the next critical round of international climate negotiations, may represent our last chance to secure a future in which our children can survive and thrive.

The global community could have taken credible climate action much earlier. Beginning a decade or two ago, we could have taken more gradual, measured steps that avoided the worsening impacts to come. That time has passed. At this point, only truly, transformative action will avoid us slipping from a crisis towards a full-blown catastrophe. That means at least halving global emissions over the coming decade, and reaching net zero emissions globally by 2040 at the latest (Steffen et al. 2020).

Given the immediate, rapidly escalating risks of climate change that we now face, every 0.1°C of warming matters, and every gigaton of carbon left in the ground will be measured in lives and livelihoods saved. Even taking into account the series of strengthened commitments made by the world's biggest emitters in 2020, optimistic assessments say we are still on track for heating of well over 2°C (Climate Action Tracker 2020), and a barely survivable future.

The events of 2019-20 have provided us with the clearest picture yet of why far stronger and more urgent action is required.

.

2. Extreme weather fuelled by climate change

When we change the climate, we change the conditions under which all shorter-term weather events form. Global emissions of greenhouse gases are making our climate system hotter and more energetic. This is leading to a marked increase in the frequency and/or severity of destructive weather events: extreme heat, intense downpours, powerful cyclones, crippling droughts, and dangerous fire weather. While no country is immune to the climate crisis, its impacts are not shared evenly. Already a land of extremes, Australia is perhaps the most vulnerable among all developed countries.

Over the past few years, attribution science has made significant progress. It tells us, with increasing confidence, the likelihood that a given event could have occurred without climate change, or the extent to which an event may have worsened due to climate change. For example, Australia's record hot spring in 2020 was deemed "virtually impossible" without the influence of human-induced climate change (Karoly 2020).

The following sections examine the influence of a warming climate on different types of extreme weather events, and include case studies of some of the unprecedented events that took place in 2019-20.

Australia's record hot spring in 2020 was deemed "virtually impossible" without climate change.

2.1 Extreme heat

The seven hottest years on record globally all occurred in the past seven years. In other words, each year between 2014-2020 was warmer than any year recorded in history prior to 2014. In decadal terms, the 2010s were warmer than any preceding decade; a full 0.2°C warmer than 2000-2009, representing a sharp acceleration in the rate of temperature increase.[1]

Today the world has warmed by around 1.1°C since pre-industrial times. However, this warming is not spread evenly, and many land areas are already significantly hotter than the global average. For example, Australia has warmed on average by 1.44°C since national records began in 1910 (CSIRO and BoM 2020).[2]

In a single year (2019), Australia recorded 33 days above 39 degrees – that's more than all such days recorded over the previous 60 years (1960-2018).

1 The global temperature has increased at an average rate of 0.07°C per decade since the 1880s. Most warming has occurred since the 1950s.

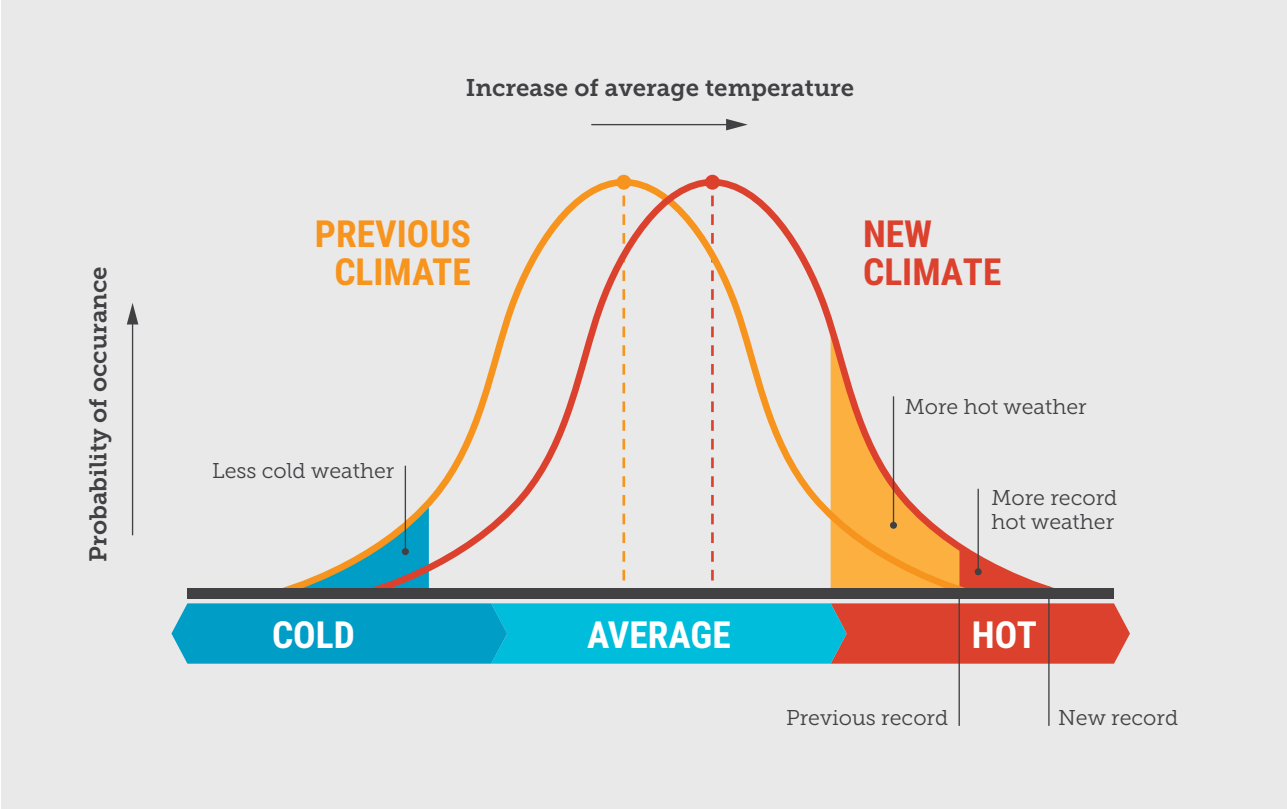
2 If using a pre-industrial baseline rather than 1910, then by 2019 Australia had warmed by more than 1.5°C.

As illustrated by Figure 1, an increase in global average temperatures means a marked increase in the probability of extreme and record-breaking hot weather, and a decrease in the probability of extreme cold weather. Climate change is creating more record hot days, and making heatwaves longer, more intense and more frequent (Steffen et al. 2019). In 2019, Australia experienced 43 "extremely warm days", more than triple the number recorded in any year last century (CSIRO and BoM 2020). Even more strikingly, in terms of the average *maximum* temperature recorded across Australia, there were 33 days that exceeded 39°C – more than the total number observed in the entire 1960-2018 period (CSIRO and BoM 2020).

Heatwaves are by far the most lethal extreme weather risk facing Australians. Since 1890, heatwaves have killed more Australians than bushfires, cyclones, earthquakes, floods, and severe storms combined (DIT 2013). Extreme heat can also be deadly for Australian animals. In late 2018, more than a third of the county's population of spectacled flying foxes died in a single heatwave (Welbergen 2019). In January 2019, extreme heat led to the death of more than 90 wild horses near Alice Springs (BBC 2019).

In 2020, the US-based National Bureau of Economic Research published new projections for the number of people likely to die from climate change-fuelled extreme

Figure 1: When average temperatures increase and the curve showing the distribution of temperatures moves to the right, there is a significantly greater probability of experiencing very hot, and record hot, weather.



heat. It concluded that if no action is taken, on average there would be 221 additional deaths per 100,000 people globally each year by 2100 – roughly equivalent to all deaths from cardiovascular disease today. Even after factoring in efforts to adapt to a changing climate, the study still projects an extra 73 deaths per 100,000 people annually by 2100 – which is greater than the number of all people who died from COVID-19 in 2020. While climate change affects all countries and communities, the study reaffirmed the stark inequity of the climate crisis, with poor communities – the same people who have contributed the least to global greenhouse gas emissions – likely to suffer far more deaths (Carleton et al. 2020).

Scientists expect that by 2100, climate change-fuelled extreme heat will kill more people across the globe annually than COVID-19 did in 2020.

Figure 2: Poor communities in developing countries are likely to suffer far more deaths from climate change, despite having contributed the least to the problem.



The oceans also provide evidence for climate-fuelled temperature extremes. The vast majority of the excess heat trapped by greenhouse gas emissions – more than 90 percent – is absorbed by oceans. Today this is an amount of energy equivalent to around five Hiroshima atomic bombs every second (Cheng et al. 2020).

The rise in ocean temperatures has been accelerating significantly since the 1990s; since 1993 the rate of ocean warming has more than doubled (IPCC 2019). In 2019, the world's oceans were their warmest in recorded history. Oceans around Australia have warmed by more than 1°C since 1910. Marine heatwaves are becoming more intense and occurring more often, causing extensive and permanent damage to many marine ecosystems, including coral reefs (See CASE STUDY: Coral mortality), kelp forests and sea grass. (CSIRO and BoM 2020.)

Figure 3: Marine heatwaves are causing extensive damage to coral reefs.



CASE STUDY: EXTREME HEAT IN WESTERN SYDNEY

On 4 January 2020, Penrith was officially the hottest place on Earth at 48.9°C. Such temperatures are already pushing the limits of human endurance, and people in urban settings like Penrith may be regularly exposed to even higher temperatures than those officially recorded due to amplifying factors such as concrete and asphalt (Thompson 2020) - the 'urban heat island' effect. In particular, extreme heat endangers children, the elderly, people with existing health conditions and other vulnerable groups (Climate Council 2016).

Extreme heat in Sydney demonstrates how climate change can exacerbate existing socio-economic inequalities. Western Sydney experiences higher summer temperatures than suburbs nearer the coast. For example, over the 2019-20 summer, western Sydney recorded 37 days over 35°C compared to six in the east of the city (Amin 2020). This matches the marked socio-economic divide between Sydney's affluent east and the fast-growing western suburbs, with incomes, job opportunities, and access to education all split along the so-called "latte line" that divides the cities' eastern suburbs and north shore from the west (Gladstone 2018).

Very high temperatures in schools make it harder for students to concentrate, contributing to reduced learning outcomes (Pfautsch et al. 2020). Research from the University of Western Sydney revealed that for students in Sydney's western suburbs, extreme summer heat in schools is often compounded by the poor design of buildings, inadequate shade and surfaces that absorb much heat (Pfautsch et al. 2020).

Without far stronger action to address climate change and support communities to adapt to new extremes, we risk further entrenching inequalities.

On 4 January 2020, Penrith was officially the hottest place on Earth. Western Sydney is suffering more than eastern Sydney under climate change.

CASE STUDY: 2020 SIBERIAN HEATWAVE

In the first six months of 2020, an intense, persistent and widespread heatwave across Siberia broke temperature records, fuelled large fires, and thawed permafrost. Overall, temperatures for the region were more the 5°C above average from January to June. This extraordinary extreme heat event made global headlines when the Russian town of Verkhoyansk recorded a temperature of 38°C in June, likely the highest temperature ever recorded in the Arctic (Dunne 2020).

Also in June, satellite images detected signatures of "zombie fires", remnants from the previous season's record fires that had continued smouldering underground throughout winter in the carbon-rich peat and had flared up again with warm temperatures. Pyrocumulonimbus clouds, or "fire thunderstorms" – a rare phenomenon anywhere and especially unusual at such high latitudes – were also detected (Deacon 2020).

In July, an attribution study concluded that the 2020 Siberian heatwave would have been "almost impossible" in the absence of climate change, showing with high confidence that the event "was made at least 600 times more likely as a result of human-induced climate change" (Ciavarella et al. 2020).

Siberia is one region where global warming has a particularly devastating effect, not only on local ecosystems and communities, but also on the climate system as a whole as the release of greenhouse gases through thawing permafrost and large fires contributes to further warming.

CASE STUDY: CORAL MORTALITY

Just as we are experiencing more frequent and severe heatwaves on land, climate change is also driving deadly marine heatwaves that are devastating ocean ecosystems.

There can be no more striking illustration of the frightening pace of climate change and its profound impacts on living systems than the plight of Australia's Great Barrier Reef (GBR). The GBR is the world's largest coral reef system, and in its current form is about 8,000 years old. Between 1995 and 2017 – a mere blink of an eye compared to its age – the GBR lost more than half its hard corals due to warmer seas driven by the greenhouse gas emissions from burning coal, oil and gas (Dietzel et al. 2020).

Back-to-back bleaching events in 2016 and 2017 damaged two thirds of the reef. In March 2020, as Australia was scrambling to contain the COVID-19 outbreak, news emerged of the third mass bleaching event within five years (GBRMPA 2020). The marine heatwave that caused widespread bleaching of the GBR in 2016 was made 175 times more likely due to climate change (King et al. 2016).

In its Special Report on 1.5°C, the Intergovernmental Panel on Climate Change (IPCC) projected that even if the global average temperature rise is held to 1.5°C, coral reefs will decline by a further 70-90 percent. At 2°C, tropical reef-building corals are expected to "mostly disappear", with the loss of more than 99% of the corals.

While we often communicate the price of these losses in terms of the estimated $6 billion value of the GBR to the Australian economy and the 64,000 jobs it supports (Deloitte Access Economics 2017), in reality these numbers do little to convey the gravity of the crisis unfolding before our eyes. As Chief Councillor Tim Flannery notes in his 2020 book *The Climate Cure:*

> *"[Coral] reefs are home to the greatest biodiversity in the oceans, and their loss would reverberate throughout Earth's ecosystems, both marine and terrestrial. And the human impacts would be immense. Entire nations (the coral atoll nations) depend upon them for food and protection against erosion. Many consequences of the loss of coral reefs are probably not conceivable until they eventuate."*

In 2020 the International Union for Conservation of Nature, advisory body to the UNESCO World Heritage Committee, escalated its conservation outlook for the Great Barrier Reef from "significant concern" to "critical" (IUCN 2020).

There's no more striking illustration of the frightening pace of climate change and its profound impacts on living systems than the plight of the Great Barrier Reef.

2.2 Intense rainfall

A warmer atmosphere can hold more water vapour – approximately 7 percent more for every degree of warming (Trenberth 2011). A warmer and wetter atmosphere also provides more energy for weather systems that generate intense precipitation (rain, snow, hail). So, while climate change may mean only a modest increase in the overall amount of precipitation globally – limited by the moisture holding capacity of the atmosphere – it's leading to a marked increase in the heaviest and most damaging storm events. In other words, more of our rain is falling in fewer extreme downpours, often interspersed with prolonged dry periods. If the current trend continues, the frequency of today's most intense precipitation events is likely to almost double with each degree of further warming (Myhre et al. 2019).

The pattern of more intense, heavy rainfall events is well established in Australia. In recent decades, the intensity of short-duration extreme rainfall events, which are often associated with flash flooding, has increased by around 10 percent in some regions, with particularly large increases observed in the north. These short-duration events are often associated with thunderstorms, cyclones, and east coast lows, and there has been an observed increase in the rainfall associated with these systems since 1979 (CSIRO and BoM 2020).

In January/February 2019, heavy rainfall caused widespread flooding across north and far north Queensland, affecting more than half of the state. It was one of the worst disasters in the region's history. The total social and economic costs were estimated at $5.68 billion, or around 14 percent of the region's annual economic output. This included damage to homes and infrastructure, impacts on health and wellbeing, and the loss of half a million cattle (Deloitte Access Economics 2017).

Australia is experiencing more intense, heavy rainfall. In 2019, heavy rainfall caused widespread flooding affecting more than half of Queensland – one of the worst disasters in the region's history.

CASE STUDY: 2020 ASIAN MONSOON FLOODS

Billions of people across the populous countries of south and east Asia depend upon the Indian and East Asian monsoons. While seasonal monsoon rains are fundamental to food and water security, they can also cause catastrophic flooding. Consistent with shifting rainfall patterns globally, the Indian monsoon is becoming more extreme, with prolonged dry spells punctuated by intense downpours (Singh 2014). A recent review of current knowledge on how climate change is affecting monsoons globally concluded with high confidence that climate change "has already caused a significant rise in the intensity and frequency of extreme rainfall events in all monsoon regions" (Wang et al. 2020).

India, Bangladesh, Nepal, China, and Pakistan all suffered heavy losses in severe floods in 2020 following intense monsoon rains. The worst flooding along the Yangtze River for decades occurred in June, killing hundreds of people in China, destroying croplands, and testing the limits of the giant Three Gorges Dam (Patel 2020). In July, flooding in India (Assam) and Nepal killed at least 200 people and displaced millions, hindering efforts to slow the spread of COVID-19 (Ellis-Petersen 2020). In Bangladesh, no stranger to floods, the worst monsoon flooding for many years left around a third of the country submerged (Hasina 2020). Pakistan set a new monthly rainfall record in August, and the military was deployed to rescue people from flooded areas of Karachi (Qayum and Dilawar 2020).

Figure 4: The Indian monsoon is becoming more extreme.



2.3 Storms and cyclones

Tropical cyclones, known as hurricanes in the north Atlantic and northeast Pacific, typhoons in the northwest Pacific, and cyclones in the South Pacific and Indian Oceans, are among the most destructive extreme weather events.

Many Pacific Island Countries, including Fiji, Vanuatu, Solomon Islands and Tonga, lie within the South Pacific cyclone basin. In recent years, a run of extraordinarily damaging cyclones in the Pacific has taken a heavy toll on local economies. In 2015, Category Five Cyclone Pam, then the strongest South Pacific cyclone on record,[3] caused damages equivalent to 64 percent of Vanuatu's Gross Domestic Product (GDP). A year later, Cyclone Winston, an even stronger cyclone, devastated Fiji with damages amounting to 31 percent of GDP. In 2018, Cyclone Gita hit Tonga, causing losses equivalent to 38 percent of GDP. Most recently, in 2020, Cyclone Harold – the second strongest cyclone to hit Vanuatu after Cyclone Pam – severely affected Vanuatu, Solomon Islands, Fiji and Tonga, compounding the economic impact of COVID-19 (Taylor 2020.) In Australia, Cyclone Yasi in 2011 and Cyclone Debbie in 2017 remain two of our most costly disasters.

Climate change is affecting the conditions in which tropical cyclones form and develop. Climate change is linked to many different aspects of cyclone formation and behaviour, including how often they form, maximum windspeed and amount of rainfall (IPCC 2012), the speed at which a system intensifies (Bhatia et al. 2019), the speed at which a system moves (known as translation speed) (Kossin 2018), how much strength is retained after reaching land (Li and Chakraborty 2020), the duration of cyclone seasons, and the geographic range of tropical cyclones (Kossin et al. 2014).

Cyclones form most readily when there is a very warm ocean surface and a strong temperature gradient through the atmosphere – i.e. a big difference in the temperature of the air at the surface and the air higher up. A warming climate means that the temperature gradient is likely to decrease, so the conditions in which cyclones form may occur less often. This means that the overall number of cyclones that form will likely decrease. However, rising ocean surface temperatures and a warmer, wetter atmosphere provide a larger source of energy for cyclones to draw on once they do form. It is thus likely that tropical cyclones will become more intense with climate change in terms of maximum wind speed and the amount of rainfall they produce (IPCC 2012). For example, the amount of rainfall in two of 2017's most destructive hurricanes – Irma and Maria – was likely six percent and nine percent higher, respectively, compared to a world without climate change (Patricola and Wehner 2019).

In summary, there are likely to be fewer cyclones overall but a higher number of those that do form will likely be more intense and destructive.

3 Measured in terms of peak 10-minute sustained windspeed.



Figure 5: Typhoon Goni, which struck the Philippines in November 2020, was the strongest landfalling cyclone on record.

Until recently, with the exception of the North Atlantic basin where records show a clear increase in the intensity of cyclones over recent decades,[4] there has not been enough historical data of sufficient quality to discern clear real-world trends in cyclone activity. However, in 2020 an analysis of nearly 40 years of satellite imagery concluded that maximum wind speeds are getting stronger for cyclones in almost every region where they form, affirming what models had long predicted (Kossin et al. 2020).

As well as reaching higher intensity, it is also possible that a warming climate is enabling cyclones to strengthen more quickly (Bhatia et al. 2019). "Rapid intensification" is a term used to describe the dramatic strengthening of cyclones over a short period of time. The US National Hurricane Center defines this as an increase in wind strength of at least 35 mph (56 kmh) within 24 hours. In the 2020 North Atlantic hurricane season (see CASE STUDY: 2020 North Atlantic hurricane season) a record-equalling ten storms exhibited rapid intensification. Two of 2020's record number of North Atlantic hurricanes, Eta and Iota, strengthened by 80mph (129 kmh) in 24 hours, an intensification rate observed only eight times before and never so late in the season. In the early 1980s, the chance of a hurricane rapidly intensifying were 1-in-100. Those odds have now shortened to less than 1-in-20 (Bhatia et al. 2018). Rapid intensification can lead to disastrous outcomes, as coastal communities may not be given adequate warning to prepare for an intense cyclone (Bhatia et al. 2019).

We should prepare for more intense and destructive cyclones due to climate change.

4 Since 1980, the number of North Atlantic hurricanes with winds stronger than 200 km/h have doubled, and those with winds stronger than 250 km/h have tripled (Rahmstorf et al. 2018).

Based on recent observations, it is also possible that cyclones are staying stronger after making landfall. A cyclone, which derives its strength from warm ocean surfaces, begins to lose strength on reaching land. However, climate change may slow down this effect, thus allowing the cyclone to wreak more destruction and reach communities further inland (Li and Chakraborty 2020). It thus appears that on a warming planet, cyclones are both powering up more quickly and winding down more gradually.

Lastly, there is evidence that cyclones are moving more slowly. That is the rate at which a system tracks across the ocean and land, known as translation speed as opposed to its maximum wind speed, is decreasing. On average, it appears that translation speed decreased by 10 percent between 1949 and 2016 (Kossin 2018). This may be the result of a slowdown in atmospheric circulation (Zhang et al. 2020). Slow-moving cyclones, such as Hurricane Maria in 2017, can be hugely destructive, dumping immense amounts of rain over a small area, while also sustaining damaging windspeeds for a longer period (Resnick 2017).

While there may be differences in the state of knowledge about these various trends and their links to climate change, there is little doubt that, overall, climate change is increasing the destructive power of tropical cyclones. This is especially true when considering other impacts of climate change that, while not directly affecting cyclone behaviour, are nonetheless increasing the dangers. For example, cyclones are now riding upon higher sea levels, meaning that storm surges – often the deadliest aspect of a cyclone – are higher and penetrate further inland than they would otherwise (Climate Council 2017). Climate change is also damaging many natural coastal defences, including coral reefs and mangroves, which leave communities and infrastructure more exposed to the destructive power of cyclones.

CASE STUDY: 2020 NORTH ATLANTIC HURRICANE SEASON

While the US West Coast burned, the East Coast, Caribbean and Central America were pummelled by a record-breaking Atlantic hurricane season. Between May and November, the region recorded 30 named tropical storms, including 13 hurricanes and six major hurricanes – more than double the number experienced during an average season (WMO 2020). Twelve named storms hit the US mainland, beating the previous record of nine. For only the second time, the US National Hurricane Centre had to use names from the Greek alphabet, as the standard list of alphabetical names had been exhausted.

The most destructive storm of the season was Hurricane Eta, which made landfall in Nicaragua on 3 November as a category four storm. Eta moved very slowly, lingering for three days over Central America, producing immense amounts of rain and killing at least 215 people. Just two weeks later, the last and strongest storm of the season, Hurricane Iota, rapidly intensified into a category five system before hitting Colombia, Nicaragua, Honduras and other countries of Central America, including areas already hit two weeks earlier by Hurricane Eta (Masters 2020).

The damage from this year's unprecedented Atlantic hurricane season is likely to increase pressure on people in Central America to migrate out of harm's way, including across borders (Palencia and Lopez 2020).

Figure 6: September 2020 saw five tropical cyclones churning in the Atlantic baisin at the same time.



2.4 Fire

In 2019-20, astonishing fire seasons across several continents, from Australia to the Amazon, Siberia and the US West Coast, ushered in a new and dangerous era of megafires. Tens of millions of hectares of forest were razed by fire, hundreds of lives and thousands of homes lost, billions of animals killed, and critical ecosystems pushed to or over the brink.



For a full account of Australia's Black Summer fires, see Climate Council's report: **Summer of Crisis**

In terms of the size of area burned, the US West Coast fires broke almost every conceivable record for the region, eclipsing California's then record-breaking and deadly 2018 season (See CASE STUDY: 2020 US West Coast fires). Australia's Black Summer of 2019-20 was similarly unprecedented in its scale and harm with 21 percent or more of eastern Australian temperate broadleaf and mixed forests burned. Typically, less than 2-3 percent of these forests burns annually, even during more extreme fire seasons (Boer et al. 2020). Large parts of the Gondwana rainforest – a living link to the former Gondwana supercontinent and a wellspring of unique Australian flora and fauna – were razed. This unique and ancient ecosystem was previously considered too wet to burn. Further south, the Gospers Mountain fire became the largest forest fire ever recorded in Australia, burning through more than half a million hectares including a large part of Wollemi National Park. A staggering 81% of the nearby Blue Mountains World Heritage Area also burned. Around three billion animals are likely to have perished or been displaced by the Black Summer fires (WWF 2020), 33 human lives were lost directly to the fires, and an estimated 429 more from the smoke that blanketed large parts of the country (Johnson et al. 2020).[5]

Higher temperatures and shifting rainfall patterns are driving increased fire risk in many of the world's great forest and grassland ecosystems, from the boreal zone to the tropics.

