Phaseout Pathways for Fossil Fuel Production Within Paris-compliant Carbon Budgets

Tyndall Centre
for Climate Change Research

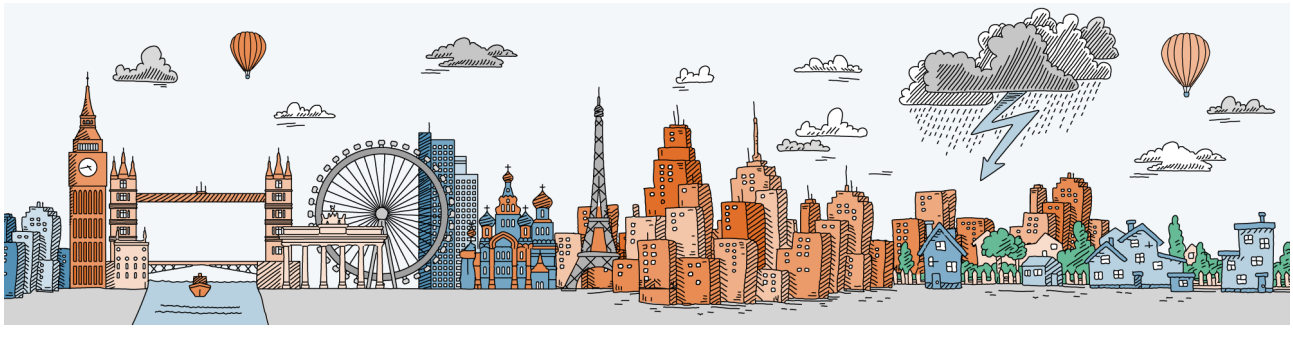
Phaseout Pathways for Fossil Fuel Production

within Paris-compliant carbon budgets

Research Report

Client: International Institute for Sustainable Development
Document ref: Tyndall Production Phaseout Report
Version: Final Text
Date: 11 March 2022

Prepared by: Dr Dan Calverley and Professor Kevin Anderson



About the Tyndall Centre for Climate Change Research

The Tyndall Centre is a partnership of universities bringing together researchers from the social and natural sciences and engineering to develop sustainable responses to climate change. We work with leaders from the public and private sectors to promote informed decisions on mitigating and adapting to climate change. The Tyndall Centre was founded in 2000 to conduct cutting edge, interdisciplinary research, and provide a conduit between scientists and policymakers. With approximately 200 members across career stages, the Tyndall Centre represents a substantial body of the UK's climate change research expertise. Since 2000, the Tyndall Centre has significantly advanced various areas of climate change research and policymaking including: the development of emission reduction pathways for major energy consuming sectors, the understanding of climate impacts, risks and adaptation options, public perceptions of climate change, and the governance of climate negotiations and policymaking. The partnership institutions are: University of East Anglia, University of Manchester, Cardiff University and Newcastle University.

For further information please see www.tyndall.ac.uk.

Acknowledgement:
This research was commissioned by the International Institute for Sustainable Development (IISD). The authors are grateful to Greg Muttitt of IISD for discussion and comments on earlier drafts; likewise to multiple reviewers from international civil society organisations for their feedback and comments. However, all views contained within this report are attributable solely to the authors and do not necessarily reflect the views of IISD, the wider Tyndall Centre or the authors' other affiliated institutions.

Dr Dan Calverley is an independent researcher; Prof. Kevin Anderson is professor of energy and climate change at the universities of Manchester (UK), Uppsala (Sweden) and Bergen (Norway).

Cite as: Calverley, D. and Anderson, K. (2022), Phaseout pathways for fossil fuel production within Paris-compliant carbon budgets. Tyndall Centre, University of Manchester.

Contents

List of Figures & Tables

Headline finding

To comply with the carbon budget for a 50:50 chance of not exceeding 1.5°C of warming requires immediate and deep cuts in the production of all fossil fuels. There are no exceptions; all nations need to begin a rapid and just phaseout of existing production. The report makes absolutely clear that there is no capacity in the carbon budget for opening up new production facilities of any kind, whether coal mines, oil wells or gas terminals. A transition based on principles of equity requires wealthy, high-emitting nations to phase out all oil and gas production by 2034 while the poorest nations have until 2050 to end production.