In Australia, extremely hot, dry conditions, underpinned by years of reduced rainfall and a severe drought, set the scene for the Black Summer fires (Hughes et al. 2020). Extreme fire weather and the length of the fire season across large parts of Australia have increased since the 1950s (CSIRO and BoM 2020). In some regions of southern Australia there is an increasing risk of more extreme bushfires that can generate thunderstorms within their smoke plumes (CSIRO and BoM 2020). Such fires are very dangerous and unpredictable. Lightning strikes from these pyrocumulonimbus clouds can spawn new fires well ahead of the main fire front.

> *"Climate change has pushed Australia into a new era of unprecedented bushfire risk, and our governments have underestimated the threat." Greg Mullins (2020)*

5 Research by Johnson et al. (2020) estimated the smoke-related health costs of the Black Summer fires at AUD$1.95 billion, driven largely by "an estimated 429 smoke-related premature deaths in addition to 3,230 hospital admissions for cardiovascular and respiratory disorders and 1,523 emergency attendances for asthma".

CASE STUDY: 2020 US WEST COAST FIRES

Australia was not the only place to experience truly unprecedented fires in 2019-20.

By the end of 2020, fires had burned more than four million acres (1.6 million hectares) of California, more than double the record set in 2018 (CalFire 2020). Five of the six largest fires on record for the state occurred in 2020. California recorded its first "gigafire" in modern history – a fire of over a million acres (Milman and Ho 2020).

> *"We have never seen this amount of uncontained fire across the state... This will not be a one-time event. Unfortunately, it is the bellwether of the future. We're feeling the acute impacts of climate change." Oregon Governor Kate Brown*

Other states also suffered one of their most destructive fires seasons. In Oregon, fires burned over a million acres (400,000 hectares), more than twice the average for a season and at one point threatened Portland's suburbs; prompting mass evacuations (McGrath 2020). Washington state recorded more fires than in any other year (O'Sullivan 2020). Colorado experienced its largest single fire on record (Lytle 2020).

The parallels between the 2020 US West Coast fires and Australia's Black Summer of 2019-20 are hard to miss. Both were unequivocally driven by climate change, following long dry periods and record heat. Both set records for the largest fires ever recorded in each country. Both left large population centres blanketed in smoke, creating eery images of national icons like the Sydney Harbour Bridge and San Francisco's Golden Gate Bridge bathed in an orange hue. Events once considered very rare, including fire tornados and pyrocumulonimbus clouds, were observed many times. Both exposed failures of national leadership and tensions between state and federal authorities over climate inaction. Both spawned renewed interest in Indigenous land and fire management, and recognition that supporting the leadership of First Nations people is an essential part of responding to the climate crisis (Commonwealth of Australia 2020, Singh 2020).

We have ushered in a new and dangerous era of megafires.

2.5 Drought

Climate change has likely brought an increase in the frequency and/or severity of drought in some regions due to shifting rainfall patterns and higher temperatures. The Mediterranean, western US, West Africa and northeast China are among the regions to have observed a reduction in rainfall over recent decades (IPCC 2013). Based on the IPCC's Special Report on 1.5°C (2018), twice as many people worldwide would be exposed to water scarcity at 2°C of warming compared to 1.5°C. The Mediterranean and Caribbean would be among the areas hit particularly hard.

Climate change has already had a significant impact on rainfall over parts of Australia, in particular the southeast and southwest. In the southeast, rainfall during the cool season (April to October) has declined by 12 percent since the late 1990s. In the southwest rainfall during the cool season (April to October) has declined by around 16 percent since 1970, and by 20 percent between May and July. A continued decrease in cool season rainfall is expected across many regions of southern and eastern Australia (CSIRO and BoM 2020).

Figure 7: Climate change has likely brought an increase in the frequency and/or severity of drought in some regions.



CASE STUDY: FLASH DROUGHT

In mid-2019 much of inland New South Wales found itself in what meteorologists have started terming a 'flash drought' (Doyle 2020). A flash drought is characterised by the sudden onset and rapid intensification of drought conditions, over a period of weeks or months. A similar situation occurred along much of Australia's east coast during the last months of 2017 and into 2018.

Flash droughts occur when there is a very fast reduction in soil moisture, typically resulting from a lack of rainfall alongside factors that increase evaporation including high temperatures, low humidity, and strong winds (Otkin et al. 2018). Acting together, these factors can quickly turn a manageable situation into severe drought conditions.

The impacts of flash droughts can be severe, as the rapid onset can mean little time for farmers to prepare and for common coping mechanisms to be deployed (Nguyen 2019). While existing dry conditions naturally leave an area at greater risk, flash droughts can even occur when prior conditions did not appear conducive to drought development (Christian 2019). Recent research has aimed at better predicting flash droughts (Nguyen et al. 2019, Pendergrass et al. 2020).

Scientists have had to coin a new phrase 'flash drought' to capture the sudden onset of such events that can catch farmers and communities unprepared.

BOX 1: COMPOUND DISASTERS

Climate change, by increasing the frequency and/or severity of destructive weather events as well as the background conditions such as average temperature and sea level, is increasing the risk of 'compound extremes': instances where multiple destructive events or elements occur at the same time or in close succession, exacerbating one another such that the overall impact is worse than if each had occurred in isolation.

Events making up a compound extreme may be similar in nature. For example, two tropical cyclones hitting the same area in close succession, as for communities in Central America that were hit by both Cyclone Eta and Iota within the span of only two weeks (See CASE STUDY: 2020 North Atlantic hurricane season). In other instances, events may be different in nature. For example, heavy rainfall falling on a landscape charred by bushfires may mean a high likelihood of landslides (Rengers et al. 2020).

Compound extremes may also be caused by a combination of events or elements that are not in themselves extreme, but when combined prove very destructive - for example, a moderate storm combined with very high tide. Another example is a series of coastal erosion events that occur in quick succession, with little time in between for the coast to be replenished, such as happened along parts of the NSW coast in July 2020 (Hannam 2020).

Compound extremes can inflict immense human suffering, economic costs and environmental damage. Climate-related disasters may also exacerbate non-climate-related challenges and vice versa. For example, when Cyclone Harold – the strongest cyclone to hit Vanuatu since record-breaking Cyclone Pam in 2015 – caused widespread destruction, urgent relief efforts had to be managed alongside necessary measures to prevent the spread of COVID-19 (Masivei 2020, Pringle 2020).

Figure 8: Vanuatu and other Pacific Island Countries had to deal with the impacts of Cyclone Harold and COVID-19 simultaneously.



3. Abrupt, nonlinear extreme events

Many changes in the climate system appear as smooth curves in which the response of the system is proportional to the level of pressure applied – that is, straight-forward cause-effect logic. An example is the rise in global average surface temperature in response to human emission of greenhouse gases. However, nonlinear changes can occur when a small increase in pressure on the system reaches a critical level. The result is often an unexpectedly large and, in some cases, irreversible change in the system.

Features of the Earth System that can exhibit abrupt, nonlinear, and and/or irreversible behaviour are called 'tipping elements', and the level of the external pressure required to trigger the response is often called the 'tipping point' (Lenton et al. 2008). Some, but not all, extreme weather events can show tipping point behaviour when a critical level of pressure - e.g., rising temperature, rainfall reduction, or both - trigger a surprising large, abrupt response. Below we describe two recent Australian examples of extreme events that display tipping point/abrupt change behaviour.

Figure 9: NSW Farmer Rob Lee, New Year's Eve 2019. The Black Summer was an esxample of an extreme event that can be explained by tipping point behaviour.



3.1 Coral reefs

(See also CASE STUDY: Coral mortality). Coral bleaching is a classic example of a tipping point being transgressed. Corals exist in a fairly narrow band of water temperature and have thrived in the relatively stable climatic conditions of the Holocene, the 11,700-year epoch up to about 1950. Since then, surface ocean temperatures have risen steadily towards the upper limit within which corals can thrive. There were virtually no bleaching events up until the 1990s, when the Great Barrier Reef (GBR) suffered significant bleaching in 1998 and 2002 (Hughes et al. 2018). This was a warning sign that coral reefs were approaching their tolerable temperature limit.

Not surprisingly, even more severe bleaching followed as temperatures continued to rise. As described earlier, extensive and damaging mass bleaching events occurred on the GBR in 2016 and 2017, and these were followed by another such event in March 2020. The latest event was the first time that significant bleaching occurred along the entire 2,300-km length of the GBR. The result of these increasingly frequent and severe bleaching events was the loss of about half of all hard corals on the GBR. When the critical temperature was breached, the corals did not just suffer a proportional increase in bleaching but suffered mass bleaching, typical of tipping point/abrupt change behaviour.

Projections from the IPCC Special Report on 1.5°C warming (IPCC 2018) warn that the majority of the world's coral reefs would be eliminated by a 1.5°C temperature and virtually all – more than 99% - would be eliminated by a 2°C rise. The band of global average temperature rise between 1°C and 2°C above pre-industrial thus represents a tipping point for coral reefs, with the precise temperature depending on the local conditions of the reef and short-term climate variability. Given the approximately 10,000-year history of coral reefs in the Holocene, a 50-year period (2000-2050) and a narrow temperature window (1°C-2°C above pre-industrial) represent a very sharp tipping point.

Bleaching of coral reefs would be largely irreversible in human timeframes given that global average temperature will remain at elevated levels for centuries even after we finally eliminate human emissions of greenhouse gases (Collins et al. 2013).

3.2 2019-20 bushfire season

(See also 2.4 Fire). The massive bushfires that burned much of eastern Australia during the 2019-20 summer are another example of an extreme event that can be explained by tipping point behaviour. Figure 10 below shows the annual burned area of various forest types.

For Australian temperate broad-leafed and mixed forests, which cover about 27 million hectares in eastern Australia, the 2019-20 fires were unprecedented, both for Australia and globally. The fires burned about 5.8 million hectares or about 21% of the entire area of the biome when typically, about 2-3 percent of these forests burn in a season. This extreme event clearly shows abrupt and unprecedented change behaviour, and the analysis of the antecedent climatic conditions strongly supports the conclusion that a tipping point had been crossed. In fact, Boer et al. (2020) describe the highly nonlinear relationship between fires and antecedent climate conditions as an 'on-off' switch, another description of tipping point-abrupt change behaviour.

In the 2019-20 bushfires, a tipping point was likely crossed, with the burning of one fifth of Australia's temperate broad-leafed forests.

Figure 10: Annual burned area percentages for continental forest biomes (2000-2019). **Source:** Boer et al. 2020.

The boxes represent the 25th to 75th percentiles, with the line in the middle the median. The vertical lines extend to 1.5 times this middle 50%, and the dots are outliers. The numbers connote different biome types from a classification scheme used by WWF: 1. tropical and subtropical moist broadleaf forests | 2. tropical and subtropical dry broadleaf forests | 3. tropical and subtropical coniferous forests | 4. temperate broadleaf and mixed forests | 5. temperate conifer forests | 6. boreal forests/ taiga | 12. Mediterranean forests, woodlands and scrub. The red horizontal line indicates the area of Australia's temperate broadleaf and mixed forest that burned in 2019-20.

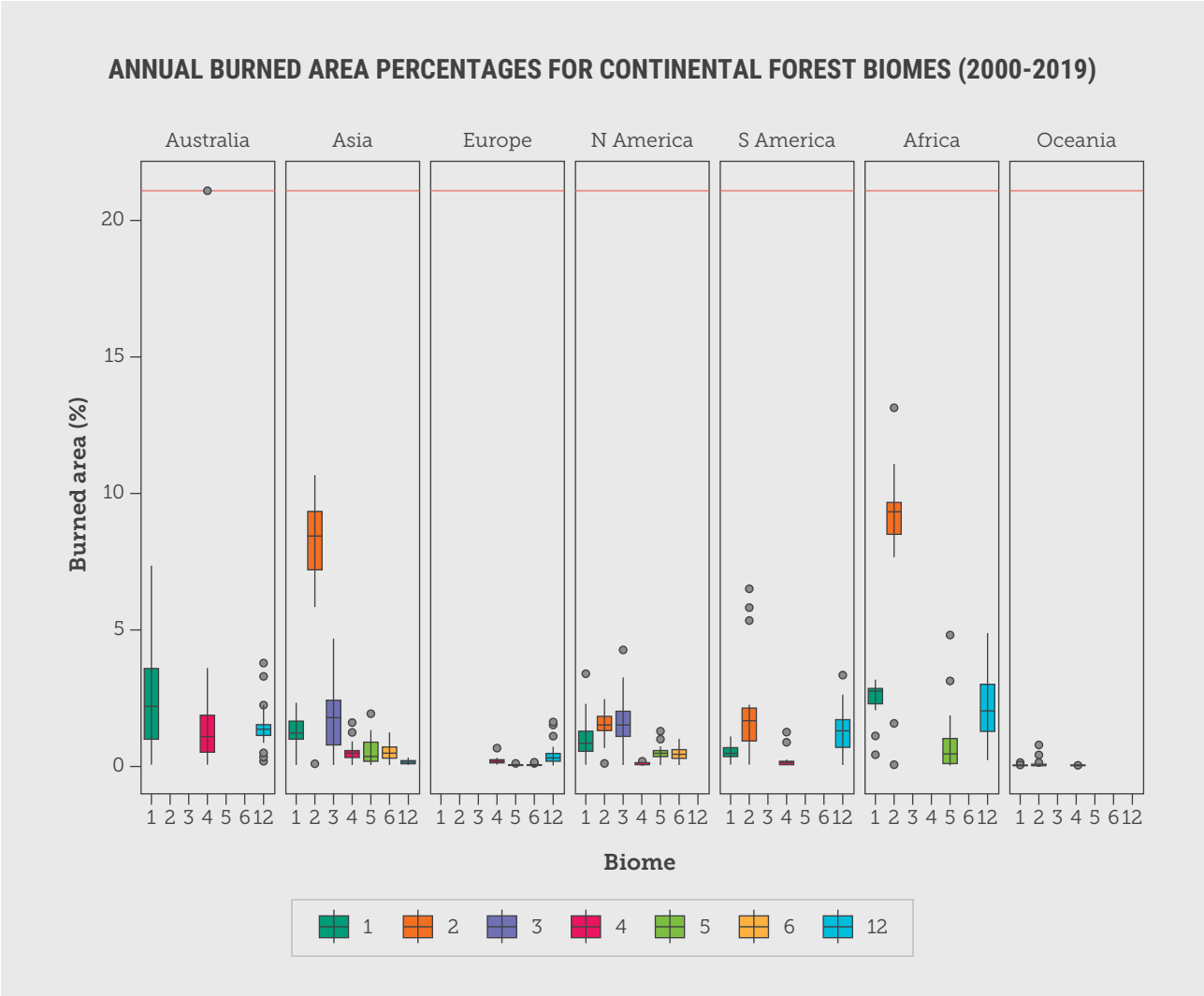
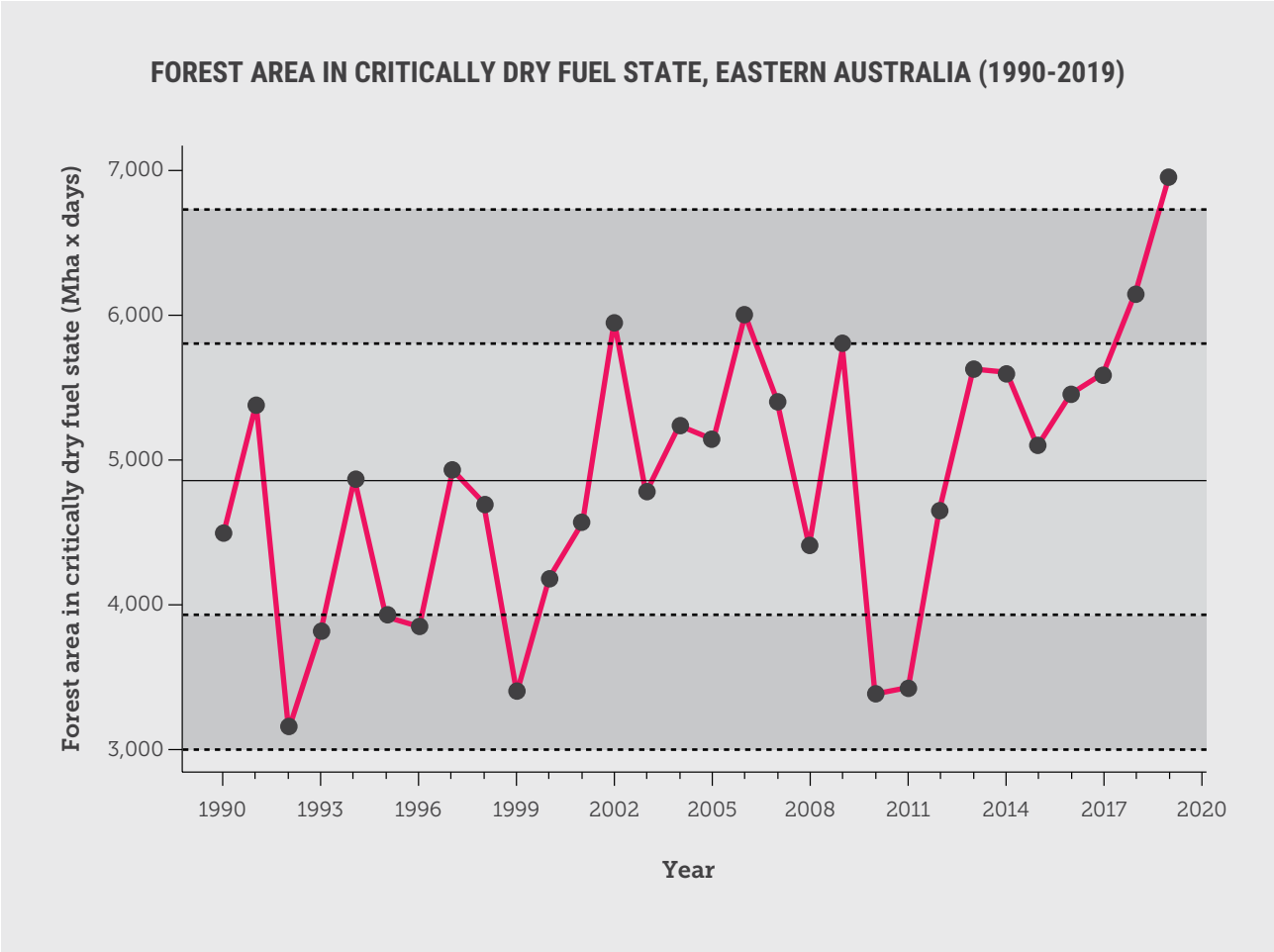


Figure 11 below shows the other factor in the bushfire tipping point - the changes in forest conditions for the 20 years leading up to the 2019-20 bushfire disaster. Up until 2017 the area of forest in a critically dry condition - caused by a combination of low rainfall and high temperature – remained within +/- one standard deviation of the average state (30-year mean) and only occasionally fell to -2 standard deviations. However, over the past few years, the area of forest in a critically dry fuel state has risen rapidly, breaching the +2 standard deviations from the mean in 2019. This can be interpreted as the crossing of a critical tipping point in 2019 in terms of extreme fire conditions, resulting in very violent fires and a massive area burnt.

Figure 11: Forest area in critically dry fuel state, eastern Australia (1990-2019). **Source:** Boer et al. (2020).



4. The cost of inaction – Where we are now compared to ten years ago

We are paying dearly for past inaction, not only in terms of the extreme weather we've already experienced but also for the lost opportunity to prevent much worse.

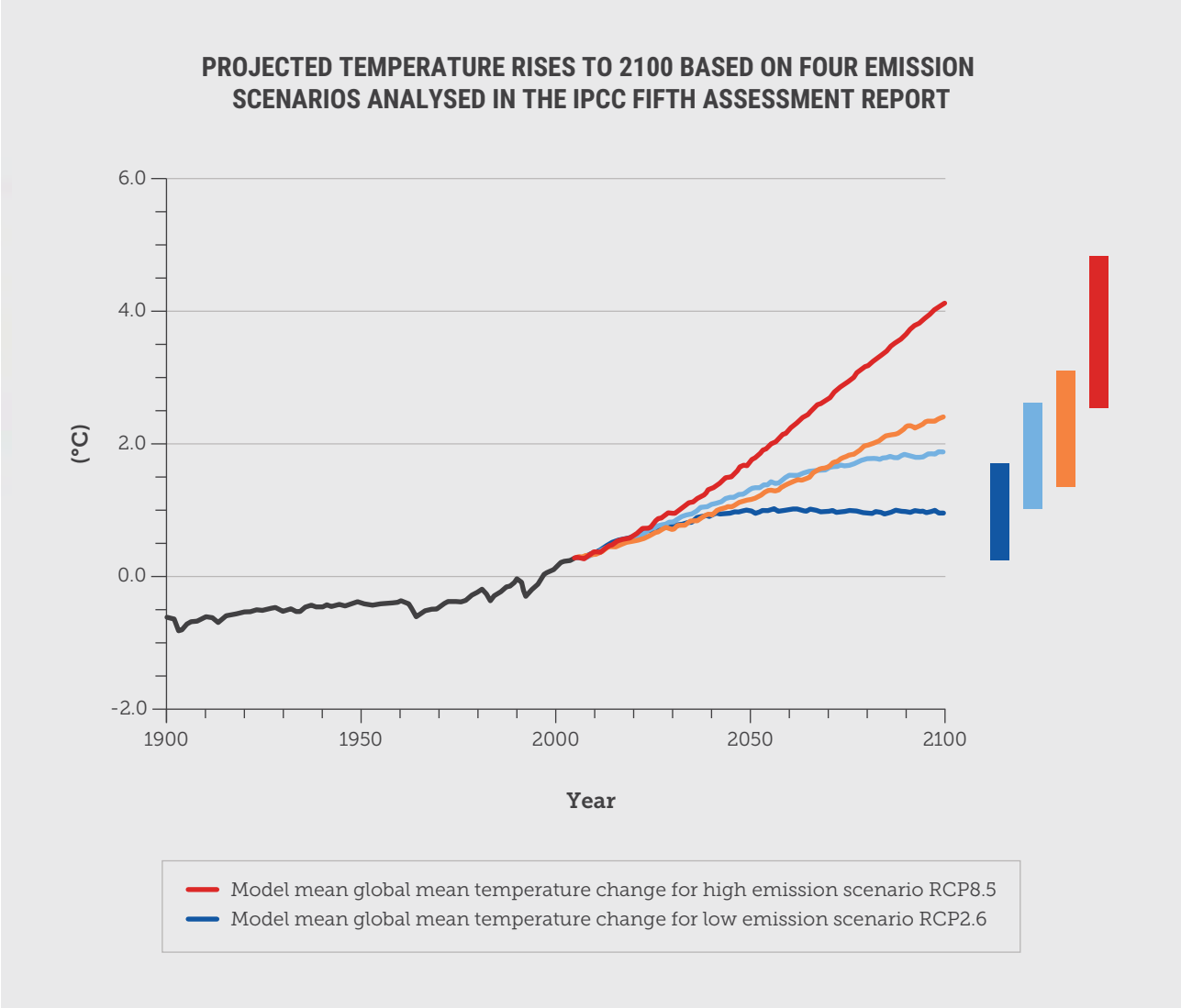
We are paying dearly for past inaction, not only in terms of the extreme weather we're experiencing but also for the lost opportunity to prevent worse.

Based on the momentum in the climate system, primarily due to the massive amount of heat that is being stored in the ocean, and the fact that it is now impossible to achieve what science said we should - net-zero emissions within a decade - there is worse to come. Figure 12 shows the temperature trajectories for the four IPCC emission scenarios, from RCP2.6 (the lowest) to RCP8.5 (the highest) from 2005 to 2100. There is very little difference in the temperature trajectories to at least 2025 and no trajectory begins to flatten until 2040-2050. As stated in the IPCC report: "Temperature increases are almost the same for all the RCP scenarios during the first two decades after 2005" (Collins et al. 2013).

Emissions have continued to climb through the 2010-2019 decade. Based on the range of emission scenarios beginning from 2020 onwards, we cannot expect a significant difference in the rise in global average temperature until at least 2040. This implies that worsening extreme weather is locked in for the next decade at least, and very likely until 2040. Looking backwards, the extreme weather we will experience in 2030 was locked in by 2010 regardless of the emission trajectory we followed over the past decade (Collins et al.2013).

The message from this analysis is clear: climate inaction is costly us dearly. Such inaction is critical because it significantly reduces our chances of staying under the Paris temperature targets and it pushes back the likely time when the climate is eventually stabilised, now around mid-century at the earliest.

Figure 12: Projected temperature rises to 2100 based on four emission scenarios analysed in the IPCC Fifth Assessment Report. Key: Dark blue: RCP2.6; light blue: RCP4.5; orange: RCP6.0; red: RCP8.5. **Source:** Collins et al. (2013).



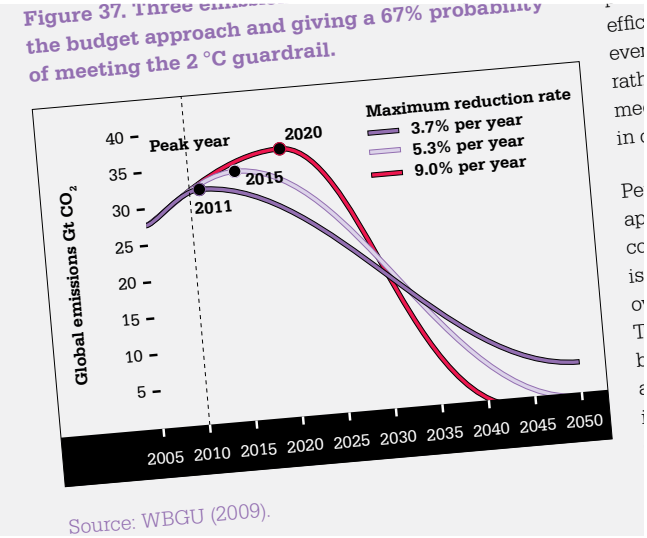
Australians are paying the price for countries 'including Australia' not cutting emissions fast enough, or deep enough.

In 2011, the newly formed Climate Commission (the forerunner of the Climate Council) published its first Critical Decade report, looking ahead towards 2020. A key feature of that report – and one that gave it the title – was the analysis of emissions trajectories that were required to have a 67% probability of staying under a 2°C target (Figure 13).

Two startling things stand out. First, we clearly knew back in 2011 how important the peaking date of our emission trajectory was as well as the level of emissions at that peak. Had our emissions peaked back in 2011, we would have been able to reduce our emissions at a maximum rate of 3.7% per year and avoid the worst climate impacts. Climate inaction has delayed that peak for at least a decade and now requires a maximum 9% emissions reduction per year as well as reaching net zero emissions no later than 2040. Even doing that will only keep temperatures under 2°C, not the lower and safer 1.5°C Paris target.

Second, note the magnitude of the emissions assumed in the three trajectories of Figure 13. It was assumed that by 2020, emissions would have peaked well under 40 Gt CO_2, possibly around 37 Gt CO_2, and fallen thereafter. In reality, global emissions were just under 43 Gt CO_2 in 2019 (Friedlingstein et al. 2019), significantly higher than the value assumed in the 2009 analysis described in Figure 13. This is important because Figure 13 is based on a carbon budget approach, in which cumulative emissions are the key indicator. So, peaking at a higher rate of emissions means that the subsequent emission reduction curves must be even steeper.

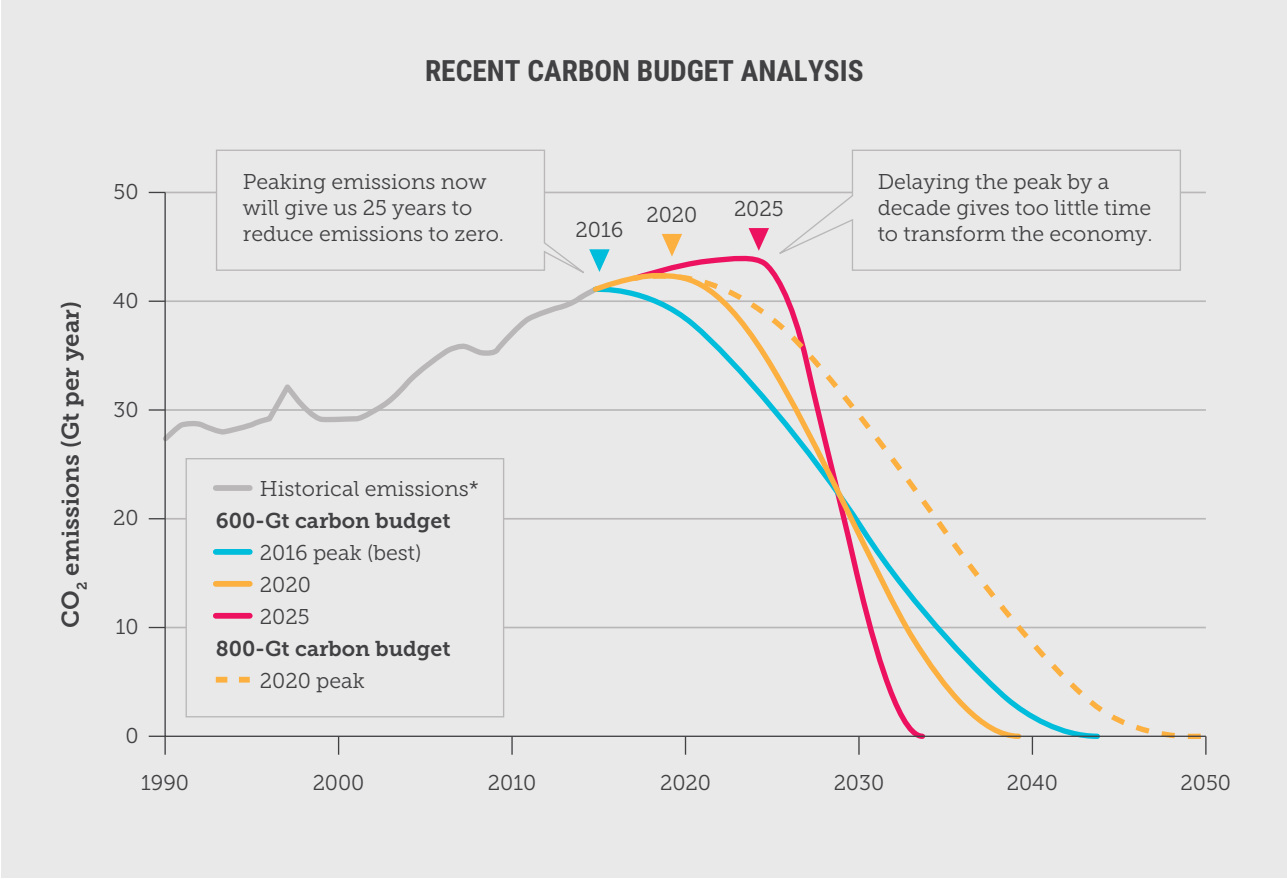
Figure 13: From the 2011 Climate Commission 'Critical Decade' report.



Application of the carbon budget approach has evolved since 2009 and more recent analyses have produced a somewhat more generous budget for a given temperature target than that used for Figure 13. Nevertheless, the decade of inaction has still cost us dearly. A more recent analysis of the carbon budgets (Figure 14) suggests that if emissions peak in 2020 – and the COVID-driven reduction in emissions gives us a chance to do that – then we might have a chance at keeping temperature rise below 2°C. However, if emissions bounce back to pre-COVID levels (of around 43 Gt CO_2 per annum) until 2025, then we face the impossible task of completely decarbonising our economies within a single decade.

In summary, inaction and delay are deadly. Had we started emission reductions a decade ago, we would be in good shape to stay under the 2°C upper and more dangerous target and may have had a chance at meeting the lower and safer 1.5°C target. Now, after a decade of inaction, we are in a climate emergency. We will miss 1.5°C (without overshoot) and we face a daunting task to keep temperature rise below 2°C. One more decade of inaction or weak action and the 2°C will likely be missed or, at the least, be extremely difficult to achieve.

Figure 14: Recent analysis of the remaining global carbon budget for keeping warming well below 2°C. Stretching the budget from 600 gigatonnes (Gt) to 800 Gt buys another 10 years, but at greater risk of exceeding the temperature limit. Figueres et al. 2017.



BOX 2: HITTING HOME – INTENSIFYING DISASTERS AND CASCADING IMPACTS

Contributed by Dr Robert Glasser, former Special Representative of the UN Secretary-General for Disaster Risk Reduction and Head of the UN Office for Disaster Risk Reduction.

It's not surprising, in the wake of *Black Summer's* unprecedented devastation, that much of the climate change discussion in Australia has focused on our growing national vulnerability to climate hazards like floods, drought and bushfires. However, the unfolding regional and global impacts of climate change will also profoundly affect our social, economic and political well-being and even undermine our national security.

We live in the most disaster-prone region in the world. Climate-related hazards, like storms, floods and drought, have affected more people – six times more people – in the Asia-Pacific than in the rest of the world combined. Unlike most other wealthy states, Australia is a near-neighbor to many less developed countries. Over 420 million people live to our immediate north in maritime Southeast Asia, densely concentrated in low-lying coastal areas and on island nations that are among the most vulnerable in the world to climate change (Eckstein et al. 2019).

As the climate continues to warm, these countries will come under enormous pressure from increasing and intensifying disasters and their cascading impacts on society. Large numbers of people will be displaced, political instability will increase and conflict will become more likely (Glasser 2019).

Figure 15: Australia is surrounded by some of the most disaster-prone countries on earth.



BOX 2: CONTINUED

The risks of food insecurity are of particular concern. The reefs of the 'Coral Triangle' of Indonesia, Malaysia, Timor-Leste, the Philippines, Papua New Guinea and Solomon Islands create the 'nursery' for roughly 10% of the global fish supply and an important source of food for more than 130 million people in the region (Cruz-Trinidad 2014). The Intergovernmental Panel on Climate Change has concluded that 70–90% of coral reefs will be lost at just 1.5°C of warming – a level we may reach in less than a decade (Xu et al. 2019) – and that 2°C of warming will result in the total loss of coral reefs from all of the world's tropical and subtropical regions.

This loss would occur simultaneously with other profound climate impacts that further undermine regional food security. For example, scientists have determined that warming oceans are already driving fish species towards the poles in search of cooler waters. At 2°C of warming, this will result in a loss of up to 60% from the fish catch in the tropics (Holmyard 2014).

Increasing temperatures, sea-level rise and extreme weather, such as droughts, floods and storms, will further undermine food security. Crop yields will be severely affected as temperatures rise, rainfall patterns change, the reach of crop pest increases and the range of the predators that keep the pests in check shifts (Miller 2017).

The flooding from sea-level rise and storm surge will disrupt livelihoods and cause large-scale population displacement. In Indonesia alone, 50 million *additional* people will be affected at 1.5°C of warming (IPCC 2018).

More frequent droughts and fires will compound the problem. The fires affecting Indonesia in 2015 were indicative of the potential scale of the impacts. Those fires, which burned 2.6 million hectares (an area four and half times the size of Bali), were fed by drought and exacerbated by an El Niño (World Bank 2016). Tens of millions of Indonesians suffered health effects and economic disruptions. The cost to the Indonesian economy was over US$16 billion.

Even without incorporating a wide range of these likely, simultaneous hazards, scientists have determined that by 2040 at 2°C of warming, Southeast Asia's per capita crop production will have declined by one-third (IPCC 2018). Similar impacts occurring outside the region will significantly reduce the options available to countries to offset the domestic effects, such as importing additional food, as Indonesia did on an unprecedented scale during its severe drought in 1998.

As the record-setting disasters of the past few years suggest, the pace of climate impacts is accelerating. At the same time, the window of opportunity to keep the warming below the critical 2-degree threshold is rapidly closing. Australia must play a leading role in advocating for urgent and ambitious climate action, not just because we're especially vulnerable to the hazards that climate change is amplifying, but also for humanitarian and national security reasons. Climate impacts that affect our regional neighbors' food security, economic interests and political stability will rapidly undermine our own security.

5. By the numbers

5.1 2019-20

At 1.52°C above the long-term average, 2019 was Australia's hottest year on record, breaking the previous record, set in 2013, by a staggering margin of 0.21°C (BoM 2020). 2019 was also Australia's driest year on record. The record heat and record low rainfall set the stage for the Black Summer of 2019-20. Globally, 2019 was the second warmest year on record at the time (NOAA 2020a), and was immediately surpassed by 2020.

Figure 16: Record heat and dryness set the stage for Australia's Black Summer.



Globally, 2020 was the second warmest year on record, just 0.02°C behind the record set in 2016 (NOAA 2021a). Remarkably, 2020 registered as the hottest year despite being a La Niña year. Under normal circumstances, we would expect La Niña years to be slightly cooler than average due to cool surface waters in the tropical Pacific Ocean. 2020, despite being a La Niña year, was warmer than any year other than 2016, including those that were boosted by an El Niño event. Also in 2020, the world's oceans reached their warmest level in recorded history (Cheng et al. 2021).

Globally, disasters caused economic losses of US$210 billion (AU$272 billion) in 2020 (Munich Re 2021). As in previous years, the vast majority of these losses were from weather-related disasters including floods, wildfires and storms. The US suffered a record year of climate-fuelled disasters, with US$95 billion (AUD$123 billion) in recorded losses, including a record 22 major disasters (defined as causing at least US$1 billion in damages) (NOAA 2021b). China's devastating floods, beginning in June, were the single most costly disaster of 2020, with losses estimated at US$32 billion (AU$42 billion) (Kramer and Ware 2020).

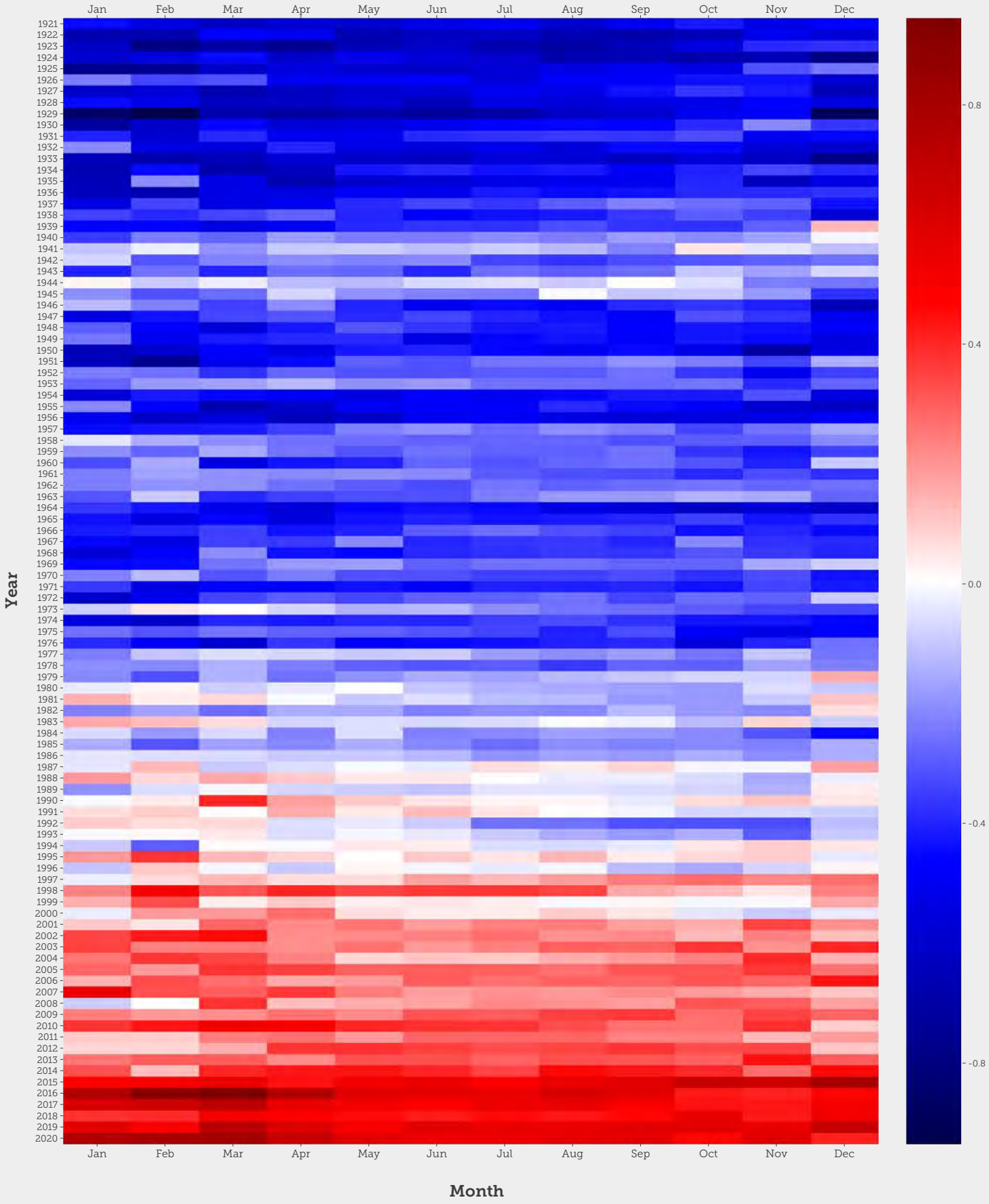
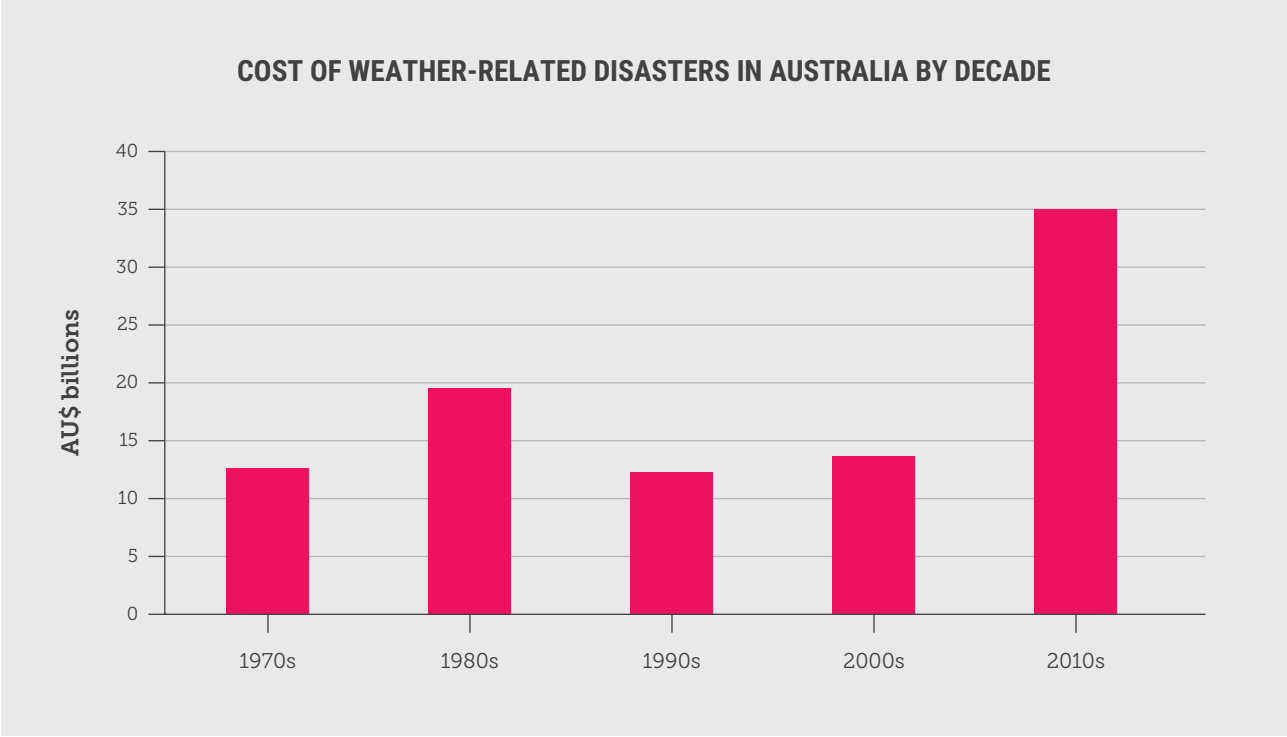


Figure 17: Global monthly temperature anomaly (relative to 1980-1999 average). **Source**: NOAA 2020b.

5.2 Long-term trends

An analysis of data from the International Disaster Database maintained by the Centre for Research on the Epidemiology of Disasters (EM-DAT) shows a significant rise in the cost of weather-related disasters in Australia. After adjusting for inflation, the costs have more than doubled since the 1970s (Figure 18). Recent modelling suggests that the economic cost of climate change to Australia will rise much further over the coming decades. Annual damages from extreme weather, along with sea-level rise and other impacts of climate change upon Australia, could exceed $100 billion by 2038 (Kompas 2020).

Figure 18: Cost of weather-related disasters in Australia by decade.[6] Based on data from EM-DAT, the International Disaster Database: https://www.emdat.be/



6 This analysis covers all weather-related events in the EM-DAT database for Australia between 1970 and 2019, in accordance with the following classifications: storm (convective storm, extra-tropical storm, tropical cyclone), flood (coastal flood, flash flood, riverine flood), wildfire, drought, extreme temperature (cold wave, heat wave, severe winter conditions) between 1970 and 2019. Costs were first converted from US$ to AU$ using the exchange rate of the day, and then adjusted for inflation so as to be equivalent to AU$ in 2019. Historical exchange rates and data on inflation was accessed from the Reserve Bank of Australia.

EM-DAT: https://www.emdat.be/

Exchange rate data: https://www.rba.gov.au/statistics/historical-data.html

Inflation data: https://www.rba.gov.au/calculator/annualDecimal.html

The rise in cost is likely due to both climate and non-climate-related factors. The latter include growth in population and the number of people living in exposed areas.

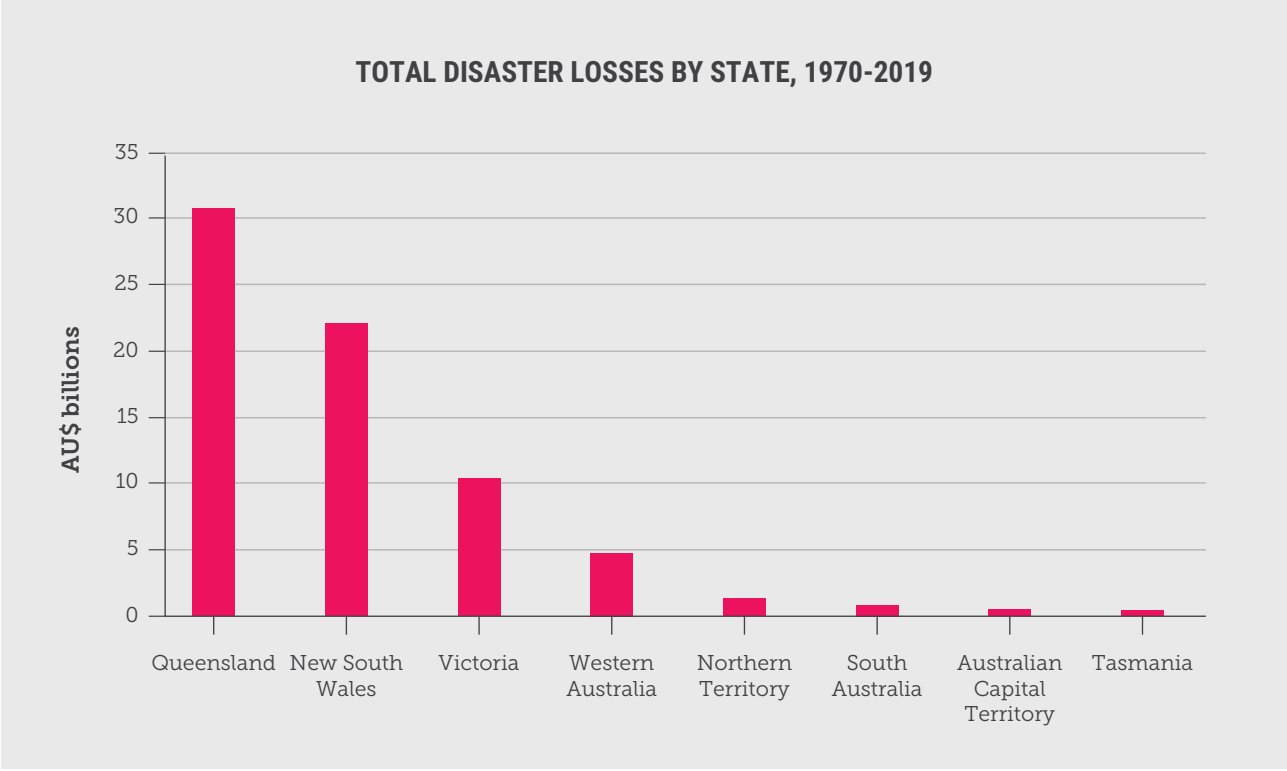
Queensland carries the greatest weight of disaster costs among Australian states and territories (Figure 19).

Queensland's total losses from extreme weather disasters since the 1970s were around three times those of Victoria, and about 50% greater than NSW. On a per person basis, Queensland's losses were more than twice the national average. Heavy damage from floods, drought, fires and storms meant New South Wales suffered greater economic damage from extreme weather disasters than any states or territory except for Queensland, which also faces heavy damage from tropical cyclones. On a per person basis, losses in New South Wales were around double those in Victoria, and quadruple those in Tasmania.

Once these cumulative costs in Figure 19 are adjusted for population size,[8] the states/territories can be ranked as follows in terms of their vulnerability to economic damages from extreme weather:

1st Queensland
2nd Northern Territory
3rd New South Wales
4th Western Australia
5th Victoria
6th Australian Capital Territory
7th Tasmania
8th South Australia

Figure 19: Cumulative economic damages by state/territory (1970-2019).[7] Based on data from EM-DAT, the International Disaster Database: https://www.emdat.be/



7 This analysis covers all weather-related events in the EM-DAT database for Australia between 1970 and 2019, in accordance with the following classifications: storm (convective storm, extra-tropical storm, tropical cyclone), flood (coastal flood, flash flood, riverine flood), wildfire, drought, extreme temperature (cold wave, heat wave, severe winter conditions) between 1970 and 2019. The costs are as recorded at the time of the event, and have been converted from US$ to AU$ using today's rate.