Key messages

1. The carbon budgets associated with "keep 1.5°C alive" and "stay well below 2°C" imply much more urgent cuts in emissions than any government is considering, and require the rapid and complete phaseout of all fossil fuel production. The maths are clear: for a 50:50 chance of not exceeding 1.5°C, the carbon budget equates to ten years of current emissions. For a 67% or better chance of 1.5°C this falls to just seven years. For a 50% chance of 1.7°C it only increases to eighteen years.
2. There is widespread recognition that coal production must be phased out urgently and that wealthy countries must act first. However, quantifying such a shift in relation to a 50% chance of 1.5°C, with an emphasis on equity, makes clear just how stark this 'urgency' really is. For developed nations, coal production needs to fall by 50% within five years and be effectively eliminated by 2030. For developing nations coal production must halve within a decade with all extraction ceased by 2040.
3. The UN's equity framing of 'common but differentiated responsibility' requires those wealthier nations with economies less dependent on oil and gas revenues lead the way with high rates of closure and early phase-out dates. Poorer nations have a little leeway, with both slower rates of closure and slightly later phaseout dates.
4. The IPCC's headline carbon budget for a 50% chance of 1.5°C places very tight constraints on the production of oil and gas. For the wealthiest group of 'producer nations', with the highest capacity to achieve a 'just transition', output of oil and gas needs to be cut by 74% by 2030, with complete phase out by 2034. For the middle-income group with medium capacity for a just transition, the timeframe extends a little, with a 28% cut by 2030, and a zero-production year of 2043. For the poorest group with lowest capacity, a 14% cut is required by 2030, with all production ended by 2050.
5. There is no practical emission space within the IPCC's carbon budget for a 50% chance of 1.5°C for any nation to develop any new production facilities of any kind, whether coal mines, oil wells or gas terminals. This challenging conclusion holds across all nations, regardless of income or levels of development.
6. From a mitigation perspective alone, it is no longer possible to deliver an equitable division of the small and rapidly shrinking carbon budgets. Although poorer countries have longer to phase out oil and gas production, many will be hit hard by the loss of revenue with an attendant risk of political instability. An equitable transition will require wealthy high-emitting nations make substantial and ongoing financial transfers to poorer nations to facilitate their low-carbon development, against a backdrop of dangerous and increasing climate impacts.

How confident are we in our findings?

It is certainly possible to 'fine tune' some of the assumptions that underpin the quantitative analysis within this report. However, within the tight IPCC carbon budgets for 1.5–2°C, and with serious attention paid to the UN framing of equity, the key messages outlined here are sufficiently robust to provide a strong guide to mitigation policy.

A potential exception to this is whether it is considered appropriate or not to expand the IPCC's carbon budgets through future 'carbon dioxide removal', deployed at planetary scale and principally in the second half of the century. This issue receives careful attention within the report. Specifically, in relation to emissions of carbon dioxide from the energy sector, the inclusion of highly-speculative-at-scale CDR is judged inappropriate, as it works against the tenets of precaution. Moreover, whilst CDR is now ubiquitous in mitigation analyses, the IPCC's estimates of additional feedbacks, potentially reducing carbon budgets, are seldom if ever included. For this analysis, a conservative approach is adopted, neither easing the mitigation burden through CDR nor increasing it through additional feedbacks.

1 Introduction

This section provides the key context and landscape from which the report's analysis is subsequently developed.

The Paris Agreement commits us, as a minimum, to acting to hold global warming to well below 2°C, and in doing so to strive for no more than 1.5°C of warming.

1.1 Commitments, temperatures and probabilities

The 2015 Paris Agreement undertakes to hold "the increase in the global average temperature to well below 2°C … and to pursue efforts to limit the temperature increase to 1.5°C." [1]. The temperature goals of the Paris Agreement are themselves proxies for suites of climate impacts (more accurately, for the rate of change of impacts) and their attendant consequences for people and the wider biosphere[1].

In the years since Paris, evidence has accumulated that the impacts of 1.5°C of warming will likely be more severe and occur much earlier than previously anticipated [2]. The Working Group I (WGI) contribution to the IPCC's Sixth Assessment Report (AR6) published in August 2021 gives a best-estimate of when mean global surface temperature will surpass 1.5°C [3]. This is now expected to fall between 2030 and 2035, in the absence of stringent and rapid mitigation policies.