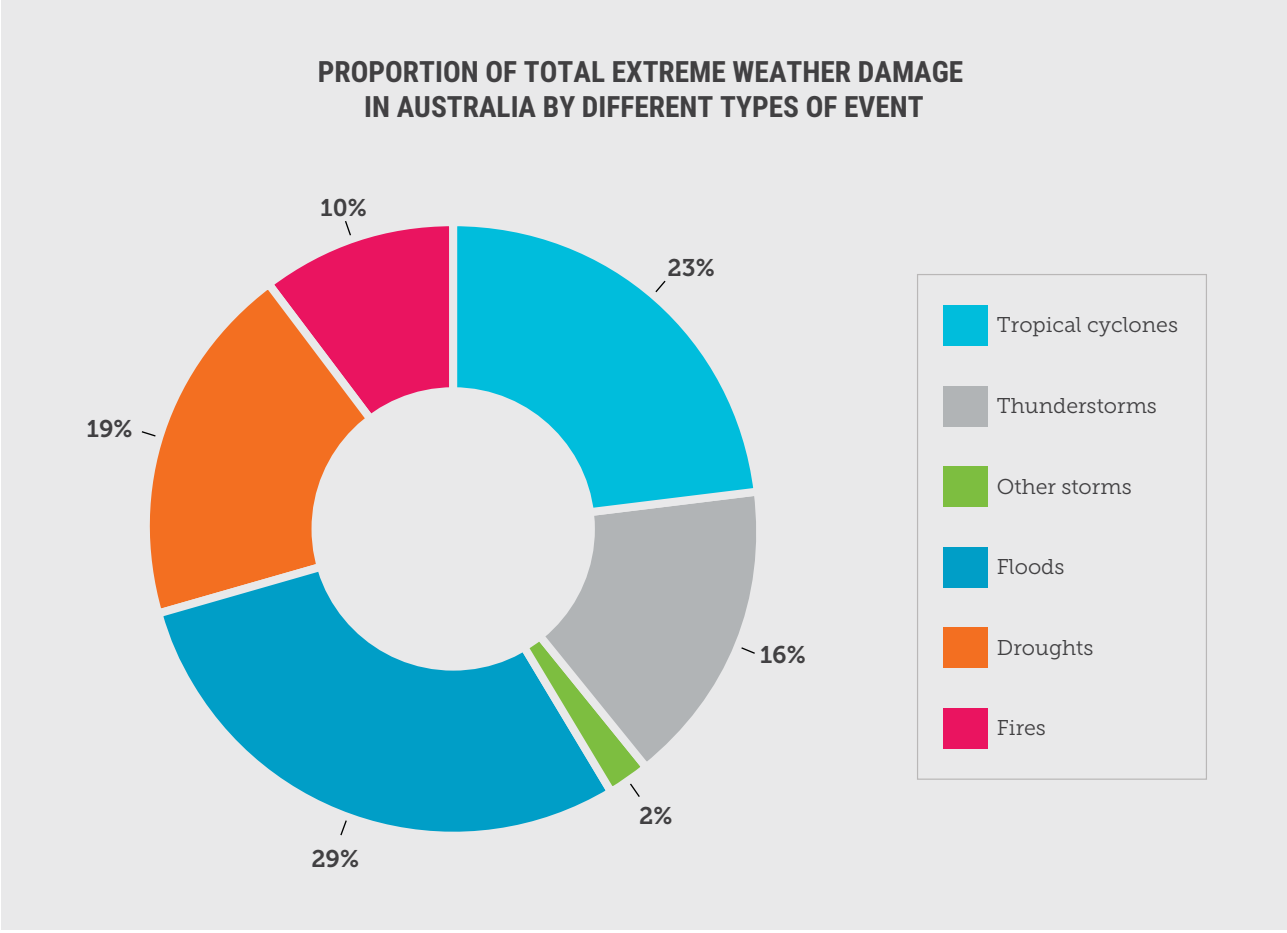
EM-DAT: https://www.emdat.be/

8 Population data: https://www.abs.gov.au/statistics/people/population/national-state-and-territory-population/latest-release

Floods made up the greatest proportion of economic damages from extreme weather in Australia over the last decade, followed by tropical cyclones and droughts (Figure 20).

Globally, the 2010s was by far the costliest decade on record for extreme weather catastrophes (Aon 2020). Australia has faced particularly heavy costs relative to many other countries. On a per capita basis, economic damages from extreme weather disasters in Australia were around seven times the global average. While slightly lower than those for the US, they were far greater than for other developed countries including New Zealand, Canada, the UK and the average across European Union countries.[10]

Figure 20: Proportion of total extreme weather damage in Australia (2010-2019) by different type of event.[9] Based on data from EM-DAT, the International Disaster Database: http://www.emdat.be/

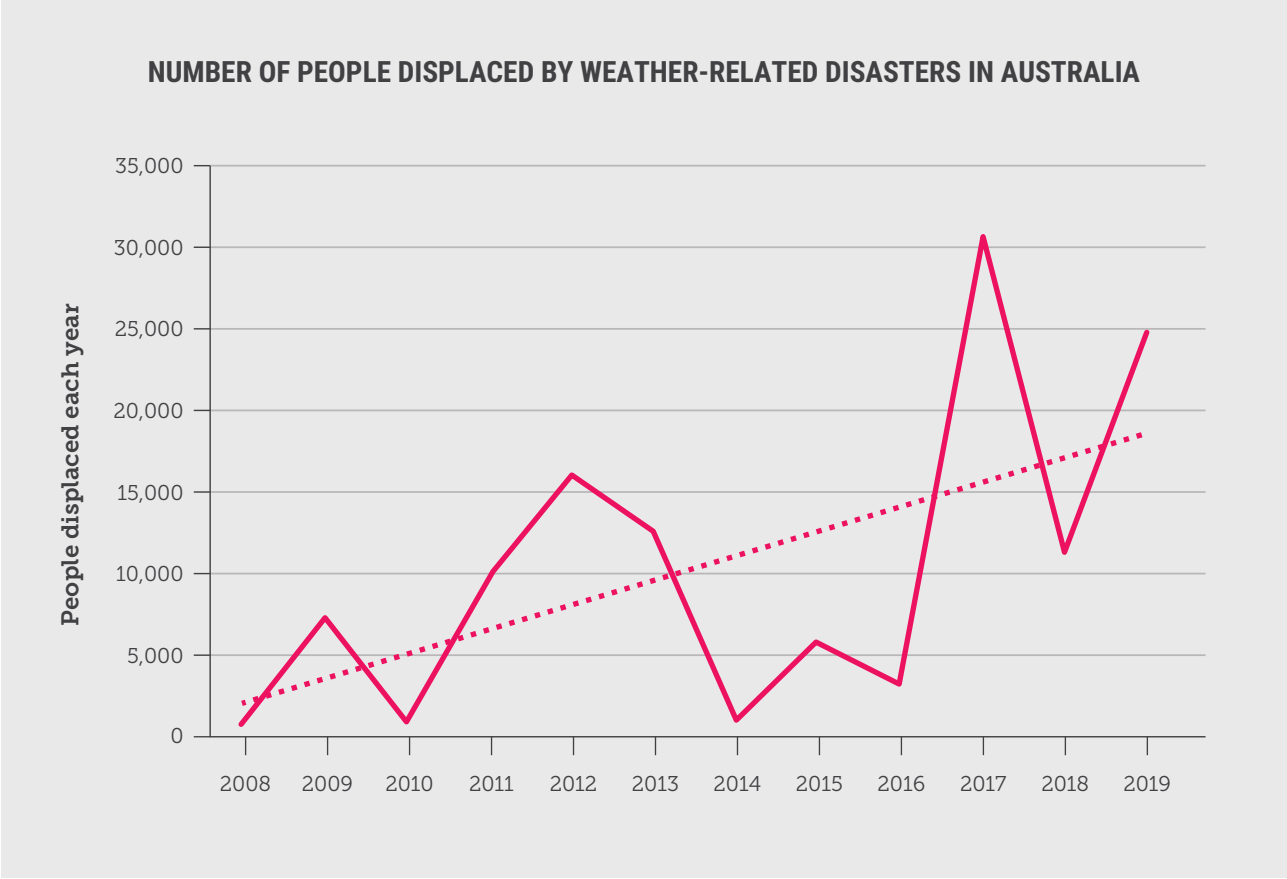


9 'Floods' includes coastal floods, flash floods and riverine floods.

Economic costs give us only part of the picture when it comes to the toll of weather-related disasters, which also result in mental trauma, damage to ecosystems, loss of wildlife and many other forms of loss and damage. Similarly, economic costs, at least when measured in absolute terms rather than as a proportion of GDP,[11] do not capture the disproportionate impact of weather-related disasters upon lower-income countries (UNDRR 2020).

The number of people being forced from their land and home by weather-related disasters provides us with another indicator, one that may go a little further towards capturing the true human cost. Data from the Internal Displacement Monitoring Centre (IDMC) on forced displacement from extreme weather disasters in Australia shows an upward trajectory since records began in 2008 (Figure 21).

Figure 21: Number of people displaced by extreme weather disasters each year in Australia. Based on data from the Internal Displacement Monitoring Centre (IDMC): https://www.internal-displacement.org/



10 Based on data from EM-DAT, the International Disaster Database: http://www.emdat.be/
Population data: https://data.worldbank.org/indicator/SP.POP.TOTL

11 Notably, when measured as a proportion of GDP, economic damages among Pacific Island Countries are much higher than in Australia, even though Australia's losses per capita are greater than those in the Pacific. The latter is in part a function of the greater wealth and greater monetary value of property, infrastructure and other assets in Australia.

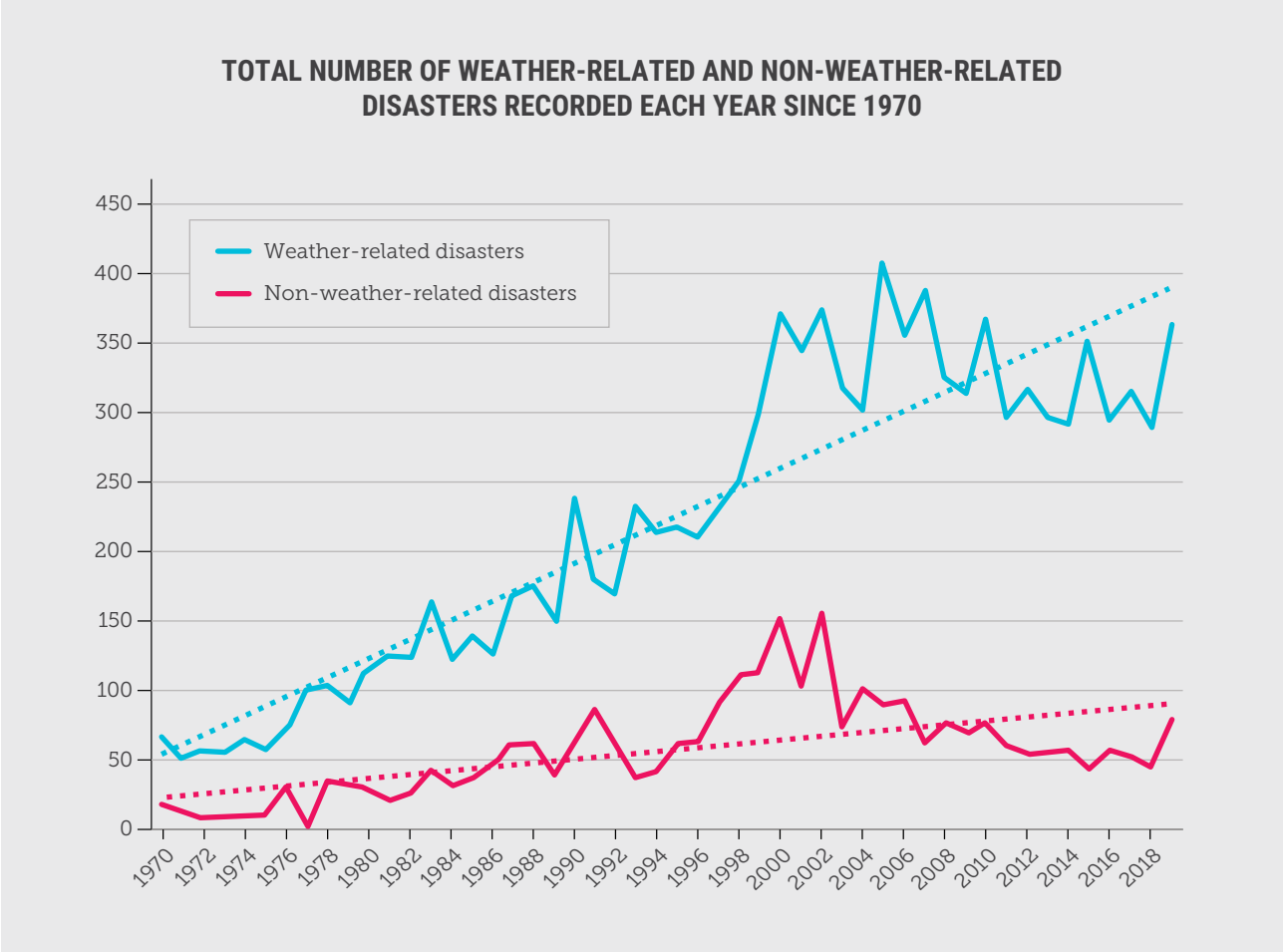
Australians are five times more likely to be displaced by a climate-fuelled disaster than Europeans.

IDMC data also enables us to assess the relative vulnerability of Australians to forced displacement compared to citizens of other countries. Our analysis shows that in Australia, the risk of being displaced by a climate-fuelled disaster is, on average, around five times greater than for people living in Europe.[12] However, for a person living in the Pacific, the risk of displacement is on average more than 100 times greater than for a person living in Europe. The latter highlights the disproportionate impact of climate change on Australia's Pacific neighbours, who despite contributing almost nothing to the causes of climate change are facing some of the most severe consequences.

Overall, data from the Centre for Research on the Epidemiology of Disasters (EM-DAT) show a large increase in the number of extreme weather disasters worldwide since the 1970s (Figure 22). A possible explanation could be that we have simply become more thorough in our recording of events than in the past. However, were that the case, we would expect to see a similar rise in the number of non-weather-related disasters such as earthquakes to the number of storms, floods and other weather-related disasters. Notably, the data show a much steeper rise in the number of weather-related disasters than non-weather-related disasters, strongly suggesting that the rise in recorded weather-related-disasters reflects a genuine trend.

12 We used the full IDMC dataset for weather-related disasters to determine the relative risk of displacement in different countries by calculating the percentage of each country's population that faced displacement, on average, across each year for which data is available.

Figure 22: Total number of weather-related and non-weather-related disasters recorded each year since 1970. Based on data from EM-DAT, the International Disaster Database: https://www.emdat.be/

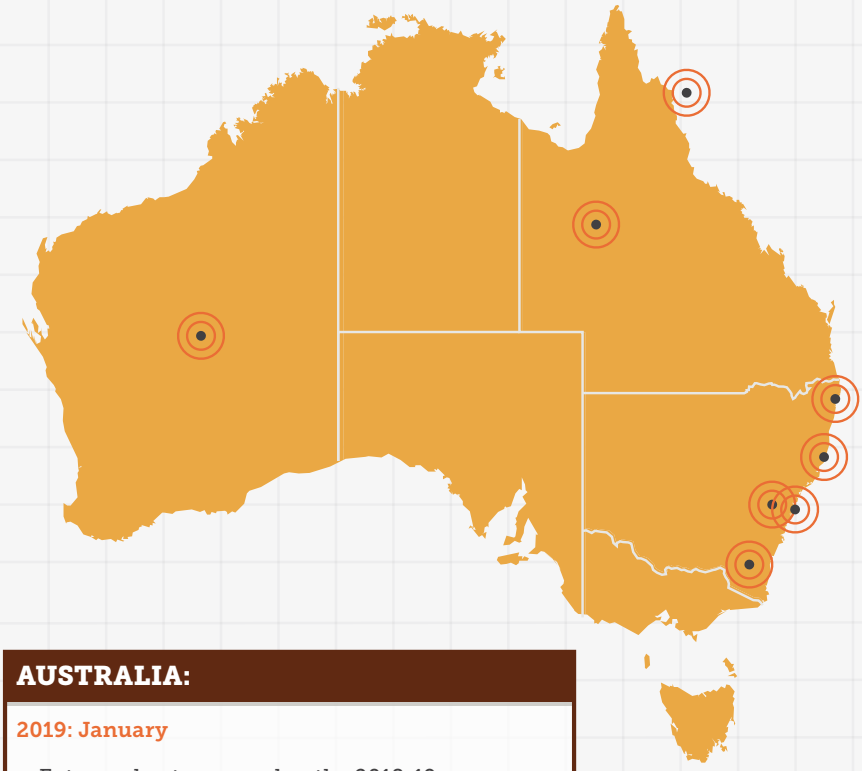


6. Major events in Australia and around the world

Figure 23: Flooding in Townsville,2019.



2019/20 MAJOR EVENTS ACROSS AUSTRALIA



AUSTRALIA:

2019: January

> Extreme heatwave makes the 2018-19 summer the hottest on record at the time.

2019: November to December

> The unprecedented Black Summer fires burn through millions of hectares and kill or displace around 3 billion animals.

2019: December

> Driest and by far the warmest December recorded in Australia.

2020: September to November

> Hottest spring and hottest November on record, despite La Niña event. Deemed virtually impossible in absence of climate change.

QUEENSLAND:

2019: February

> Over half a million cattle are killed by floods in northwest Queensland.

2020: March

> The third mass bleaching event in five years is reported on the Great Barrier Reef. See CASE STUDY: Coral mortality.

NEW SOUTH WALES:

2020: January

> 4 Jan: Penrith was the hottest place on earth at 48.9˚C.

2020: February

> 7-10 Feb: Sydney receives more rain in four days than over the entire six months prior, dousing fires and filling dams.

2020: July

> In one of many severe coastal erosion events this year, huge swells and high tides damaged beaches and property along Sydney's northern beaches and the NSW Central Coast.

2020: December

> Heavy rain, high winds and high tides wreak havoc across NSW northern rivers and southern Queensland, including catastrophic beach erosion at Byron Bay.

WESTERN AUSTRALIA:

2019:

> Warmest year and second driest year on record.

2020:

> Second warmest year on record.

CANBERRA:

2020: January

> 20 Jan: Giant hailstones batter Canberra, damaging cars and houses.

2019/20 MAJOR EVENTS AROUND THE WORLD

NORTH AMERICA:

2019: January to February

> A severe and deadly cold wave hits the US Midwest and eastern Canada.

2019: August

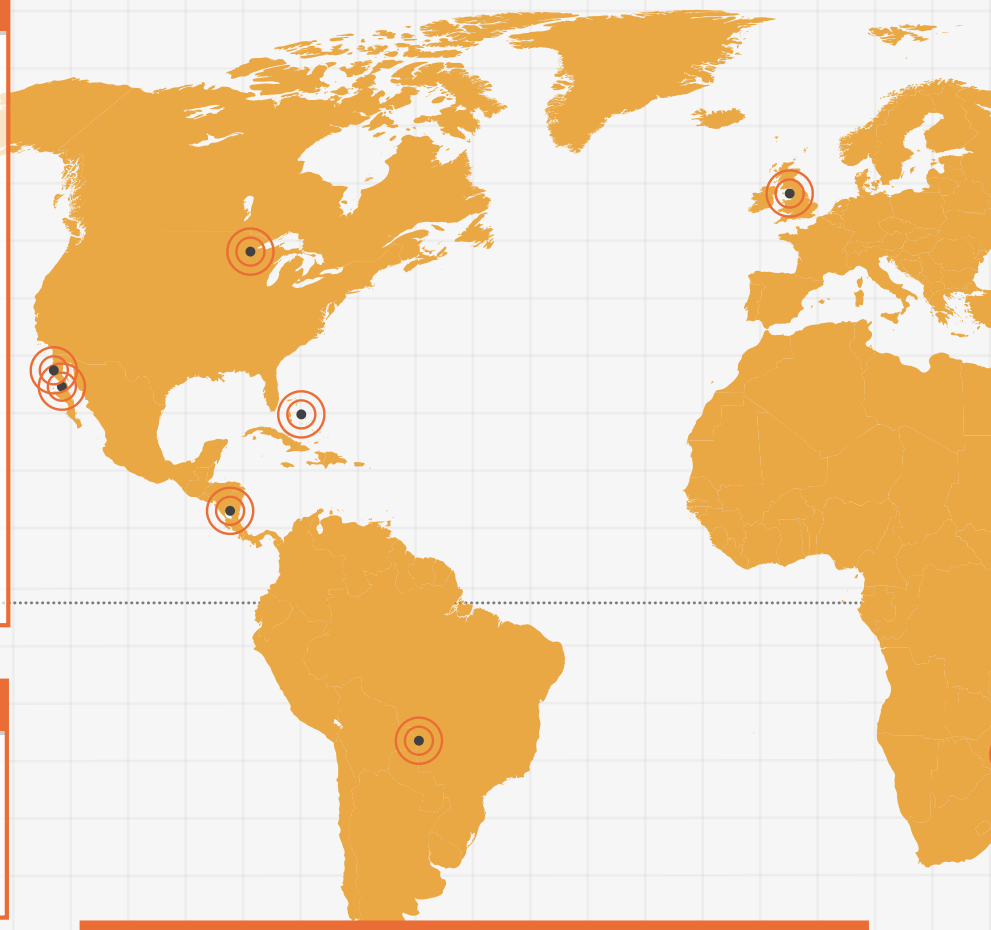
> Hurricane Dorian is the strongest cyclone on record to hit the Bahamas and the worst disaster in the country's history.

2020: August

> 16 Aug: 54.4°C recorded in Death Valley, possibly the highest temperature ever reliably recorded on Earth.

2020: October

> Record-breaking US fire season reaches its peak, with California recording its first 'gigafire'. See CASE STUDY: 2020 US West Coast fires.



CENTRAL AMERICA:

2020: November

> Back-to-back hurricanes Eta and Iota devastate many communities across Central America. See CASE STUDY: 2020 North Atlantic hurricane season.

SOUTH AMERICA:

2020: August to September

> Record fires burn over a quarter of the Pantanal, the world's largest tropical wetlands.

AFRICA:

2019: March

> Cyclone Idai, one of the deadliest cyclones on record in the Southern Hemisphere, causes catastrophic damage in Mozambique, Zimbabwe and Malawi.

2019: April

> Cyclone Kenneth, the strongest recorded cyclone to make landfall in Mozambique, hits just a month after Cyclone Idai.

2020: March to May

> Intense rainfall causes widespread flooding and landslides in East Africa. Hundreds are killed and hundreds of thousands are affected. Kenya and Somalia are among the worst affected countries.

2020: November

> Cyclone Gati, the strongest landfalling cyclone recorded in Somalia, brings over a year's worth of rain in two days.

ANTARCTICA:

2020: February

> Highest temperature ever recorded on Antarctica – 18.4°C.

UK:

2020: October

> 3 Oct: UK records wettest day since records began in 1891.

SIBERIA:

2020: January to June

> An intense, persistent and widespread heat wave across Siberia broke temperature records, fuelled large fires, and thawed permafrost. See CASE STUDY: 2020 Siberian heatwave.

NORTHERN HEMISPHERE:

2020: July to August

> Hottest northern hemisphere summer on record.

2020: July

> Lowest Arctic sea ice extent for July since beginning of satellite observations in 1979.

ASIA:

2019: June to October

> Monsoon floods cause 1,750 fatalities in India – 2019's most deadly extreme weather event.

2019: October

> Typhoon Hagibis is the strongest and deadliest cyclone to hit Japan since Typhoon Tip in 1979.

2020: January

> Record floods in Indonesia kill at least 19 people. Highest daily rainfall in Jakarta since records began.

2020: May

> Cyclone Amphan rapidly intensifies into a category five storm before tearing into eastern India and Bangladesh. It becomes the costliest cyclone on record for the north Indian Ocean, with losses in India of around US$14 billion.