While the Paris Agreement places an unambiguous obligation on its signatories to limit warming to 'well below 2°C', the language of 'pursue…1.5°C' is rather less imperative. Nevertheless, anticipating the findings of AR6 and recognising the serious threats to life and wellbeing from impacts at 1.5°C, in May 2021 the council of environment ministers of the G7 group of nations published a communiqué explicitly pledging to hold warming to 1.5°C [4].

Since Paris, the case for limiting warming to 1.5°C has strengthened considerably.

The undertaking in the G7 communiqué arguably suggests a higher than 50% probability of restricting warming to no more than 1.5°C. In a similar vein, the November 2021 COP26 event had as its strapline "keep 1.5°C alive" [5]; multiple previous COP events also had a strong focus on 1.5 rather than 2°C. Notwithstanding these clear scientific and political precedents for fortified efforts to limit warming to 1.5°C, the magnitude and rapidity of mitigation action needed to deliver such a target cannot be overstated. The window of opportunity is fast closing for the transformative system-wide decarbonisation needed to achieve even a reasonable chance of not exceeding 1.5°C of warming.

1.2 The logic of addressing production

To achieve the reductions in emissions necessary for staying within 1.5–2°C of warming, fossil fuel use must be urgently curtailed [2], [6], [7]. Clearly,

mitigating the consumption of fossil fuels at the downstream level will have direct and clear implications for the upstream production of those fuels[2]. Without the ability to store significant surpluses of fossil fuels, supply (production) corresponds with demand (consumption).

At the global level, then, annual fossil fuel production and consumption are effectively in lockstep (see §4.1 for more detail). At the level of individual nations, however, there are important differences in the relationship of production to consumption across the three primary fossil fuel types: coal, oil and gas.

1.3 Focus on oil and gas

Oil is used by all countries – regardless of whether they produce it or not.

Oil is currently used in significant quantities by virtually every nation of the world, developed and developing, almost irrespective of each nation's level of oil production. Its prevalence can be attributed to a combination of high energy density, inherent portability and versatility, and an extensive legacy of production and distribution infrastructure. As a highly traded commodity, oil is moved around the world by tanker and pipeline, with production and consumption typically occurring in geographically separated locations, i.e. in different countries, often on different continents.

This is less the case with gas, which although increasingly traded via both pipeline and in the form of LNG (liquefied natural gas), is more costly to move from point of production to distant points of consumption. While gas is used by many countries that do not produce it, these tend to be wealthier, developed countries with long-term sale and purchase agreements with producer nations, and with well-established and high capital cost gas infrastructures.

Coal, as the least energy dense, bulkiest fossil fuel, is far less traded than either oil or gas, hence its consumption is more geographically tied to production. That is to say, coal is not widely used by countries that do not produce it (see §4.3.1 for details on the differences in coal consumption and production patterns across developing and developed nations).

Coal is being targeted for urgent phaseout by international climate organisations.

As a consequence of its lower energy density, coal has much higher CO_2 emissions per unit of useful energy produced[3]. Coal combustion is also responsible for much higher levels of particulate air pollution than other fossil fuels, which are directly hazardous to human health[4]. Thus, ending coal-fired power generation has become the focus of international mitigation efforts, with the Secretary General of the United Nations emphatically calling for its urgent phaseout [8], and many countries declaring moratoria on coal consumption under the banner of the Powering Past Coal Alliance (PPCA) [5].

In this report, we take the growing consensus on coal phaseout as a given. Assumptions about coal are key to establishing the starting position for oil and gas, so are treated early in the analysis (see §4.3). Thereafter, we turn our attention specifically to oil and gas. Less than half of the nations of the world have oil and gas extractive industries of any consequence – a disparity that arises both from the uneven distribution of hydrocarbon deposits in the Earth's crust and centuries of geopolitical wrangling over access rights to those deposits. The world's oil and gas production is therefore highly concentrated and supplied by a minority of nations.

95% of global oil and gas production takes place in just thirty-three countries; 99.7% in eighty-eight. nations.

1.4 Equity in production phaseout pathways

Oil-and-gas-producing nations (hereafter 'producer nations' or simply 'producers') have economies that are, to a greater or lesser extent, dependent on revenue from the extraction and sale of that oil and gas. While mitigation of fossil fuel use must be pursued by all nations (with universal acknowledgement that wealthy, high-emitting nations must make the deepest and most urgent cuts[5]), the economic consequences of diminishing production will be experienced primarily by producer nations.

Ending consumption of oil and gas will economically and socially impact the minority of nations that produce those fuels.

Importantly, within the top eighty-eight producer nations, major disparities exist across a range of indices of economic prosperity, wellbeing and internal inequality. This in turn reveals a wide discrepancy in the capacities of different producer nations to transition away from fossil fuels in as fair a way as possible to those who are currently dependent on fossil fuel production for their livelihoods (a 'just transition') .

These disparities will see some producer countries face much greater difficulty than others in ensuring both a just transition for their extractive workers and the funding of basic development needs of their wider citizenries as they phase out fossil fuel production. These difficulties are most likely to arise in nations where revenue from fossil fuel extraction dominates the economy, and hence where the functioning of much of society is dependent on that revenue. Such precarious positions are exacerbated where there is already a low level of underlying economic development and high internal inequality (expressed as a low IHDI score), or both. These vulnerabilities, and their implications for political stability and the provision of basic needs, must remain a key consideration when detailing specific national phaseout schedules.

Producer nations differ widely in their:
- *dependency on revenue from fossil fuels;*
- *ability (or capacity) to ensure fair treatment for their extractive workers as the world ends its use of fossil fuels.*

In adopting this approach, we remain cognisant of wider equity concerns. For example, the processes of extraction may violate the rights and indeed safety and security of those living nearby. Or, more simply, the benefits of fossil fuel revenue may be confined to a relatively small proportion of a country's

population. Such localised aspects of equity are beyond the scope of this report. Consequently, it is important to understand that the analysis presented here provides 'provisional' phase-out schedules for oil and gas production, and that these may need to be accelerated or delayed depending on country-specific circumstances.

Precisely because of the considerable variation in the capacities of producer nations to deliver a real-world[6] and, preferably, just transition, one phaseout pathway patently does not fit all.

1.5 Why use a production-emissions budget methodology?

Fossil fuels, once extracted, are inevitably burned. Using fuel-specific emissions factors allows conversion of a quantity of fossil fuel produced into its ultimate CO_2 emissions outcome. Note that in this analysis, production emissions refers to the emissions from the ultimate combustion of the fossil fuel at point of end-use, not just the emissions incurred in extracting or processing it (see §4.1 for more details on this approach).

Tonnes of coal, oil or gas produced can be expressed as the amount of CO_2 that will be emitted when the fuel is burned.

Translating fossil fuels into CO_2 emissions allows us to determine the amount of production that would 'fit' into an agreed global carbon budget. Thus, 'production budgets' are simply the amount of fossil fuels, expressed as their CO_2 equivalent, that can be extracted (and subsequently combusted) within a given carbon budget.

Production budgets are fuel-specific and will vary according to the assumptions made about the relative split of coal to oil to gas within the global primary energy mix. Such budgets can be disaggregated to groups of producer nations according to their relative capacity to make a just transition. Finally, national production budgets can be transposed into plausible production phaseout pathways and, ultimately, end dates.

Plausible production phaseout pathways reveal what would have to change in the annual outputs of producer nations if we are to keep within a temperature-derived global carbon budget, while respecting the equity principles of the Paris Agreement.

Our approach differs notably from the majority of contemporary analyses of production in that it proceeds from transparent and sequentially reasoned assumptions about key determinants. For example, we make clear our reasoning and treatment of: coal production, uncertainties around earth systems feedbacks, emissions from land use change, forestry and agriculture, and the presumption of still speculative-at-scale carbon dioxide removal techniques.

Such transparency and wider accessibility is arguably lacking from analyses that utilise integrated assessment models (IAMs) [10]. Most IAMs are complex, cost-optimised models that use assumptions about rising carbon prices, elasticities of demand, discount rates, etc, to drive changes away from

fossil fuels and towards renewables and other forms of low-carbon energy supply. Almost all incorporate (often uncritically) unprecedented amounts of negative emissions technologies (NETs) and/or 'nature-based solutions' (NbS) to remove CO_2 from the atmosphere after it has been released. The majority of IAMs use embedded algorithms designed to deal with marginal (i.e. relatively small) changes near to economic equilibrium and typically informed by historical norms (e.g. existing elasticities of demand and discount rates). They are not constituted to model the immediacy, depth or pace of profound transformation required to stay within the 1.5 °C or even "well below 2°C" carbon budgets.

Most IAMs invoke 'carbon dioxide removal' to capture huge quantities of CO_2 from the atmosphere, after it has been emitted from burning fossil fuels.