2020: June

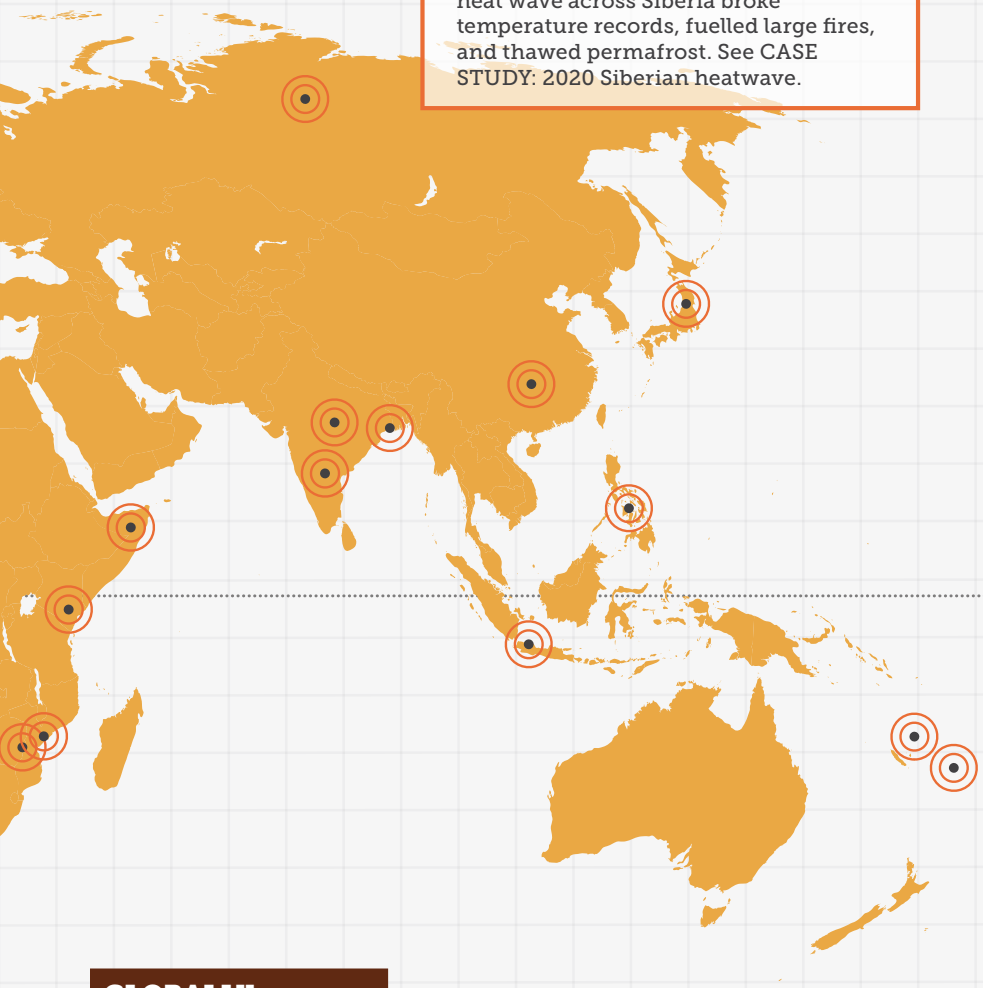
> Worst flooding along the Yangtze and its tributaries for decades affect more than 60 million people and cause estimated losses of US$32 billion.

2020: July

> Flooding in India (Assam) and Nepal displaces millions. A third of Bangladesh is underwater. See CASE STUDY: 2020 Asian Monsoon floods.

2020: November

> The Philippines hit by Typhoon Goni, the strongest landfalling tropical cyclone on record.



GLOBALLY:

2019: July

> Hottest month ever recorded globally.

2020: January

> Hottest January on record globally.

2020: September

> Hottest September on record globally.

2020: November

> Hottest November on record globally.

PACIFIC:

2020: April

> Cyclone Harold, the strongest cyclone to hit Vanuatu since record-breaking Cyclone Pam in 2015, causes widespread damage in Vanuatu, Solomon Islands, Fiji and Tonga.

2020: December

> Cyclone Yasa, exceptionally strong for this early in the season, causes heavy damage on Fiji's northern island of Vanua Levu.

7. We must act with more urgency

Politically, 2021 will be the most important year for international action on climate change since the Paris Agreement was adopted in 2015, and perhaps ever. The intervening years have revealed the tremendous - and rapidly escalating - costs of the climate crisis and the perilous gap between the action that countries have committed to taking and the pace of action required to avert catastrophe. Nowhere is this starker than in Australia.

Countries have until November 2021 – before the next crucial round of international climate negotiations at COP26 in Glasgow – to announce new commitments that will close the gap between current collective efforts and what the science demands. Decisions made in the lead up to Glasgow, including how governments choose to spend trillions of dollars in economic renewal, will profoundly affect the security, wellbeing and prosperity of generations to come – and reverberate beyond human timescales.

Despite, or perhaps because of, the disruption of COVID-19, there has been an encouraging upswing in the world's response to the climate crisis in 2020. Less than a year ago, only around a fifth of Australia's two-way trade was with countries committed to net zero emissions by around mid-century. By the end of 2020, that number had shot up to more than 70%, including the three biggest buyers of Australian coal and gas: China, Japan and South Korea. More and more countries have recognized that climate action, and in particular clean energy, is not only essential to our common wellbeing but is also the fast track to economic recovery from COVID-19.

When the US is included, more than 60% of global emissions are covered by a commitment to net zero emissions by around mid-century. More importantly, many of the world's biggest emitters, including the EU, US, UK, China and Japan, have either strengthened their commitments to 2030 or plan to do so.



Figure 24: Australia has enormous potential for renewable energy and clean industries.

Encouraging as these developments have been, they remain insufficient if we are to stay under the long-term temperature limits identified in the *Paris Agreement* and ensure a future in which Australians everywhere can not only survive but thrive. To maintain a fair chance of limiting warming to well below 2°C, we must halve global emissions over the coming decade, and achieve net zero emissions before 2040 (Steffen et al. 2020). While few countries, and almost no major economy, are acting with the urgency that this crisis demands, Australia is a true outlier. We stand alone in refusing to commit to achieving net zero emissions by 2050 or earlier (or 2060 in the case of China), or to strengthening our 2030 emissions reduction target.

Today the Australian government faces pressure from many angles to commit to much stronger climate action – both domestically and internationally.

Australia now faces serious pressure from the US, our number one strategic ally, to do far more to address the climate crisis. Commitments by our big trading partners in Asia to move beyond fossil fuels adds to this international pressure and will soon translate into lost export revenues and jobs unless Australia rapidly shifts towards renewable-generated exports. We also face the very real prospect of carbon tariffs being placed on our exports, beginning with the EU, until we have a carbon price of our own.

Closer to home, Pacific leaders have grown angry and impatient with Australia for recklessly endangering the future of their communities and our region. China's growing presence in the region – and its willingness to go further in taking climate action - should be a cause of concern for us. Even the UK's historical, strategic and cultural ties to Australia have not prevented it from calling out our failures ahead of COP26, which it will host.

Despite the federal government's climate inaction, Australia is still making progress thanks to leadership from the states and territories, local governments and business. The Australian public, 80% of whom were in one way or another directly affected by the Black Summer fires (Biddle et al. 2020), continue to demand that our national government rise to the challenge. Similarly, investors are increasingly using their voice and their dollars to drive change.

Just as the pressure for action has never been greater, nor coming from so many different directions, so too have the opportunities for Australia to flourish in a post-carbon world never been clearer.

Renewable energy is already cheaper than fossil fuels, employs more people – particularly in regional Australia - and can be rapidly expanded (Climate Council and Alpha Beta 2020). Australia has many competitive advantages that are the envy of the world: we are the sunniest and one of the windiest countries and have the space and technical expertise necessary to make use of our renewable resources. Tapping into renewable energy can repower our homes, businesses and transport. It can also become the foundation for new low and zero carbon manufacturing industries, tapping into growing global demand. Furthermore, renewable hydrogen and other emerging technologies provide Australia with an opportunity to build a world-leading renewable export industry, setting up economic prosperity for generations to come. Yet despite our enviable natural advantages, Australia currently risks being left behind.

Not so long ago, it was common to say that we must limit warming to below 2°C below pre-industrial levels to "avoid dangerous climate change". Today, it is clear there is no "safe" level of warming. Already, at 1.1°C of warming, we are witnessing a deadly rise in extreme weather events and damage to critical ecosystems upon which our lives depend. Limiting warming to 1.5°C – as agreed in Paris – would avoid even more severe risks associated with 2°C or more of warming (IPCC 2018). However, decades of inaction have already rendered this virtually impossible. Allowing warming of 2°C and beyond would risk tipping the Earth onto a perilous 'Hothouse' trajectory and a barely survivable future (Steffen et al. 2018; Lenton et al. 2019).

Australia is facing enormous pressure from many quarters, but we also have a massive opportunity to become a post-carbon world powerhouse.

As we enter the decisive and transformative decade for climate action, Australia must do everything it can to help, recognizing our unique natural advantages, our responsibilities as an advanced economy and the vulnerability of our own communities and economy. This begins with targets based on the science, and a comprehensive plan of action that mobilises every section of our society around a shared vision. It means acting today, not tomorrow. It means at least halving our emissions by 2030, and achieving net zero emissions as soon as possible, and by 2040 at latest. It means pivoting from being one of the world's largest exporters of fossil fuels to being a global powerhouse of renewable energy and clean industries.

Failure will be felt in loss of life, catastrophic economic losses, in more people being forced from their homes by extreme weather disasters, in the loss of species and entire ecosystems, and in the undermining of everything we hold dear. In other words, failure is not an option.

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Image credits

Cover image: Townsville Floods. Andrew Rankin / Australian Associated Press.

Page 6: Figure 2 – Vendors and rickshaw drivers sleep in the open on a hot summer morning in Karachi, Pakistan. AP Photo / Fareed Kahn).

Page 7: Figure 3 – Fish Swims amongst bleached coral. Milan Degraeve.

Page 12: Figure 4 – A woman wades through a flooded village in Bihar, India. Reuters / Cathal McNaughton.

Page 14: Figure 5 – A Red Cross volunteer surveys damage from Typhoon Goni. Philippine Red Cross via AP.

Page 16: Figure 6 – Satellite image showing Hurricane Sally over the Gulf of Mexico, Hurricane Paulette over Bermuda, the remnants of Tropical Storm Rene, and Tropical Storms Teddy and Vicky. NOAA via AP.

Page 19: Figure 7 – Kerry, Queensland, 2019. Josh Withers.

Page 21: Figure 8 – Damage from Tropical Cyclone Harold, April 2020. AAP image / Supplied by Julian Bluett.

Page 22: Figure 9 – NSW Farmer Rob Lee, New Year's Eve, 2019. Kim Lee.

Page 31: Figure 15 – Causeway, Funafuti, Tuvalu. Simon Bradshaw.

Page 33: Figure 16 – Bushfire, NSW, October 2019. Ash Hogan.

Page 41: Figure 23 – Flooding in Townsville, 2019. Andrew Rankin.

Page 46: Figure 24 – Bungala Solar Power Project, South Australia. Andrew Correll.

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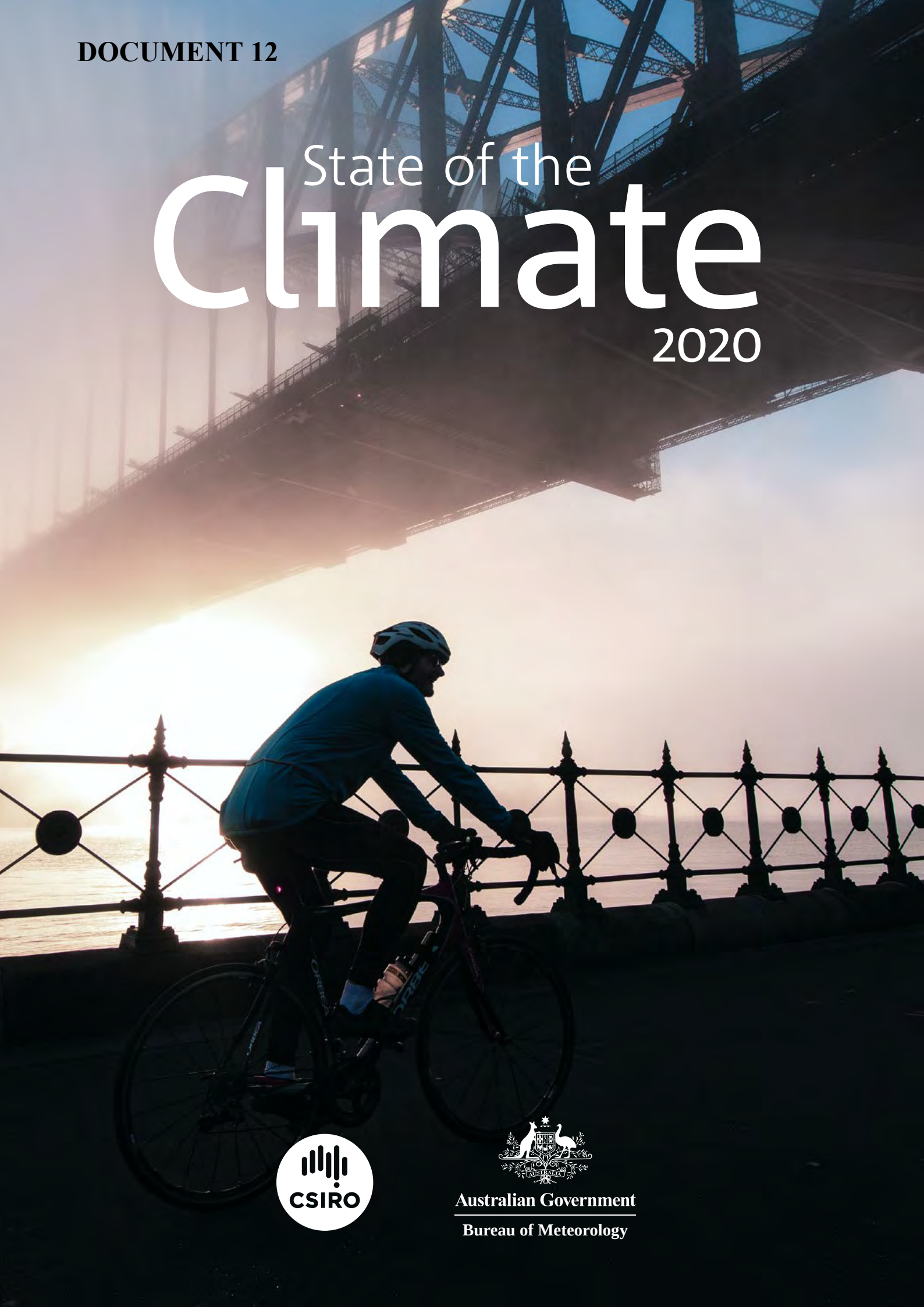
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DOCUMENT 12

State of the Climate 2020



CSIRO

Australian Government
Bureau of Meteorology

Report at a glance

The Bureau of Meteorology and CSIRO play an important role in monitoring, analysing and communicating observed and future changes in Australia's climate.

This sixth biennial State of the Climate report draws on the latest climate research, encompassing observations, analyses and projections to describe year-to-year variability and longer-term changes in Australia's climate. The report is a synthesis of the science informing our understanding of climate in Australia and includes new information about Australia's climate of the past, present and future. The science informs a range of economic, environmental and social decision-making by governments, industries and communities.

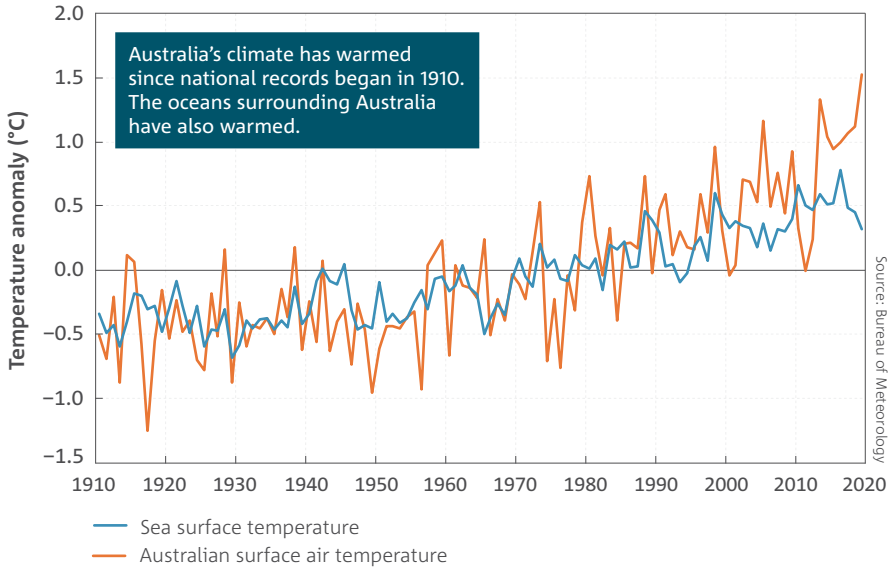
Observations, reconstructions and climate modelling paint a consistent picture of ongoing, long-term climate change interacting with underlying natural variability. Associated changes in weather and climate extremes—such as extreme heat, heavy rainfall and coastal inundation, fire weather and drought—have a large impact on the health and wellbeing of our communities and ecosystems. They affect the lives and livelihoods of all Australians.

Australia needs to plan for and adapt to the changing nature of climate risk now and in the decades ahead. Reducing global greenhouse gas emissions will lead to less warming and fewer impacts in the future.

Key points

Australia

- Australia's climate has warmed on average by 1.44 ± 0.24 °C since national records began in 1910, leading to an increase in the frequency of extreme heat events.
- There has been a decline of around 16 per cent in April to October rainfall in the southwest of Australia since 1970. Across the same region May–July rainfall has seen the largest decrease, by around 20 per cent since 1970.
- In the southeast of Australia there has been a decline of around 12 per cent in April to October rainfall since the late 1990s.
- There has been a decrease in streamflow at the majority of streamflow gauges across southern Australia since 1975.
- Rainfall and streamflow have increased across parts of northern Australia since the 1970s.
- There has been an increase in extreme fire weather, and in the length of the fire season, across large parts of the country since the 1950s, especially in southern Australia.

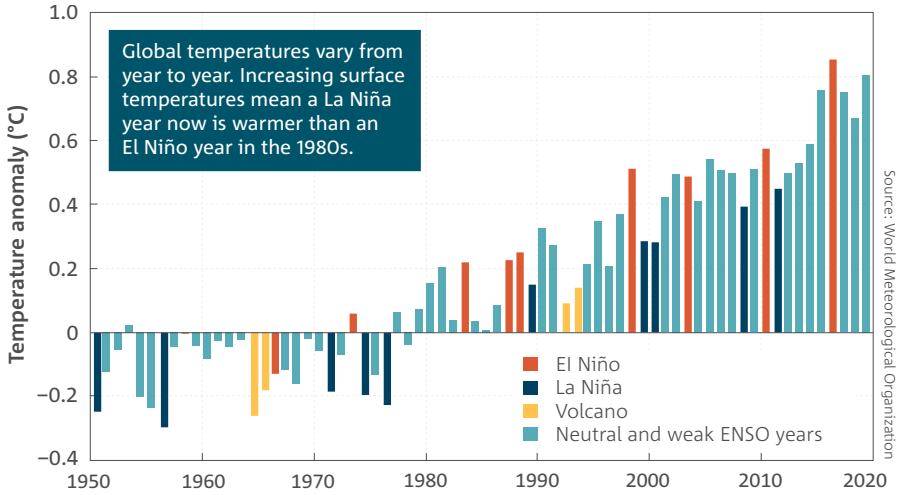


Anomalies in annual mean sea surface temperature, and temperature over land, in the Australian region. Anomalies are the departures from the 1961–1990 standard averaging period. Sea surface temperature values (data source: ERSST v5, www.esrl.noaa.gov/psd/) are provided for a region around Australia (4–46 °S and 94–174 °E).

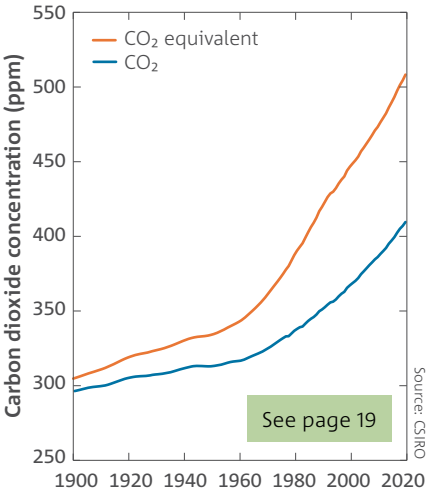
- There has been a decrease in the number of tropical cyclones observed in the Australian region since 1982.
- Oceans around Australia are acidifying and have warmed by around 1 °C since 1910, contributing to longer and more frequent marine heatwaves.
- Sea levels are rising around Australia, including more frequent extremes, that are increasing the risk of inundation and damage to coastal infrastructure and communities.

Global

- Concentrations of all the major long-lived greenhouse gases in the atmosphere continue to increase, with global annual mean carbon dioxide (CO_2) concentrations reaching 410 ppm in 2019 and the CO_2 equivalent (CO_2-e) of all greenhouse gases reaching 508 ppm. These are the highest levels seen on Earth in at least two million years.
- Despite a decline in global fossil fuel emissions of CO_2 in 2020 associated with the COVID-19 pandemic, this will have negligible impact in terms of climate change. Atmospheric CO_2 continues to rise, and fossil fuel emissions will remain the principal driver of this growth.
- Globally averaged air temperature at the Earth's surface has warmed by over 1 °C since reliable records began in 1850. Each decade since 1980 has been warmer than the last, with 2010–19 being around 0.2 °C warmer than 2000–09.
- The world's oceans, especially in the southern hemisphere, are taking up around 90 per cent of the extra energy resulting from enhanced greenhouse gas concentrations.
- More than half of all CO_2 emissions from human activities are being absorbed by land and ocean sinks, thus slowing the rate of increase in atmospheric CO_2.
- Global mean sea levels have risen by around 25 cm since 1880 and continue to rise at an accelerating rate.



Global surface temperature anomalies of the Earth (land and ocean) for 1950 to 2019. Anomalies are with respect to the 1961–1990 standard averaging period. Major tropical volcanic eruptions are associated with cooler global temperatures. Strong El Niño–Southern Oscillation (ENSO) years see a response in annual global temperatures, such that the year following the start year of an ENSO event is typically warmer than usual with an El Niño, and cooler with a La Niña. This is seen in 2016—the warmest year in this dataset—which followed the start year of the 2015–16 El Niño. Neutral years are those with no moderate or strong El Niño or La Niña events. Data from World Meteorological Organization.



Global mean CO_2 concentration and global mean of all greenhouse gas concentrations expressed as CO_2 equivalent.

Future

In the coming decades Australia will experience ongoing changes to its climate. Australia is projected to see:

- Continued increases in air temperatures, more heat extremes and fewer cold extremes.
- Continued decrease in cool season rainfall across many regions of southern and eastern Australia, likely leading to more time in drought, yet more intense, short duration heavy rainfall events.
- A consequential increase in the number of dangerous fire weather days and a longer fire season for southern and eastern Australia.
- Further sea level rise and continued warming and acidification of the oceans around Australia.
- Increased and longer-lasting marine heatwaves that will affect marine environments, such as kelp forests, and raise the likelihood of more frequent and severe bleaching events in coral reefs around Australia, including the Great Barrier and Ningaloo reefs.
- Fewer tropical cyclones, but a greater proportion projected to be of high intensity, with large variations from year to year.

Australia's changing climate

Temperature

- Australia's climate has warmed on average by 1.44 ± 0.24 °C since national records began in 1910, leading to an increase in the frequency of extreme heat events.

Australia's weather and climate are changing in response to a warming global climate. Australia has warmed on average by 1.44 ± 0.24 °C since national records began in 1910, with most warming occurring since 1950 and every decade since then being warmer than the ones before. Australia's warmest year on record was 2019, and the seven years from 2013 to 2019 all rank in the nine warmest years. This long-term warming trend means that most years are now warmer than almost any observed during the 20th century. When relatively cooler years do occur, it is because natural drivers that typically cool Australia's climate, such as La Niña, act to partially offset the background warming trend.

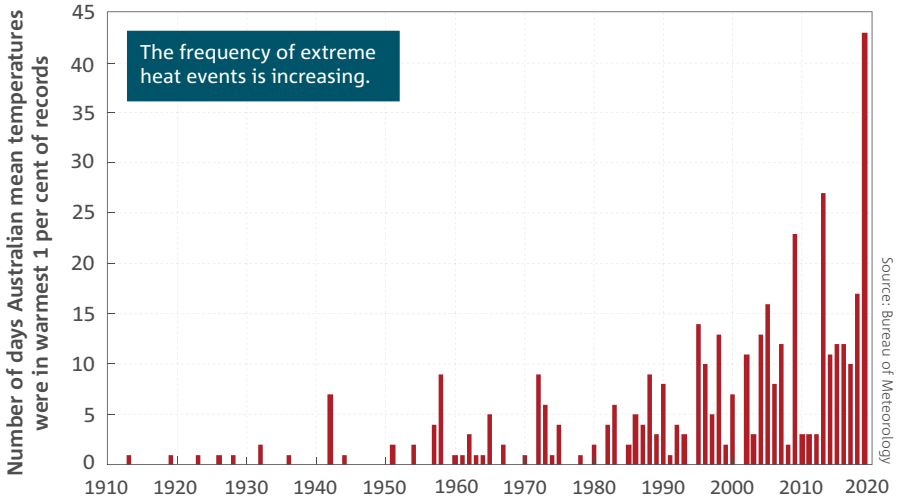
Warming is observed across Australia in all months with both day and night-time temperatures increasing. This shift is accompanied by more extreme nationally averaged daily heat events across all months. For example, 2019 experienced 43 extremely warm days, more than triple the number in any of the years prior to 2000. This increasing trend is observed at locations across all of Australia.

In summer we now see a greater frequency of very hot days compared to earlier decades. In terms of national daily average maximum temperatures, there were 33 days that exceeded 39 °C in 2019, more than the number observed from 1960 to 2018 combined, which totalled 24 days.

Australia's climate has warmed by over 1 °C since 1960, which has caused an increase in the frequency of months that are much warmer than usual. Very high monthly maximum temperatures that occurred nearly 2 per cent of the time in 1960–1989 and over 4 per cent of the time in 1990–2004, now occur over 12 per cent of the time (2005–2019). This is more than a sixfold increase over the sixty-year period. Very warm monthly night-time temperatures that occurred nearly 2 per cent of the time in 1960–1989 and over 5 per cent of the time in 1990–2004, now occur around 11 per cent of the time (2005–2019).

This shift in extremes has many impacts on human health, ecosystems and infrastructure and informs climate impact and risk assessments.