Another important point of divergence is that central to our approach is the consideration of equity. IAMs, by contrast, are not configured in a way that can cope with the nuanced reasoning and weighing of contextual factors required to ascertain the 'least unfair' outcomes for disparate constituencies[7].

IAMs do not deal with complex, nuanced issues of equity or fairness.

1.6 The core concepts of precaution and equity

This report takes the precautionary principle as a guide to the development of its methodology and assumptions, recognising that for the past thirty years the collective global response to climate change has been the opposite of this. Disturbingly, reliance on speculative negative emissions technologies and the uncertain manipulation of nature still pervade much of the mitigation debate today. The ubiquitous adoption of carbon dioxide removal (CDR) and carbon capture and storage (CCS) to weaken the rapid phaseout of fossil fuels implied by 1.5°C carbon budgets (see §3.2 below) demonstrates a clear and ongoing rejection of precaution in favour of minimising disruption to the status quo.

1.7 The case for financial transfers

While evoking the precautionary principle, it is important to acknowledge that, to a significant degree, our application of it has necessarily been weakened by our judgement of what is now, in 2022, achievable. This judgement call similarly is played out when considering the fossil-fuel phaseout schedules between the different country groups.

It is the view of the authors that 1.5 to 2°C carbon budgets (see §2.3) are now so depleted that equity between nations cannot be delivered through differential mitigation alone. In this regard, and with practicality still guided by principles of equity, the best that can be achieved is the 'least unfair distribution' of the remaining carbon budget.

It is now too late to deliver equity simply through later phaseout dates for developing countries – financial transfers will be essential.

This is a highly inequitable and far from satisfactory position. In large part this situation has come about because the nations with greatest historical emissions have so far abdicated their "common but differentiated

responsibility" to rapidly cut their emissions. The upshot of this failure is that substantial levels of financial assistance [11] and reparations [12] are now required, if poorer nations are to deal with the climate impacts knowingly imposed on them while simultaneously developing their societies without recourse to ongoing revenue from fossil fuel production.

1.8 Key question for this research

Building on the foregoing context, this research report addresses the following question.

> How, within a given **global emissions budget** aligned with the Paris Agreement goals, could **oil and gas production be differentially phased-out** in producer nations, while taking account of the principle of **equity** as embedded in principle of common but differentiated responsibilities and respective capabilities (CBDR-RC)?

In so doing, we develop phaseout pathways appropriate for countries with higher capacities that are able to make a rapid and just transition at one end of the scale (phasing out production faster), and for countries with lower capacities to transition at the other (phasing out production more slowly – or perhaps more accurately, "not as fast").

The pathways are informed by careful consideration of issues of equity (as captured in CBDR-RC), and all comply with the remaining carbon budgets for given probabilities of specific temperatures consistent with the Paris Agreement goals. We identify what these pathways tell us about the phaseout schedules and the required end dates for production of oil and gas in producer countries. All this is guided by nations' respective dependence on oil and gas revenues and their capacity to rapidly transition away from fossil fuel production.

This analysis uses science-based budgets, carefully reasoned and transparent assumptions about mitigation and a careful consideration of equity.

SECTION FOOTNOTES

[1] While mitigating impacts of climate change is the primary concern of both this report and the Paris Agreement, it is worth noting that the temperature goals of the treaty are situated in the context of wider sustainable development, equity and poverty eradication goals.

[2] It has been argued that from a mitigation perspective it is simpler to deal with a smaller number of supplying entities (whether they be nationalised industries or private companies) than a much larger number of consuming entities (individual end-users). While such arguments may be compelling, this work does not seek to advance nor contradict them.

[3] Both in direct combustion and still more so when used for electricity generation

[4] Historically, the phase out of coal in many wealthy nations has been driven as much by clean air directives as by climate change mitigation. The impact of coal on air quality is now also a serious concern for many rapidly industrialising nations, particularly China and India.

[5] Agreed as part of the 1992 UNFCCC [20] and the attendant principle of CBDR-RC, with the latter remaining central in all subsequent United Nations COPs.

[6] For some nations, oil and gas revenue forms such a large part of the economy that rapidly removing it could destabilise what are sometimes fragile governments.

[7] For example, from a technical perspective, this would require embedding concepts such as the 'marginal value of money' (determined not by modelers in the global north, but by sociological/anthropological analyses of diverse populations in 'poorer' nations) and compensation principles (e.g. Kaldor-Hicks-Scitovsky, including the thorny issue of whether such compensation should actually be paid or simply theoretically possible). These would then need to be considered in relation to key factors in GE models, not just as technical adjustments, but rather informed by much deeper cultural and philosophical considerations of nations where the tenets of GE modelling are far removed from the functioning of such societies. Ultimately, IAMs and GE models are constructs of a particular and highly technocratic worldview, and as such are unable to embed the diverse political economies that comprise and inform the multi-layered process and dialogues feeding into the COP negotiations and agreements.

2 Global carbon budget framing

This section addresses the question: what CO_2 emissions space (expressed as a carbon budget range) is left for global energy use if the temperature and equity goals of the Paris Agreement are to be delivered?

2.1 Cumulative carbon budgets

Carbon budgets delimit the total additional quantity of CO_2 that can be released into the atmosphere for a named probability of not exceeding a given temperature threshold. The WGI contribution to AR6 updates the carbon budgets associated with a range of temperature stabilisation levels from those published in the IPCC's previous major report, SR1.5 [2].

For this research report, three scenarios based on AR6 carbon budgets[8] have been selected to represent:

(i) A 50% chance of staying within 1.7°C. This budget also gives a greater than 83% chance of staying within 2°C, as per the Paris Agreement.
(ii) A 50% chance of staying within (or stabilising at) 1.5°C.
(iii) A 67% chance of staying within (or stabilising at) 1.5°C.

This report revolves around three core scenarios, based on different probabilities of not exceeding 1.5°C and 1.7°C.

The 'headline' budgets in AR6 are for all global CO_2 emissions from the start of 2020 onwards, to cover the rest of the twenty-first century and beyond[9].

2.2 Adjustments to the headline budgets

From the headline AR6 budgets, we now make a series of deductions to identify how much is available for emissions from fossil fuels.

2.2.1 Earth system feedbacks

Earth system feedbacks (ESFs) include positive and negative climate responses to rising temperatures, for example, they may trigger the release of naturally stored greenhouse gases through thawing permafrost, increased frequency and extent of forest fires, or methane released from wetlands [13]. Whereas the budgets presented in SR1.5 did not include ESFs in their headline numbers[10], the AR6 budgets already account for 26 $GtCO_2$ (±97 $GtCO_2$) of ESFs per degree Celsius of warming.

Feedbacks within the climate system have the potential to make the AR6 carbon budgets considerably smaller.

For the purposes of this research, no adjustment has been made to the headline budgets for ESFs. That is, we use the AR6 headline budgets, which have already been reduced by 26$GtCO_2$ per degree for ESFs, with no further adjustment for the ±97 $GtCO_2$ per degree uncertainty range.

However, the scale of these potential feedbacks must always be borne in mind when considering the potential for overshooting the budget and temperature

target. This sobering point is all the more important to recall whenever unproven-at-scale methods of carbon dioxide removal (CDR, see §3, below) are proposed as a means of extending the budget space available for a given temperature and probability.

Though different in character, both CDR and the additional ESFs share high levels of uncertainty. Consequently, from a precautionary perspective, it would be reasonable to expect a family of emission scenarios with carbon budgets reduced in line with the estimates of additional ESFs (97 $GtCO_2$ per °C)[11]. Instead, the four headline scenarios in AR6 all assume the huge roll-out of CDR: three reliant on NETs and one that adopts very significant levels of afforestation. None of the four headline scenarios takes account of the significantly reduced carbon budgets from including the additional ESFs.

In keeping with AR6, we do not adjust the global carbon budgets for possible additional feedbacks within the climate system.

Set within the context of high levels of uncertainty associated with both CDR and additional ESFs, the analysis developed for this report adopts a conservative approach. As such, it uses the AR6 headline budgets, not increasing them through the inclusion of CDR (see section 3) nor reducing them through additional ESFs.

2.2.2 Recent emissions

The Global Carbon Project [5, 6] reports that global CO_2 emissions from fossil fuels (energy and processes) in 2020 were 34 $GtCO_2$, with CO_2 from land use change and forestry (LUCF) adding a further 3.2 $GtCO_2$. Data analysis for 2021 emissions is not yet finalised, but it is expected that 2021 will see a slight rebound of the COVID-19-induced downturn, resulting in total emissions of around 36.7 $GtCO_2$ from fossil fuels and 3.8 $GtCO_2$ from LUCF. We remove this combined 78.5 $GtCO_2$ of emissions in 2020 and 2021 from the AR6 budgets to give values commencing in 2022.