The frequency of extremely cold days and nights has declined across Australia. An exception to this is for extremely cold nights in those parts of southeast and southwest Australia which have seen significant cool season drying, and hence more clear winter nights. The frequency of frost in these parts is relatively unchanged since the 1980s.



Number of days each year where the Australian area-averaged daily mean temperature for each month is extreme. Extreme daily mean temperatures are the warmest 1 per cent of days for each month, calculated for the period from 1910 to 2019.

Fire weather

- There has been an increase in extreme fire weather, and in the length of the fire season, across large parts of Australia since the 1950s, especially in southern Australia.

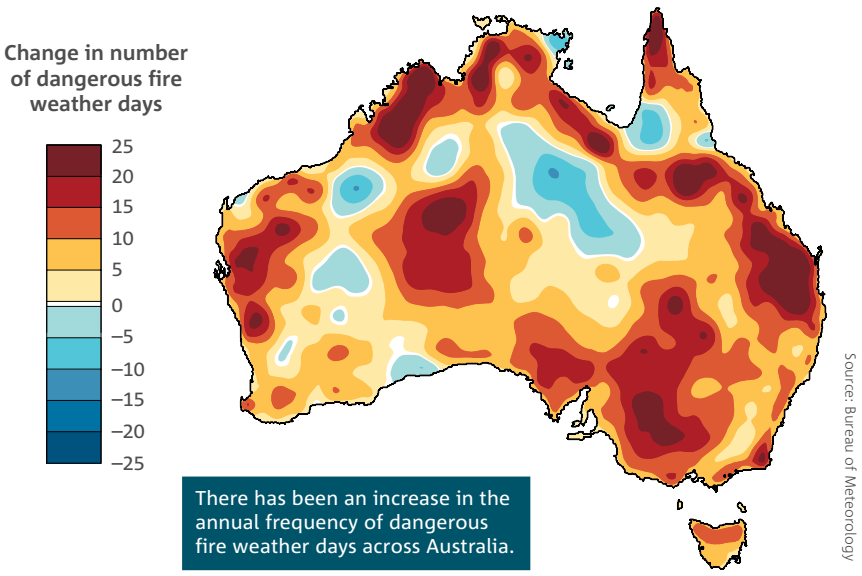
Fire weather is largely monitored in Australia using the Forest Fire Danger Index (FFDI). The FFDI indicates the fire danger on a given day based on observations of temperature, rainfall, humidity and wind speed. The frequency of the most dangerous 10 per cent of fire weather days has increased significantly in recent decades across many regions of Australia, especially in the south and east. These increases are particularly evident during spring and summer and are associated with an earlier start to the southern fire weather season. Climate change is contributing to these changes in fire weather including by affecting temperature, relative humidity and associated changes to the fuel moisture content. Considerable year-to-year variability in fire weather also occurs. La Niña years, for example 2010–11 and 1999–2000, are associated with wet and cool climate anomalies and a lower number of days with high FFDI values.

Dry lightning that occurs without significant rainfall is the primary source of natural ignition for bushfires. Understanding changes to bushfire ignition in Australia is a current area of active research, including the frequency of dry lightning.

There is a significant trend in some regions of southern Australia towards more days with weather conditions conducive to extreme bushfires that can generate thunderstorms within their smoke plumes. These fire-generated thunderstorms can lead to extremely dangerous fire conditions, as observed during the 2019–20 summer, and for the Canberra (2003) and Victorian Black Saturday (2009) fires. In some cases, the lightning strikes produced from the smoke plumes generate new fires.

Climate change influences long-term trends in some of the key risk factors for bushfires in Australia. While the influence of climate change on long-term trends is clear, the attribution of a single fire event to climate change is difficult and is the subject of current research.

Climate change affects the dryness and amount of fuel, through changes in rainfall and air temperature and atmospheric moisture content that exacerbate landscape drying. Furthermore, increased CO_2 can also alter the rate and amount of plant growth, which may also affect the fuel load. Increased frequency and intensity of extreme heat as a result of climate change can also worsen extreme fire weather risk.



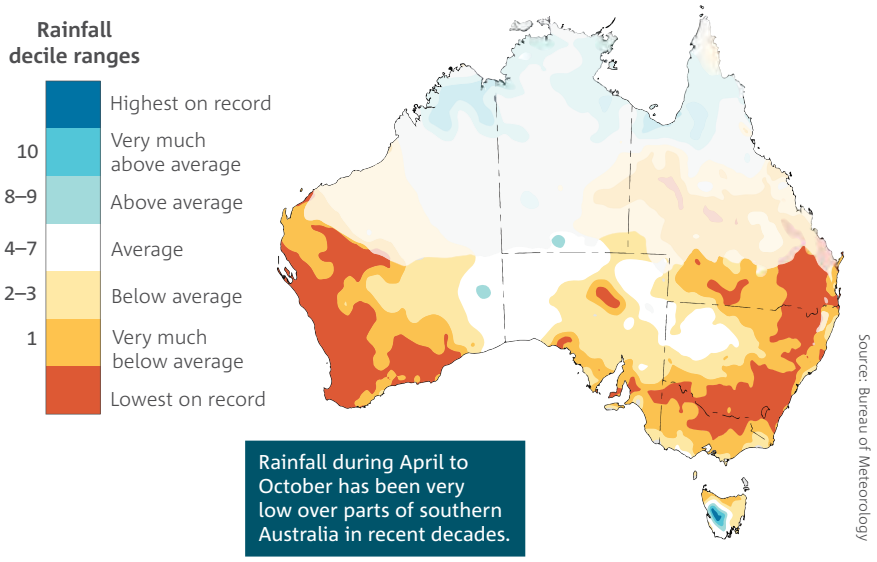
There has been an increase in the number of days with dangerous weather conditions for bushfires. This is based on the change in the annual (July to June) number of days between the two periods: July 1950 – June 1985 and July 1985 – June 2020 that the Forest Fire Danger Index exceeds its 90th percentile, which is an indicator of dangerous fire weather conditions for a given location.

Rainfall

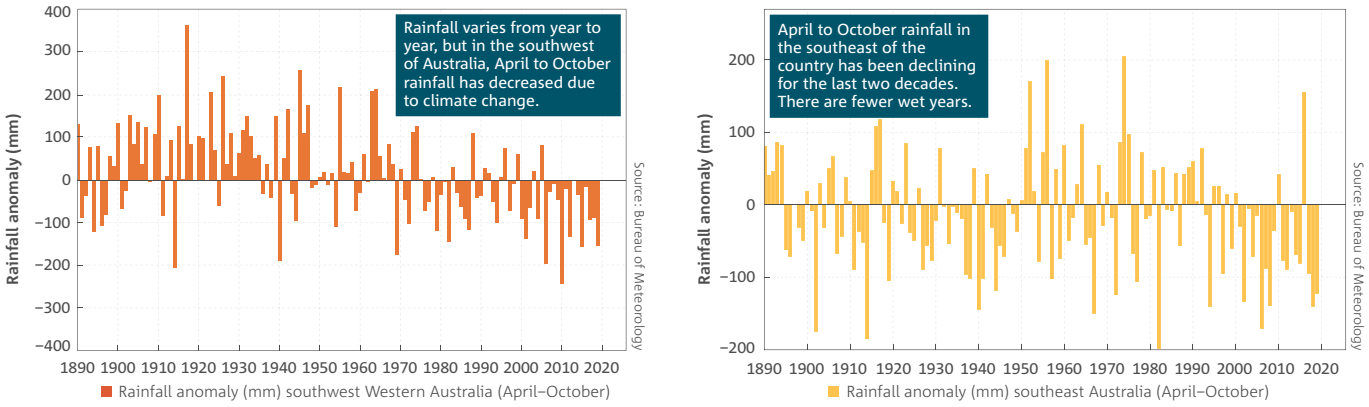
- There has been a decline of around 16 per cent in April to October rainfall in the southwest of Australia since 1970. Across the same region May to July rainfall has seen the largest decrease, by around 20 per cent since 1970.
- In the southeast of Australia there has been a decline of around 12 per cent in April to October rainfall since the late 1990s.
- Rainfall has increased across most of northern Australia since the 1970s.

Australian rainfall is highly variable and is strongly influenced by drivers such as El Niño, La Niña, the Indian Ocean Dipole and the Southern Annular Mode. Despite this natural variability, long-term trends are evident in Australia's rainfall record. There has been a shift towards drier conditions across the southwest and southeast, with more frequent years of below average rainfall, especially for the cool season months of April to October. In 17 of the last 20 years, rainfall in southern Australia in these months has been below average. This is due to a combination of natural variability on decadal timescales and changes in large-scale circulation caused by increased greenhouse gas emissions.

Recent years with above-average rainfall in southern Australia were generally associated with drivers of higher than usual rainfall, such as a strong negative Indian Ocean Dipole in 2016, and La Niña in 2010–11. In contrast to southern mainland Australia, cool season rainfall has been above average in western Tasmania during recent decades.



April to October rainfall deciles for the last 20 years (2000–19). A decile map shows where rainfall is above average, average or below average for the recent period, in comparison with the entire rainfall record from 1900. Areas across northern and central Australia that receive less than 40 per cent of their annual rainfall during April to October are faded.

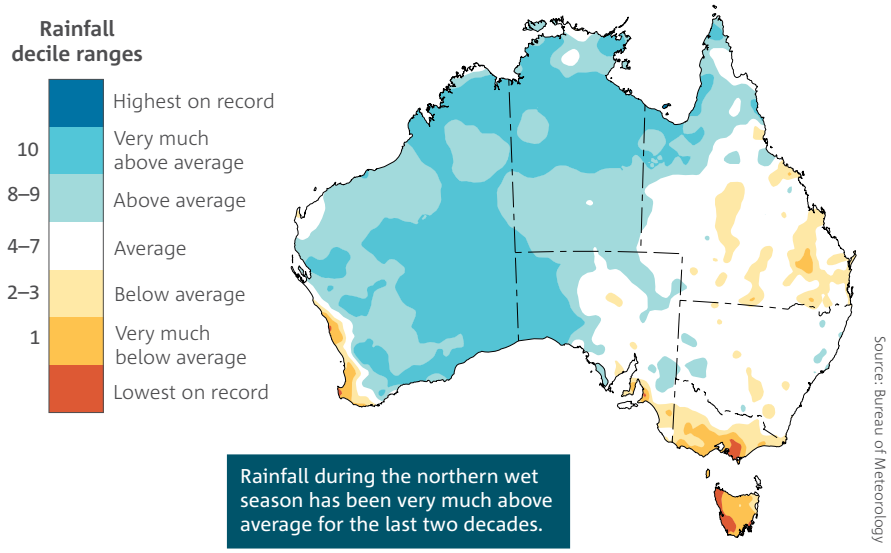


Anomalies of April to October rainfall for southwestern (southwest of the line joining the points 30° S, 115° E and 35° S, 120° E) and southeastern (south of 33° S, east of 135° E inclusive) Australia, with respect to 1961 to 1990 averages.

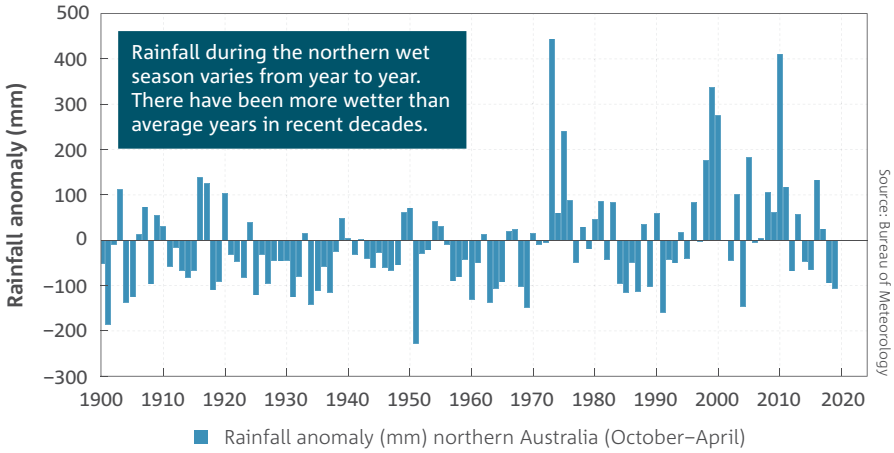
The drying trend in southern Australia has been most evident in the southwest and southeast of the country. Rainfall analyses in these regions can be extended back to around 1890 due to greater data coverage, enabling current droughts to be compared to historical droughts such as the Federation drought (1895 to 1902). The recent drying across these regions is the most sustained large-scale change in observed rainfall since the late 1880s. The trend is particularly strong for the period from May to July over southwest Western Australia, with rainfall since 1970 around 20 per cent less than the average from 1900 to 1969. Since 2000, this decline has increased to around 28 per cent. For the southeast of the continent, April to October rainfall for the period 2000 to 2019 has decreased by around 12 per cent when compared to 1900–1999. This period encompasses most of the Millennium drought, which saw low annual rainfall totals across the region from 1997 to 2009. However, cool season rainfall totals are still around 10 per cent below the 1900–1999 average in the years since the Millennium drought.

The cooler months between April and October are important hydrologically across southern Australia. The declining trend in rainfall during this period is associated with a trend towards higher surface pressure in the region and a shift in large-scale weather patterns—more highs and fewer lows. This increase in surface pressure across southern latitudes is a known response to climate change. There has been a reduction in the number of cold fronts and lows that produce rainfall in both southwest and southeast Australia, which are the most important weather systems for rainfall in these areas during the cool half of the year.

In contrast, northern Australia has been wetter across all seasons, but especially in the northwest during the northern wet season (October to April). However, rainfall variability remains high, with, for example, below average rainfall totals in northern Australia during both the 2018–19 and 2019–20 wet seasons.



Northern wet season (October–April) rainfall deciles for the last 20 years (2000–01 to 2019–20). A decile map shows where rainfall is above average, average or below average for the recent period, in comparison with the entire national rainfall record from 1900.



Anomalies of October to April rainfall for northern Australia (north of 26° S inclusive). Anomalies are calculated with respect to the 1961 to 1990 average.

Heavy rainfall

- Heavy rainfall events are becoming more intense.

Observations show that there has been an increase in the intensity of heavy rainfall events in Australia. The intensity of short-duration (hourly) extreme rainfall events has increased by around 10 per cent or more in some regions and in recent decades, with larger increases typically observed in the north of the country. Short-duration extreme rainfall events are often associated with flash flooding, and so these changes in intensity bring increased risk to communities. This is particularly so in urban environments where the large amount of impervious ground cover (e.g. concrete) leads to increased flooding during heavy downpours.

Heavy rainfall events are typically caused by weather systems such as thunderstorms, cyclones and east coast lows. Daily rainfall totals associated with thunderstorms have increased since 1979, particularly in northern Australia. This is due to an increase in the intensity of rainfall per storm, rather than an increase in the number of storms in general.

At the same time, the number of low-pressure systems that can bring heavy rainfall to heavily populated parts of southern Australia have declined in recent decades. This could have implications for recharging water storages and water resource management.

As the climate warms, heavy rainfall events are expected to continue to become more intense. A warmer atmosphere can hold more water vapour than a cooler atmosphere, and this relationship alone can increase moisture in the atmosphere by 7 per cent per degree of global warming. This can cause an increased likelihood of heavy rainfall events. Increased atmospheric moisture can also provide more energy for some processes that generate extreme rainfall events, which further increases the likelihood of heavy rainfall due to global warming.

Compound extreme events

Climate change influences the frequency, magnitude and impacts of many types of extreme weather and climate events. When extreme weather and climate events occur consecutively within a short timeframe of each other, or when multiple types of extreme events coincide, the impacts can compound in severity. For example, heatwaves can have a larger impact when combined with the stress of long-term drought.

Extreme events are more likely when natural climate variability acts to amplify the background influence of climate change. For example, record-breaking extreme heat and record-breaking fire weather are more likely when the El Niño–Southern Oscillation or the Indian Ocean Dipole favour warmer and drier conditions in Australia, since this reinforces warming and drying trends.

The spring and early summer of 2019 provides a good example of compounding extreme weather and climate conditions and illustrates the effect of background climate trends amplifying natural climate variability. In this period record-breaking low rainfall coincided with extreme heat, and both continued into early 2020. An extreme positive Indian Ocean Dipole and rare Antarctic stratospheric warming in 2019 provided the naturally occurring climate variability that exacerbated long-term climate trends. These combined influences led to severe drought, record-breaking heatwaves and fire weather.

Natural climate variability, which affects Australia's climate from one year to the next, means that not every year will see weather and climate that was as extreme as in 2019. However, the warming trend, primarily caused by climate change, increases the likelihood of extreme events that are beyond our historical experience. Multiple lines of evidence, including from observations and future climate change projections, point to a continuing trend of more frequent compound extreme events. Projecting the occurrence and severity of extreme events is therefore essential for current and future risk assessments, and for climate adaptation strategies and responses.

Streamflow

- Three quarters of hydrologic reference stations around Australia show a declining trend in streamflow.

The observed long-term reduction in rainfall across many parts of southern Australia has led to reduced streamflow. Declines in annual median streamflow have been observed in the Murray–Darling Basin, the South West Coast, the South Australian Gulf, the South East Coast (Victoria) and the South East Coast (New South Wales) drainage divisions. In each of these, between half and three quarters of gauges show a declining streamflow trend since 1975.

In the Tanami–Timor Sea Coast drainage division in northern Australia, which includes Darwin and much of the Northern Territory, there is an increasing trend in annual median flows at about 67 per cent of the gauges since 1975.

This is consistent with the observed increase in rainfall since the 1970s in the region.

In the Murray–Darling Basin, more than three quarters of the long-term streamflow gauges show a declining trend since records began in 1970. This is more severe in the northern Basin where 94 per cent of the gauges show a declining trend in streamflow. In the northern Basin catchments, where these trends are strongly evident, there are statistically significant declining trends in the headwaters, including the Namoi, Condamine–Culgoa and Gwydir River catchments. In the Murrumbidgee, Lachlan, Goulburn and Loddon River catchments of the southern Basin, more than three quarters of the streamflow gauges show declining trends; these trends are statistically significant in one third of these gauging stations. In the Darling River region, declining trends were observed in all 19 streamflow gauges, of which half show a statistically significant declining trend.

Three quarters of Australia's hydrologic reference stations show a declining trend in streamflow, with a quarter of these showing a statistically significant declining trend. Hydrologic reference stations are an indicator of long-term impacts from climate change on streamflow, as they are gauges in catchments with little disturbance from human activities and with at least a 30-year record.

Tropical cyclones

- There has been a decrease in the number of tropical cyclones observed in the Australian region since 1982.

Tropical cyclone activity in Australia's cyclone region varies substantially from year to year. This is partially due to the influence of large-scale climate drivers; the number of cyclones in our region generally declines with El Niño and increases with La Niña.

There has been a downward trend in the number of tropical cyclones observed in the Australian region since 1982. The trend in cyclone intensity is harder to quantify or estimate.

Snowfall

- A downward trend in maximum snow depth has been observed for Australian alpine regions since the late 1950s, with large year-to-year variability.

Downward trends in maximum snow depth have been observed for Australian alpine regions since the late 1950s, with the largest declines during spring and at lower altitudes. Downward trends in the temporal and spatial extent of snow cover and the number of snowfall days are also observed.

Snow depth is closely related to temperature, and the observed declines are associated with the observed warming trends. Maximum snow depth remains highly variable and is strongly influenced by rare heavy snowfall days, which have no observed trends in frequency. Several heavy snowfall events contributed to average to high maximum snow depths in the seasons from 2017 to 2019.

Oceans

Sea surface temperature

- Sea surface temperatures have risen around Australia; the ocean surface has warmed by over a degree since 1900.

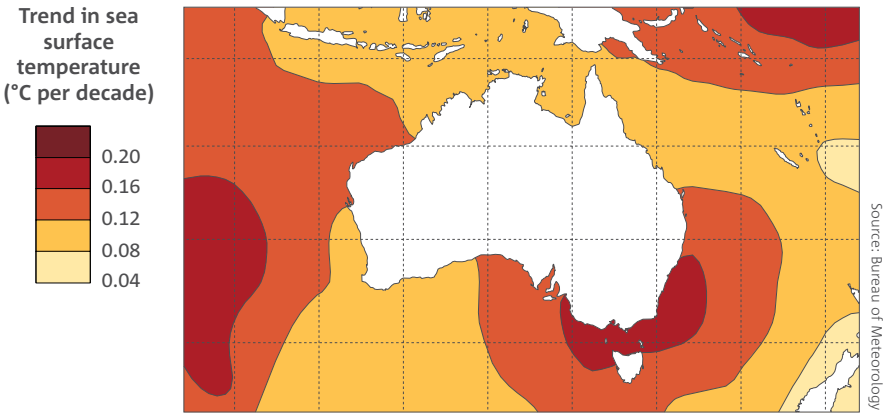
Average sea surface temperature in the Australian region has warmed by more than 1 °C since 1900, with eight of the ten warmest years on record occurring since 2010. The warmest year on record was 2016, associated with one of the strongest negative Indian Ocean Dipole events on record.

The greatest ocean warming in the Australian region since 1970 has occurred around southeastern Australia and Tasmania. The East Australian Current now extends further south, creating an area of more rapid warming in the Tasman Sea where the warming rate is now twice the global average. There has also been warming across large areas of the Indian Ocean region to the southwest of Australia.

Warming of the ocean has contributed to longer and more frequent marine heatwaves. Marine heatwaves are defined as periods when temperatures are in the upper range of historical baseline conditions for five days or more. Heatwaves in the ocean often persist much longer than heatwaves on land, sometimes spanning multiple months or even years.

The increasing frequency of marine heatwaves around Australia in recent years has caused permanent impacts on marine ecosystem health, marine habitats and species. These impacts include depleting kelp forests and sea grasses, a poleward shift in some marine species, and increased occurrence of disease. Recent marine heatwaves are the primary cause of mass coral bleaching and widespread damage to coral reefs around Australia, including the Great Barrier and Ningaloo reefs although other pressures such as tropical cyclones, nutrient runoff and disease also affect the health of some areas of the Great Barrier Reef.

The ocean surface around Australia has warmed, with more rapid warming in oceans to the southeast.



Trends in sea surface temperatures in the Australian region (4–46° S and 94–174° E) from 1950 to 2019.

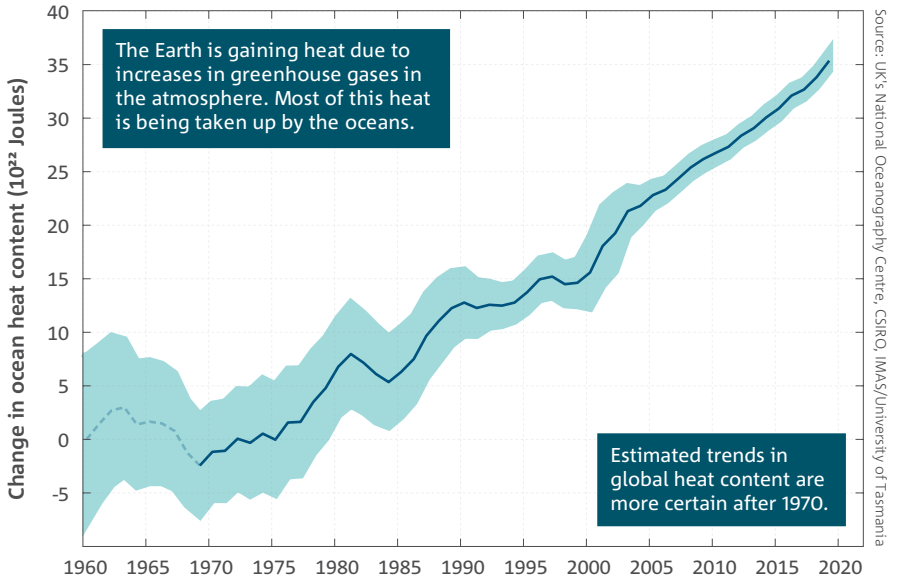
Ocean heat content

- The world's oceans are taking up around 90 per cent of the extra energy stored by the planet as a result of enhanced greenhouse gas concentrations. Measuring changes in ocean heat content is therefore an accurate way to monitor global warming.
- The rate at which the oceans are taking up heat has increased over recent decades.

The world's oceans are a major component of the Earth's climate system and have a profound effect on the climate by redistributing heat and influencing wind patterns.

Sea water stores about four times more heat for every degree of temperature rise than dry air of the same weight. The total weight of water in the ocean is about 280 times greater than the weight of the Earth's atmosphere, so the capacity for the ocean to store heat is vast. For example, if all the extra energy stored in the oceans was released to the atmosphere, the resulting temperature change in the atmosphere would be approximately 1000 times larger than the equivalent temperature change in the ocean.

While the absolute temperature changes over the whole ocean depth are small compared to those at the land and ocean surface, the ocean has taken up approximately 90 per cent of the extra energy from enhanced greenhouse gas concentrations. Oceans have therefore slowed the rate of warming near the Earth's land and ocean surface. Heat absorbed at the surface is redistributed both horizontally and vertically by ocean circulation. As a result, the ocean is warming both near the surface and at depth, with the rate of warming varying between regions and depths.