Adjustments are made to the global budgets to account for recent emissions and global cement process emissions.

2.2.3 Global cement production

Following the logic elaborated in Anderson et al's 2020 Climate Policy paper, *A Factor of Two* [16] (hereafter *Factor of Two*), process CO_2 emissions from global cement production is treated here as a 'global overhead'. That is to say, process emissions from cement production are treated as the responsibility of all nations, rather than purely of those developing nations from which the majority of these emissions will arise as they continue to expand and upgrade their infrastructure.

Cement process emissions are a largely unavoidable consequence of creating new infrastructure. We treat them as a global overhead, i.e. the collective responsibility of all nations.

Treating cement process emissions in this way recognises that the remaining carbon budget for all nations has already been affected by the cement-related emissions from previous infrastructure development in wealthy nations. It also applies pressure to innovate and reduce emissions from cement manufacture

for all nations, since all bear the consequences (less emissions space for energy) of ongoing high emissions from cement anywhere.

Acknowledging the very high level of optimism in applying the IEA's Cement Technology Roadmap [17] estimate of growth in global cement production in *Factor of Two*, in our 1.7°C scenario here we adopt a slightly more conservative (but still ambitious) value of 100 $GtCO_2$ to account for cement-based process emissions out to 2075 (the point at which the IEA roadmap posits elimination of all cement process emissions). However, AR6 budgets for a 50% and 67% chance of staying within 1.5°C are too small to admit of this precaution without severely constraining the energy pathways of developing countries. Therefore, in the 1.5°C scenarios a global overhead of 60 $GtCO_2$ is assumed for cement, as in *Factor of Two*, and removed from the post-2022 budgets[12].

Our assumed pathway for cement manufacture is ambitious and will be highly challenging for the industry to deliver.

Note that 100$GtCO_2$ assumes a growth rate in cement production that corresponds to the lowest recorded period of growth in recent years (following the 2008 international financial crisis), while the 60$GtCO_2$ assumes annual growth in cement production at a rate that is an order of magnitude lower than any value recorded since the 1950s. Clearly both are optimistic assumptions. To comply with the much tighter budgets for 1.5°C, all systems, energy and processes alike, are pushed as hard as can be practically conceived, hence we use the highly optimistic 60$GtCO_2$ overhead. In the 1.7°C budget there is a little more space for energy and process emissions alike, so it was deemed appropriate that some of that flexibility should accrue to the cement sector. Hence 100$GtCO_2$ was judged the more suitable overhead.

2.2.4 Global iron and steel production

Steel is a vital construction material, which will inevitably play a large role in expanding the renewable energy networks of all countries. As such, it might be argued that iron and steel production should be treated as a global overhead in the emissions budget, in much the same way as cement process emissions. The explicit focus in this project on fossil fuel production also suggests that metallurgical coal, which is used to make coke for the iron and steel industries, might be considered a global overhead.

High levels of process emissions are not inevitable for iron- and steelmaking, so we do not treat those industries like cement manufacture.

Coke is both a fuel source and a reducing agent in the blast furnace–basic oxygen furnace (BF-BOF) method of primary steelmaking. Process emissions from iron and steelmaking are 12% of direct emissions in the BF-BOF method, specifically 0.3 $GtCO_2$ of 2.6 $GtCO_2$ total direct[13] emissions in 2019 [18].

However, there exist proven, viable alternatives to BF-BOF that do not require the use of coke either as a fuel source or as the carbon-based reducing agent. These include as direct reduced iron (DRI) furnaces and electric arc furnaces

(EAF), with renewable-produced ("green") hydrogen as the reducing agent. Both DRI and EAF are currently in use in several countries and being upscaled. Thus even accepting that BF-BOF is the most common method of primary steelmaking today, its process emissions are (i) a much smaller proportion than in cement making, and (ii) mitigable with readily available, existing technology. For these reasons, process emissions from metallurgical coal for the iron and steelmaking industries is not treated as a global overhead. No further distinction is drawn between thermal and metallurgical coal in this project.

2.2.5 Emissions from global land use change and forestry

In the same way that cement process emissions are treated as the joint responsibility of all the nations of the world, so too we consider emissions from deforestation as a 'global overhead' within the carbon budget. The reasons for this are threefold.