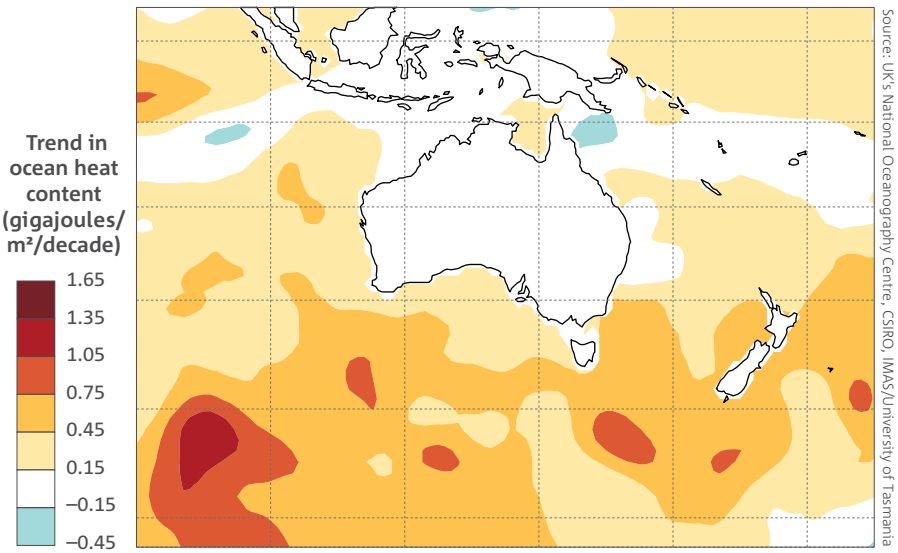


Estimated change in ocean heat content over the full ocean depth, from 1960 to 2019. Shading provides an indication of the confidence range of the estimates. The measurements contributing to the early part of the record, before 1970, are sparse and trends estimated over this period are small compared to the confidence range and hence are considered less reliable.

The rate at which oceans are taking up heat has increased in recent decades. Over its full depth, the global ocean gained 35 x 10^{22} joules of additional heat from 1960 to 2019. Southern hemisphere oceans take up much of the extra heat. This is because the Southern Ocean circulation takes heat from near the surface and transfers it into the deep ocean. A warming ocean affects the global ocean and atmospheric circulation, global and regional sea levels, uptake of anthropogenic CO_2, and causes losses in oxygen and impacts on marine ecosystems.

Long-term temperature trends in the deep ocean, below 2000 metres, show a slow but steady warming. However, there are currently far fewer observations below this depth compared to the upper ocean, so the magnitude of this warming is less certain.

Southern hemisphere oceans have taken up the majority of the extra heat from global warming.



Estimated linear decadal trend in ocean heat content between 1970 and 2019 in the upper 2000 m of the ocean, showing the highest uptake of heat in regions where the circulation draws heat into the deep ocean, such as the Southern Ocean.

Marine heatwaves and coral reefs

Warming oceans, together with an increase in the frequency, intensity and duration of marine heatwaves, pose a significant threat to the long-term health and resilience of coral reef ecosystems. Globally, large-scale mass coral bleaching events have occurred with increasing frequency and extent since the 1970s. Large-scale bleaching is a stress response of corals that occurs primarily in response to elevated ocean temperature. As waters warm, the symbiotic relationship between coral and its zooxanthellae (single-celled organisms that live within the corals) breaks down, eventually resulting in coral bleaching where the zooxanthellae are expelled. Without zooxanthellae, most corals struggle to survive. Recovery is possible, but mortality can occur if the thermal stress is too severe or prolonged.

Bleaching on the Great Barrier Reef has occurred with increased frequency in recent decades. Widespread bleaching occurred in 1998 and 2002, however over the last 10 years three mass coral bleaching events have occurred in 2016, 2017 and 2020. In 2016, bleaching was associated with some of the warmest sea surface temperatures ever recorded which, in turn, led to the largest recorded mass bleaching on the Great Barrier Reef. The impact of the mass bleaching in 2020 appears to be second only to 2016 and was associated with severely bleached coastal reefs along the entire 2300 km length of the Great Barrier Reef.

These three recent bleaching events are associated with marine heatwaves driven by anthropogenic climate change. Rapidly recurring bleaching events do not give the reef ecosystem time to recover from the damage caused by these events.

Climate models project more frequent, extensive, intense and longer-lasting marine heatwaves in the future. Coupled with a background warming of ocean temperatures, this implies more frequent and severe coral bleaching events are likely on the Great Barrier Reef and globally, leading to the potential loss of many types of coral throughout tropical reef systems worldwide. Along with ocean acidification and nutrient runoff, the increased severity and frequency of marine heatwaves are likely to reduce reef resilience and hinder coral recovery from future bleaching events.

Worsening impacts on coral reefs from marine heatwaves are expected in the future with continued warming but the intensification of marine heatwaves is much larger with higher global greenhouse gas emissions.

Sea level

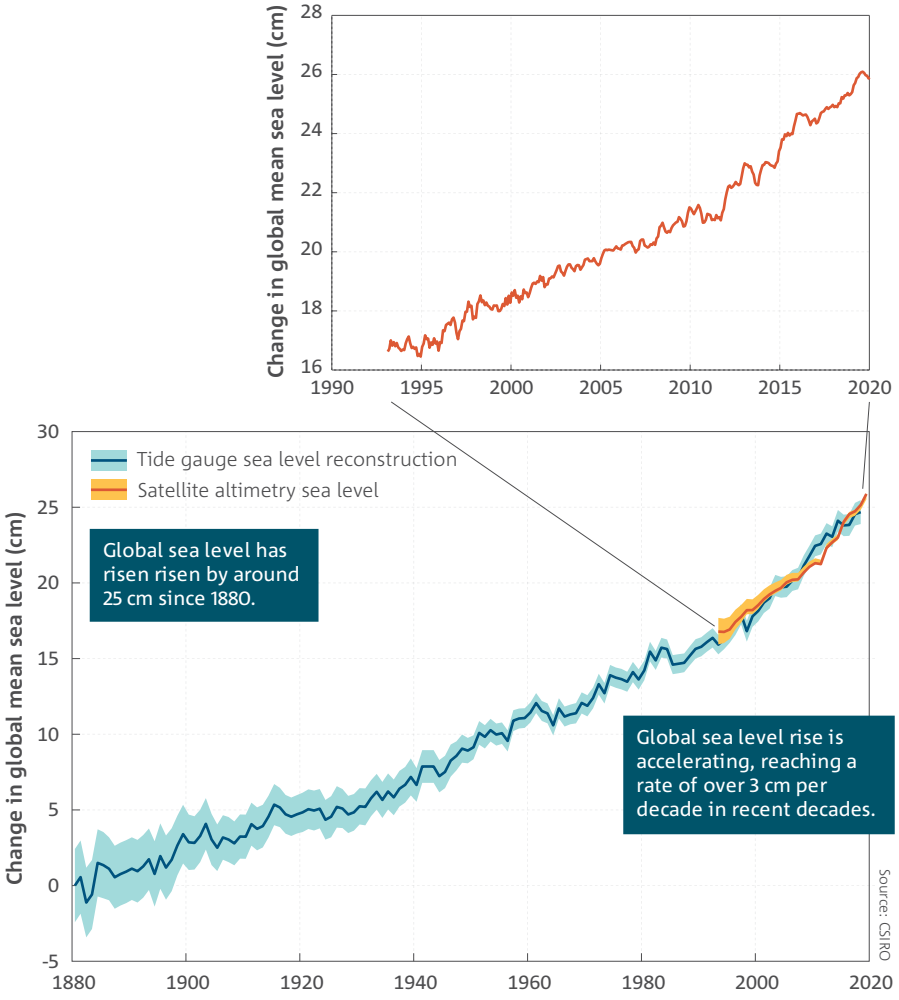
- Global mean sea level has risen by around 25 cm since 1880; half of this rise has occurred since 1970.
- Rates of sea level rise vary across the Australian region, with the largest increases to the north and southeast of the Australian continent.

As the ocean warms it expands and sea level rises. This thermal expansion has contributed about one third of the sea level rise observed globally, around 25 cm since the late 19th century. Ice loss from glaciers and polar ice sheets, together with changes in the amount of water stored on the land, contribute the remaining two thirds of the observed global sea level rise. Ice loss from Greenland, Antarctica and glaciers has been the dominant contributor to global sea level rise from 1993 to the present.

Global mean sea level rise is accelerating. Tide gauge and satellite altimetry observations show that the rate of global mean sea level rise increased from 1.5 ± 0.2 cm per decade (1901–2000) to 3.5 ± 0.4 cm per decade (1993–2019). The dominant cause of global mean sea level rise since 1970 is anthropogenic climate change.

Confidence in assessing changes in mean global sea level has continuously improved because there has been more analysis of satellite altimetry and longer records. Efforts to reliably quantify the various contributions to sea level rise have also led to greater confidence and process understanding.

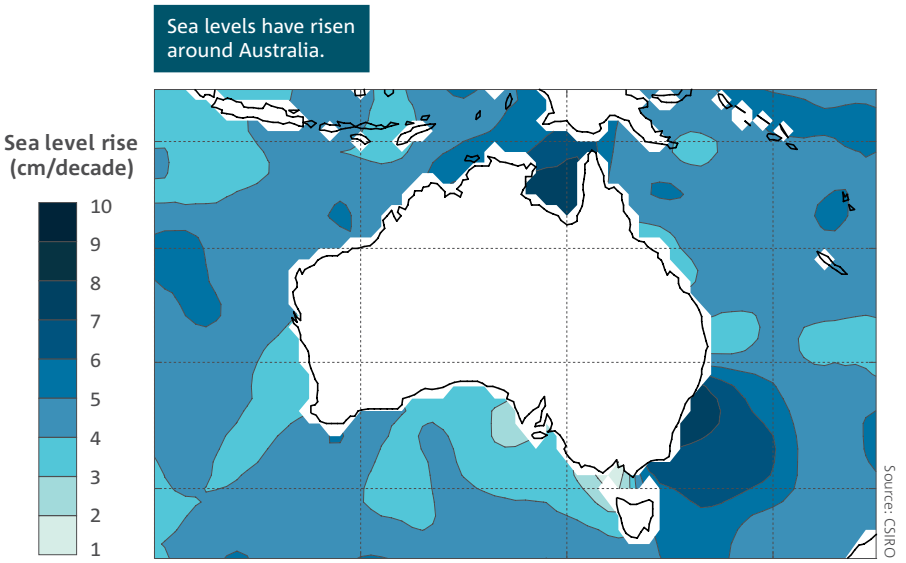
Australia, like other nations, is already experiencing sea level rise. Sea level varies from year to year and from place to place, partly due to the natural variability of the climate system from the effect of climate drivers such as El Niño and La Niña. Based on satellite altimetry observations since 1993, the rates of sea level rise to the north and southeast of Australia have been significantly higher than the global average, whereas rates of sea level rise along the other coasts of the continent have been closer to the global average.



Annual global sea level change from 1880 in tide gauge data (1880–2019, blue line, shading indicates confidence range), and annual sea level change in satellite altimetry (1993–2019, orange line). The pull-out figure shows monthly sea level change from 1880, measured using satellite altimetry from 1993 to 2019.

The long-term altimetry sea level record is typically restricted to the offshore region, beyond 25–50 km, while changes closer to Australia's shoreline are estimated from tide gauge measurements at a limited number of locations. Local coastal processes, the effects of vertical land motion, and changes in site and/or reference levels affect local estimates of sea level change. For example, estimates from nearshore tide gauge measurements may differ from estimates derived from satellite altimetry tens of kilometres offshore. Nevertheless, tide gauges with good long-term records around Australia show overall changes in sea level rise consistent with offshore observations from satellite altimetry.

Rising sea levels pose a significant threat to coastal communities by amplifying the risks of coastal inundation, storm surge and erosion. Coastal communities in Australia are already experiencing some of these changes.



The rate of sea level rise around Australia measured using satellite altimetry, from 1993 to 2019.

Ocean acidification

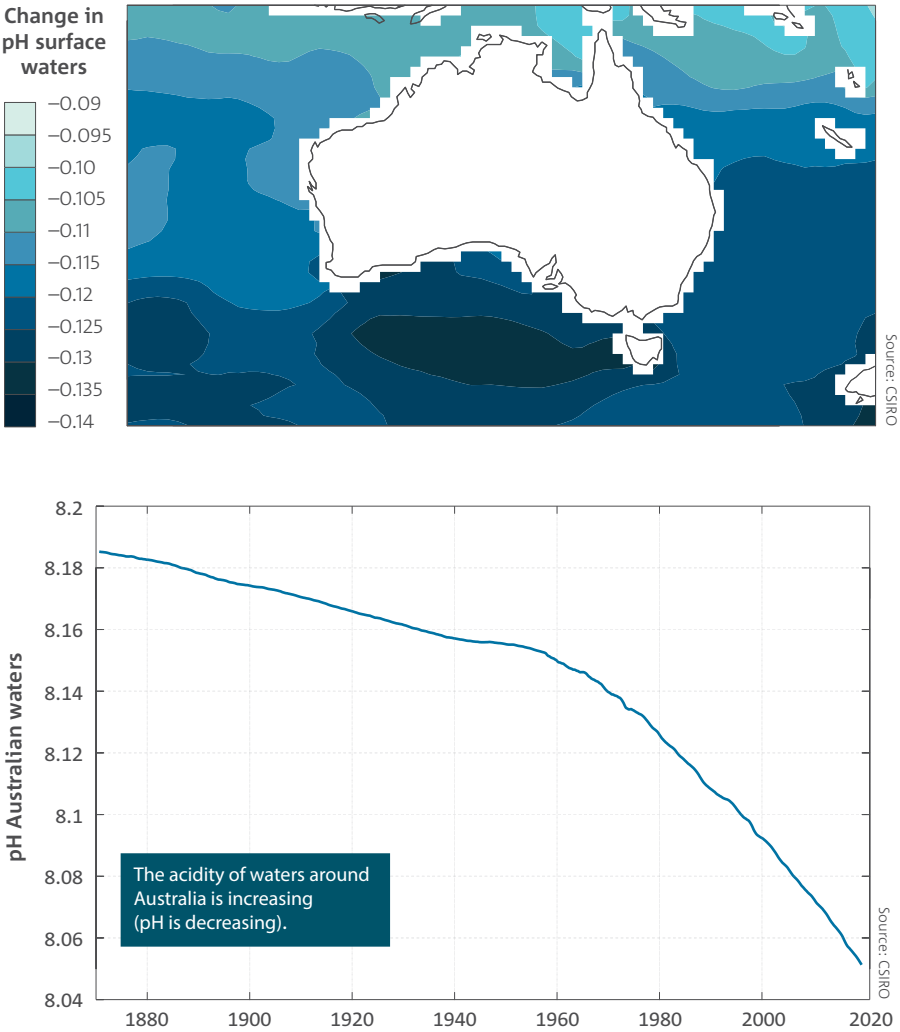
- The acidification of the oceans around Australia continues (pH is decreasing), and the impacts of these changes are detectable in areas such as the Great Barrier Reef.

Rising atmospheric CO_2 levels increase the uptake of CO_2 by the oceans, which affects their carbonate chemistry and decreases their pH; a process known as ocean acidification. In conjunction with other environmental changes, such as ocean warming and deoxygenation, ocean acidification brings additional pressures to the marine environment.

Impacts of ocean acidification to marine ecosystems include changes in reproduction, organism growth and physiology, species composition and distributions, food web structure, nutrient availability and reduced calcification rate. The last of these is particularly important for species that produce shells or skeletons of calcium carbonate, such as corals and shellfish.

Between 1880–1889 and 2010–2019, the average pH of surface waters around Australia is estimated to have decreased by about 0.12. This corresponds to a more than 30 per cent increase in acidity (and so the waters have become less alkaline). Due to latitudinal differences in ocean chemistry, the oceans to the south of Australia are acidifying faster than those to the north.

The rate of decrease in pH has accelerated to over 0.02 per decade, more than five times faster than from 1900 to 1960. This current rate of change is also 10 times faster than at any time in the past 300 million years. These changes have led to a significant reduction in coral calcification and growth rates on coral reefs such as the Great Barrier Reef, which affects their ability to recover from coral bleaching events.



The pH of surface waters around Australia. Top: change between 1880–1889 and 2010–2019, and bottom: the average pH of water surrounding Australia. Calculations are based on present-day data on the carbonate chemistry of surface seawater around Australia from the Integrated Marine Observing System and other programs, and extrapolation of atmospheric carbon dioxide concentration changes since the 1880s.

Cryosphere

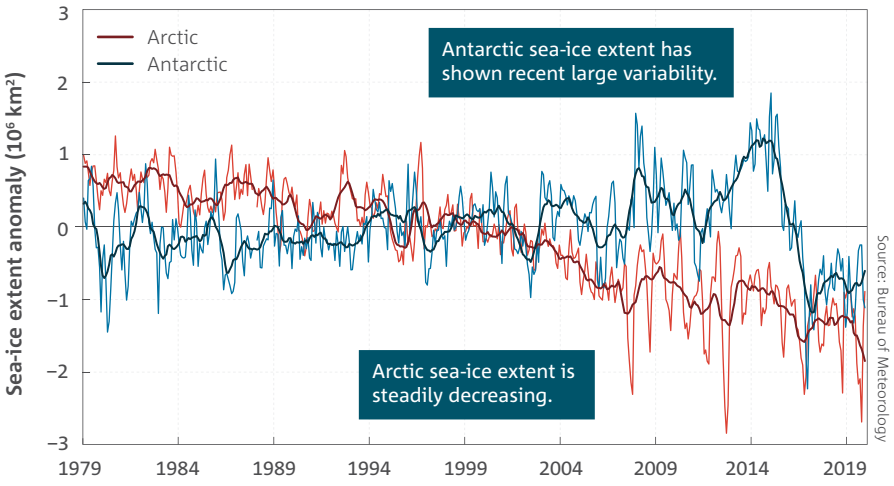
- The ice sheets and ice shelves of Antarctica and Greenland are losing ice and contributing to global sea level rise due to a warmer climate.
- The extent of sea ice in the Arctic has steadily reduced, while in the Antarctic there has been regional and seasonal variability in sea-ice cover.

The Earth's ice sheets—glacial ice that has accumulated from precipitation over land—and ice shelves, which are floating sheets of ice formed from glacial ice sheets, play crucial roles in our global climate system. Ice shelves help stabilise the Antarctic ice sheet by restricting the flow of glacial ice from the continent to the ocean. Warm ocean water penetrating below the ice shelves of the West Antarctic ice sheet is destabilising several glaciers, increasing the Antarctic contribution to sea level rise. Atmospheric warming is also causing surface melting of ice sheets and ice shelves, particularly in Greenland and on the Antarctic Peninsula. From 2003 to 2019, melt from Greenland and Antarctica combined contributed around 1.4 cm of global sea level rise.

Changes in sea ice have little direct impact on sea level because sea ice is frozen sea water that floats. When it melts it returns the original volume of water to the sea. However, the presence or absence of sea ice influences the climate, including the rate of regional climate warming. Antarctic sea ice also acts as a protective buffer for ice shelves against destructive ocean swells. Changes in Antarctic sea-ice cover can also be an indicator of wider climate changes because it is an integrator of ocean, atmosphere and cryosphere components, from local change to the tropics.

Satellite monitoring of sea ice began in the late 1970s. Since then, Arctic sea-ice cover has consistently decreased, whereas net sea-ice cover changes within the Antarctic have been mixed. Overall, Antarctic sea-ice extent showed a small increase from 1979 to 2014, but with substantial regional variations. The largest daily recorded wintertime extent of approximately 20.2 million km^2 was in September 2014.

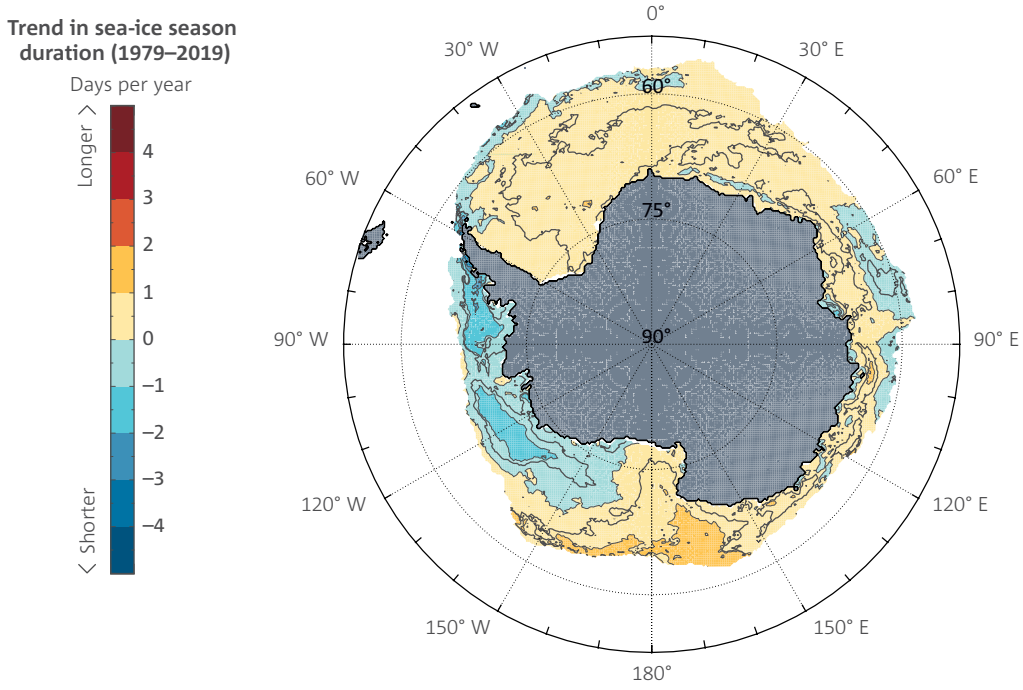
However, since then the sea-ice cover has decreased to below the long-term average, with the lowest recorded daily summertime extent of approximately 2.1 million km^2 occurring in 2017. The overall increase in Antarctic sea-ice extent during 1979–2014 has mostly been attributed to changes in westerly wind strength, whereas the marked decrease from 2015 to 2017 was predominantly related to warming in the uppermost layers of the ocean.



Antarctic and Arctic sea-ice extent (shown as the net anomaly from the 1981–2010 monthly averages in order to remove the seasonal variability) for the period January 1979 to December 2019 (10^6 km^2). Thin lines are monthly averages and indicate the variability at shorter time-scales, and thick lines are eleven-month running averages.

Observed changes in Antarctic sea-ice cover are also regionally variable, as depicted in the trends of yearly sea-ice duration. Statistically significant increases of up to two days per year in sea-ice duration have occurred in the Ross Sea, between 160° E and 150° W. Decreases in sea-ice duration of as much as four days per year are seen west of the Antarctic Peninsula and the Bellingshausen Sea offshore of West Antarctica. Recent sea-ice seasons (since 2015) have shown opposite regional responses to the long-term trend.

Changes in the Arctic sea-ice cover, since 1979, have been more seasonally and regionally uniform than those in the Antarctic, with decreasing trends in all months and virtually all regions. Sea-ice thickness in the Arctic has also decreased steadily over the last few decades, making it easier to break and melt in springtime.



Antarctic sea ice starts expanding in February and retreats from October.

The length of the sea-ice season has increased in some regions around Antarctica, but has decreased in others.

Source: Bureau of Meteorology

Trends in the length of the sea-ice season each year (in days per year) around Antarctica, from 1979–1980 to 2018–2019. Each year sea ice around Antarctica starts expanding in February and retreats from October. Duration is a measure of the number of days that a particular location is covered by sea ice.

Greenhouse gases

- Global average concentrations of all the major long-lived greenhouse gases continue to rise in the atmosphere, with the global annual mean carbon dioxide concentration reaching 410 ppm and CO_2 equivalent reaching 508 ppm in 2019.
- The rate of CO_2 accumulation in the atmosphere has increased with every passing decade since atmospheric measurements began.
- Despite the slow-down in global fossil fuel emissions of CO_2 from early 2020 associated with the COVID-19 pandemic, there will be negligible impacts in terms of climate change. Atmospheric CO_2 continues to rise, and fossil fuel emissions will remain the principal driver of this growth throughout 2020 and likely beyond.

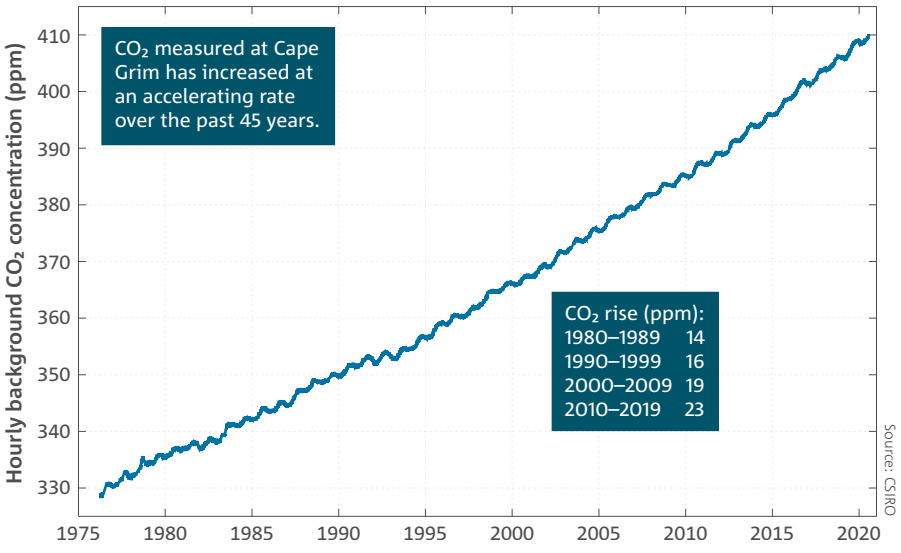
The global annual mean CO_2 level in 2019 was 410 parts per million (ppm), marking a 47 per cent increase from the pre-industrial concentration of 278 ppm in 1750. The rise in atmospheric CO_2 has been caused by emissions from fossil fuel use and land-use changes, leading to increased heat energy in the Earth's climate system.

Cumulative emissions of CO_2 will largely determine the speed and magnitude of global mean surface warming during this century and beyond. By 2019 human activities had already emitted 70 per cent of the cumulative emissions allowed to keep global temperatures below 2 °C warming (since 1850) with at least a 66 per cent chance. Because increased levels of CO_2 and other long-lived greenhouse gases, i.e. methane (CH_4), nitrous oxide (N_2O) and some synthetic gases such as the chlorofluorocarbons (CFCs), persist in the atmosphere for decades to centuries, further warming and sea level rise is inevitable.

The Cape Grim Baseline Air Pollution Station, located at the northwest tip of Tasmania, is a key site in the World Meteorological Organization's Global Atmosphere Watch program. Atmospheric concentrations of CO_2 measured at Cape Grim, like other stations around the world, show a persistent and accelerating upward trend. The annual average at Cape Grim reached 400 ppm in 2016 and climbed to 407 ppm in 2019, slightly lower than the global average.

Cape Grim CO_2 concentrations are generally lower than global averages because most CO_2 sources are in the northern hemisphere and it takes many months for this CO_2-rich air from the north to mix into the southern hemisphere and appear in the Cape Grim observations.

Two significant events from late 2019 and into 2020 have had subtle and opposing effects on the clean air CO_2 signal measured at Cape Grim. The extent and duration of the 2019–20 Australian bushfires burnt a large amount of biomass, making this an unusually large source of CO_2 from the Australian continent for that period. These bushfire emissions marginally accelerated growth in CO_2 concentrations at Cape Grim. Conversely, the impact of the COVID-19 pandemic has reduced fossil fuel CO_2 emissions in many countries, including Australia. Over the first three months of 2020, global CO_2 emissions declined by 8 per cent compared to the same three months in 2019, while global daily fossil fuel emissions were 17 per cent less in early April 2020 compared to the same period in 2019.



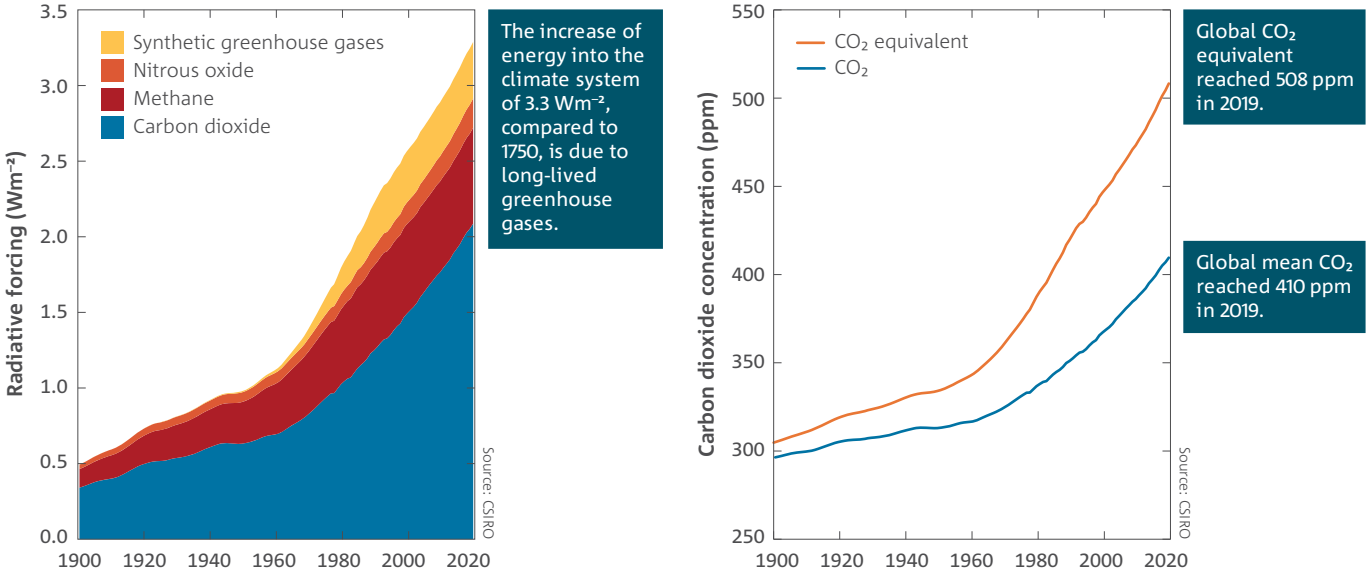
Background hourly clean-air CO_2 as measured at the Cape Grim Baseline Air Pollution Station from 1976 through to June 2020. The hourly data represent thousands of individual measurements. To obtain clean air measurements, the data are filtered to include only periods when air has come across the Southern Ocean and is thus free from local sources of pollution. The increase in CO_2 concentration for each decade from 1980 to 2019 (1 January for the start year and 31 December for the end year) is also shown.

However atmospheric CO_2 is still increasing and reduced emissions due to COVID-19 will likely reduce CO_2 accumulation in the atmosphere by only about 0.2 ppm throughout 2020. This is only about 10 per cent of the recent CO_2 growth rates of 2 to 3 ppm per year and, at most, 20 per cent of the year to year variability (~1 ppm) due to fluctuations in the natural carbon cycle. The effect on atmospheric greenhouse gas levels from COVID-19 related emissions reductions in 2020 will therefore be barely distinguishable from natural variability and negligible in terms of the mitigation needed to stabilise the climate.

Globally averaged atmospheric concentrations of all major long-lived greenhouse gases and the radiative forcing of a group of synthetic (i.e. industry-made) greenhouse gases, continue to rise.

The climate effect of the changes in all the long-lived greenhouse gases in the atmosphere combined can be expressed as an enhancement of the net radiation, or radiative forcing. CO_2 is the largest contributor to this, but other gases also make substantial and increasing contributions.

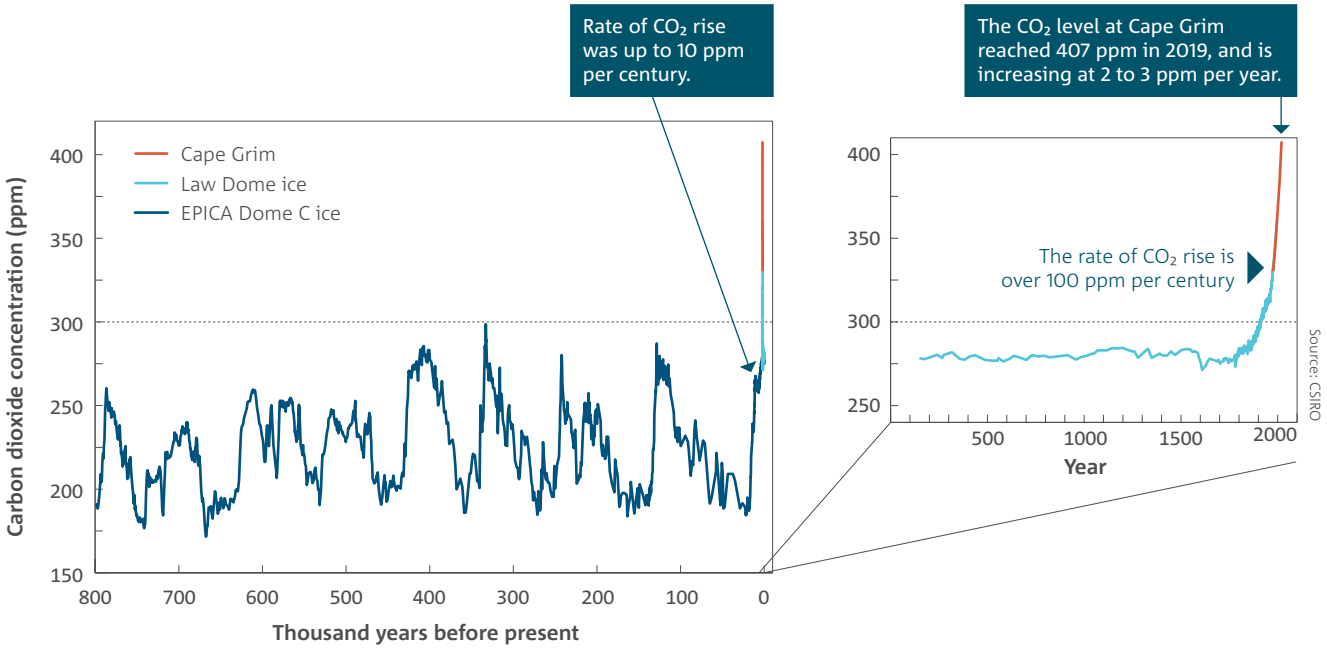
The impact of all greenhouse gases can be converted to an equivalent CO_2 (CO_2-e) atmospheric concentration. The annual average CO_2-e measured at Cape Grim reached 503 ppm in 2019, which is almost twice the pre-industrial level of 278 ppm in 1750. Measurements of the carbon isotopic ratios in CO_2 (that is, carbon-13 and carbon-14, relative to carbon-12) confirm that the increased CO_2 originates primarily from fossil fuel and land clearing emissions.



Left: Radiative forcing relative to 1750 due to the long-lived greenhouse gases carbon dioxide, methane, nitrous oxide and the synthetic greenhouse gases, expressed as watts per metre squared. Right: Global mean CO_2 concentration and global mean greenhouse gas concentrations expressed as CO_2 equivalent (ppm). CO_2 equivalent is calculated from the atmospheric concentrations of carbon dioxide, methane, nitrous oxide and the suite of synthetic greenhouse gases.

Measurements of air extracted from Antarctic ice cores extend the atmospheric composition record back before direct observations. These measurements show that CO_2 concentrations were relatively stable and averaged around 280 ppm for most of the last 2000 years until recently increasing rapidly from about 1850 to present day concentrations.

Over the previous 800,000 years, CO_2 concentrations varied between about 170 ppm during colder glacial periods to nearly 300 ppm during warmer periods like today. Air extracted from Antarctic ice has recently enabled the record to be extended back to two million years ago, at discrete intervals, showing that CO_2 concentrations during the past century are higher than at any time in the ice core record. Even older atmospheric CO_2 concentrations can be inferred from ocean sediments and show that the last time that atmospheric CO_2 concentrations were the same or higher than today was the Pliocene epoch, over 2.6 million years ago, when mean global temperatures were 2–3 °C warmer than today.



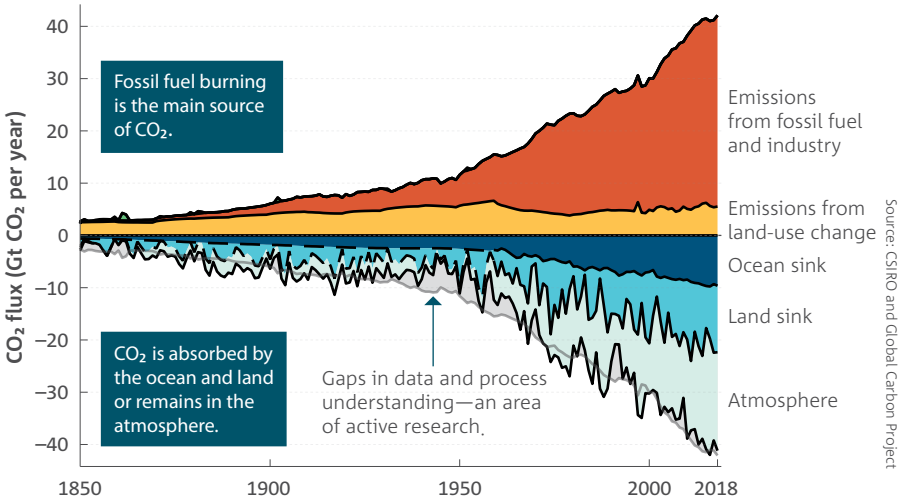
Atmospheric CO_2 concentrations, for the past 800,000 years (left), and for the past 2000 years (right). The time series, and information in the text boxes, are from measurements of air in Antarctic ice cores and at Cape Grim. Though there has been variability in the past, the rate of growth of CO_2 over the past century far exceeds (by a factor of 10 or more) the rate during the most rapid natural changes in the past (which occurred during de-glaciations).

Global carbon budget

Emissions of CO_2 from fossil fuel use and changes in land use have continued to increase. In the decade from 2009 to 2018, average global emissions were 41 ± 2.9 gigatonnes (Gt) of CO_2 per year (one gigatonne is equal to one billion tonnes). Around 85 per cent of global CO_2 emissions were from fossil fuels and 15 per cent from land-use change. Emissions reached an all-time high of 42.9 ± 2.8 Gt CO_2 in 2019. Emissions resulting from land-use change were higher in 2019 than the decadal average due to increased fire activity, particularly in Brazil.

The uptake of carbon into ocean and land sinks has grown in response to the accumulation of CO_2 in the atmosphere. In the decade from 2009 to 2018, the ocean and land sinks removed on average 9 ± 2 and 12 ± 2 Gt of CO_2 per year, respectively. Combined, these sinks are removing more than half of all CO_2 emissions from human activities and thus are slowing the rate of increase in atmospheric CO_2.

Despite this important uptake by the land and ocean sinks, atmospheric CO_2 has continued to increase, growing by 18 Gt CO_2 per year over the decade from 2009 to 2018.



Time series showing the input CO_2 fluxes per year (above zero on plot) from 1850 to 2018 due to emissions from fossil fuels and industry and land-use change; the amount of CO_2 taken up each year by the oceans and land; and the net CO_2 being added each year to the atmosphere.

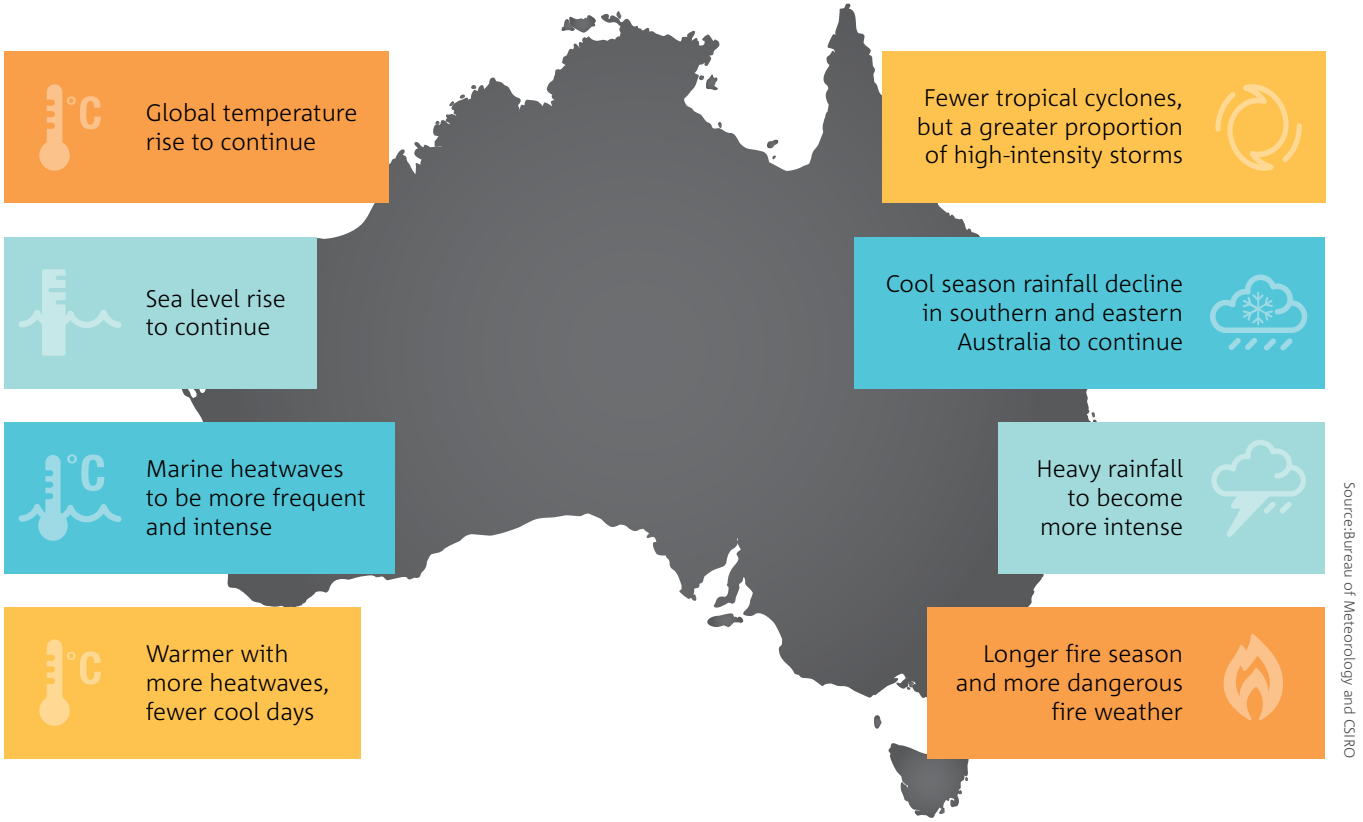
Future climate

A new set of simulations from the latest generation of global climate models are now available, including simulations from Australia's climate model, ACCESS. Analyses show that these new results are largely consistent with the existing projections for Australia at www.climatechangeinaustralia.gov.au, and add new insights. They show that over the coming decades, Australia is projected to experience:

- Continued warming, with more extremely hot days and fewer extremely cool days.
- A decrease in cool season rainfall across many regions of the south and east, likely leading to more time spent in drought.
- A longer fire season for the south and east and an increase in the number of dangerous fire weather days.
- More intense short-duration heavy rainfall events throughout the country.
- Fewer tropical cyclones, but a greater proportion projected to be of high intensity, with ongoing large variations from year to year.
- Fewer east coast lows particularly during the cooler months of the year. For events that do occur, sea level rise will increase the severity of some coastal impacts.
- More frequent, extensive, intense and longer-lasting marine heatwaves leading to increased risk of more frequent and severe bleaching events for coral reefs, including the Great Barrier and Ningaloo reefs.
- Continued warming and acidification of its surrounding oceans.
- Ongoing sea level rise. Recent research on potential ice loss from the Antarctic ice sheet suggests that the upper end of projected global mean sea level rise could be higher than previously assessed (as high as 0.61 to 1.10 m global average by the end of the century for a high emissions pathway, although these changes vary by location).
- More frequent extreme sea levels. For most of the Australian coast, extreme sea levels that had a probability of occurring once in a hundred years are projected to become an annual event by the end of this century with lower emissions, and by mid-century for higher emissions.

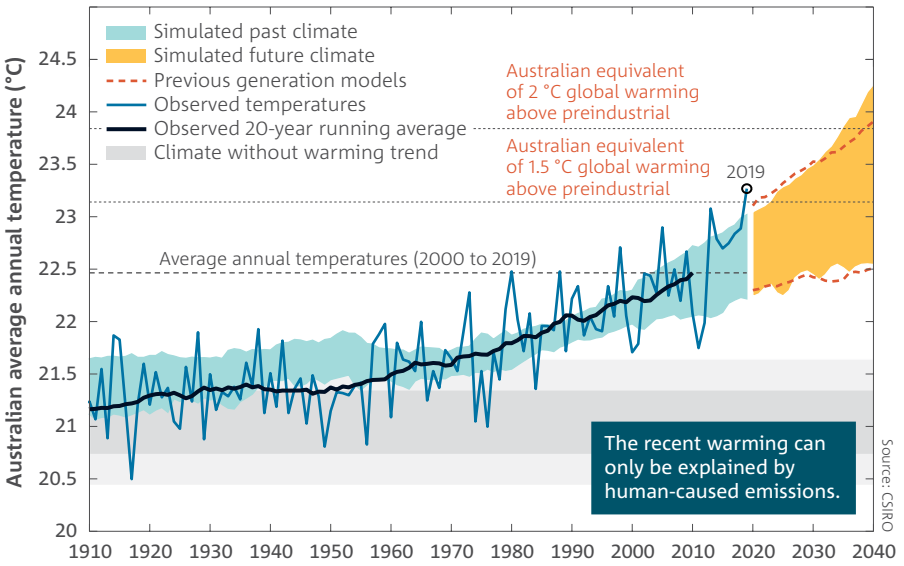
Projections of Australia's average temperature over the next two decades show:

- Every year is now warmer than the range it would have been in a world without human influence, known as climate change 'emergence'.
- The year 2019 was Australia's hottest year on record, due to the combination of climate variability and long-term warming. This is expected to be an average year in a world where the global mean temperature is 1.5 °C above the pre-industrial baseline period of 1850–1900.



Source:Bureau of Meteorology and CSIRO

- While the current decade is warmer than any other decade over the last century, it is also likely to be the coolest decade for the century ahead.
- The average temperature of the next 20 years is virtually certain to be warmer than the average of the last 20 years.
- The amount of climate change expected in the next decade is similar under all plausible global emissions scenarios. However, by the mid-21st century, higher ongoing emissions of greenhouse gases will lead to greater warming and associated impacts, while reducing emissions will lead to less warming and fewer impacts.

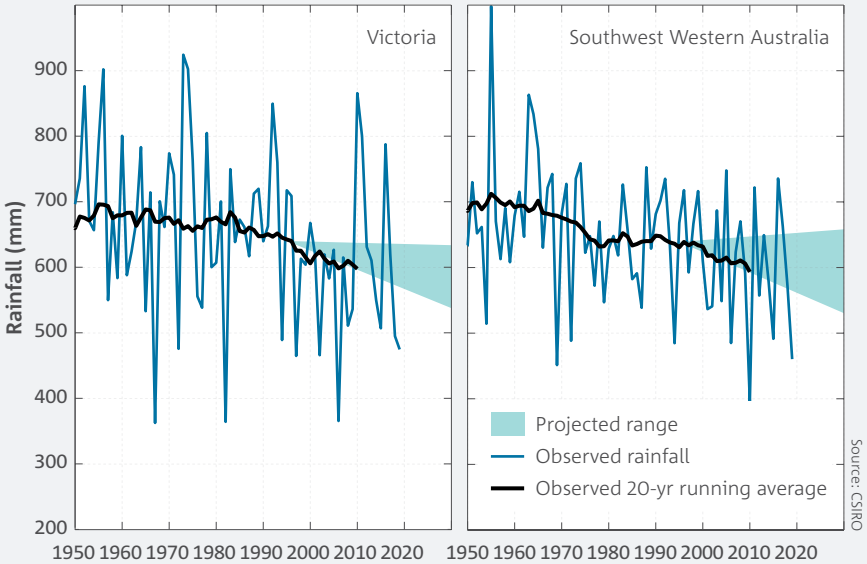


Australian average annual temperature observed and simulated from global climate models. Past and future bands show the range of 20-year running average of new generation climate model results, dashed lines show the equivalent from the previous generation of global climate models. Climate without warming trend shows both an inner and an outer band which are one and two standard deviations, respectively, from the 1850–1900 average, i.e. prior to the rapid growth in greenhouse gas emissions from human activities. The black dashed lines show the Australian equivalent of the global warming thresholds 1.5 °C and 2 °C above the pre-industrial baseline period 1850–1900, equating to warming levels of around +2.1 °C and +2.8 °C respectively, based on the observed ratio of Australian to global temperature of around 1.4.

Evaluation of average annual rainfall projections for Australia

Climate projections are given for a future climate period relative to a past baseline. Recent climate projections estimated changes in rainfall from 1986–2005 to 2020–2039. Now that it is 2020, we can see how the observed rainfall trend is tracking against these projections. This is an indication of their reliability thus far, noting that the projections can't be fully evaluated until the climate of 2020–2039 has emerged in its entirety.

Rainfall in southwest and southeast Australia has been declining in recent decades and is projected to likely decline further, especially in the cooler half of the year. The observed 20-year running average annual rainfall has been tracking the dry end of the projections (even though year-to-year values may fall outside the range), showing that the observed trends are consistent with these projected changes in rainfall. Importantly there is no evidence that the climate projections are overestimating the ongoing drying trend to date.



Evaluation of average annual rainfall projections for two example regions in Australia. Projected range starts at 1995 (mid-point of the 1986–2005 baseline).
Left: For Victoria, projection from the Victorian Climate Projections 2019 VCP19;
Right: Southwest Western Australia, projection from Climate Change in Australia, the national climate change projections for Australia. Southwest Western Australia is defined as a cluster of Natural Resource Management regions covering the southwest of the State; and differs from the area in the rainfall section.

About State of the Climate

The State of the Climate report draws on the latest monitoring, science and projection information to describe variability and changes in Australia's climate.

Changes to our climate affect all Australians, particularly the changes associated with increases in the frequency or intensity of heat events, fire weather and drought. Australia will need to plan for and adapt to climate change.

This is the sixth State of the Climate report. The report has been published every two years since the first report in 2010.

Further information

The Bureau of Meteorology

The Bureau of Meteorology is Australia's national weather, climate, ocean and water agency. Through regular forecasts, warnings, monitoring and advice spanning the Australian region and Antarctic territory, the Bureau provides one of the most fundamental and widely used services of government.

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