First, wealthy countries have to a large extent already deforested their territories during the process of industrialising their economies. By making land available for agriculture and industry, they have already economically benefited from their own programme of deforestation (much as they have already benefited from emissions from cement for their own infrastructure).

Emissions from deforestation are also treated as the collective responsibility of all nations.

Second, treating deforestation emissions as a global overhead better encourages all nations to assess their own influence on global deforestation activities, such as through finding alternatives to meat-based diets that require large areas of cleared land for cattle ranches.

Third, this approach denies any claim by wealthy, long-deforested nations, to emissions 'credit' – effectively additional budget for energy emissions – from reforestation and afforestation projects, whether in their own territories or abroad. Treating the balance of deforestation emissions as a global overhead, therefore prevents a possible weakening of mitigation in wealthy high-emitting countries that would seek such offset credits.

However, in keeping with *Factor of Two*, it is also assumed that a global mitigation programme compliant with temperature-derived carbon budgets would have to include a vigorous development of forest-based carbon sequestration practices, in tandem with an urgent suppression of deforestation emissions themselves. It is therefore assumed that over the period 2022 to 2100 emissions from deforestation are balanced out by an equivalent quantity of carbon dioxide sequestered from LUCF[14].

We assume that CO_2 emissions from deforestation are balanced out over the century by sequestration from the wider land use sector.

While we consider this zero-sum balancing an optimistic assumption, we note that many mitigation modellers invoke considerably higher levels of optimism in assuming that forests will remove huge quantities of carbon dioxide from the atmosphere over the course of the century (see §3 for discussion of why we adopt a more precautionary approach to carbon dioxide removal). Note that no such assumption about balancing out is made for emissions of non-CO_2 greenhouse gases from LUCF or agriculture, which must be considered the prime candidates for technology-based CDR if and when such technologies become viable and deployed at scale.

We assume that non-CO_2 emissions from the wider land use sector (including agriculture) will remain largely unavoidable during the rest of the century, and must be compensated for.

2.3 Global budgets for scenarios in this project

Taking account of the adjustments to AR6's headline temperature-derived budgets described in section 2.2, we can determine the following range of global budgets for CO_2 emissions from energy only from January 2022 onwards.

Scenario	Headline global budget in AR6, i.e. from start of 2020	Less 2020-21 emissions (budget from start of 2022)	Less cement process emissions (fossil fuel budget)	Years at current emission rate
50% 1.7°C	850	771	**671**	18.3
50% 1.5°C	500	421	**361**	9.8
67% 1.5°C	400	321	**261**	7.1

Table 1: Global emissions budgets and key adjustments under three scenarios.

There is less than ten-years'-worth of current emissions remaining for a 50:50 chance of limiting global warming to 1.5°C.

NB: All budget values in billion tonnes of CO_2 ($GtCO_2$). The budget for 50% chance of 1.7°C is the same as for 83% chance of 2°C.

SECTION FOOTNOTES

[8] AR6, Table SPM.2

[9] CO_2 is atmospherically stable (chemically unreactive), so accumulates and exerts a warming effect for centuries, potentially millennia, to come. The budgets in AR6 are therefore effectively 'forever' budgets, unless and until direct air capture and permanent sequestration of CO_2 is developed and successfully implemented at the global scale.

[10] Table 2.2 of SR1.5 specifies a reduction to the budgets of $100GtCO_2$ over the century to reflect climate feedback uncertainties.

[11] Scenarios could also be developed for an increase in the budgets by 97GtCO_2/°C (as the per the IPCC estimate of additional ESFs), however this would work directly against a more precautionary perspective. In addition, it could be argued that given *all* the IPCC's headline mitigation scenarios adopt significant levels of highly uncertain CDR (effectively expanding the carbon budget), then indirectly at least, the effect of increasing the budget through ESFs should be considered.

[12] For more detail on how the various estimates of growth in global cement production in the IEA Cement Technology Roadmap were applied to real world data on cement production, see *Factor of Two* (section 3.1.1 and Appendix B–Cement in Supplemental Material).

[13] Direct emissions in this case refers to the emissions only from the steelmaking process itself, not the emissions from producing the electricity and heat consumed by the sector.

[14] *Factor of Two,* written in 2019 and published in early 2020, assumed that LUCF emissions would balance out over the course of the century from the start of 2020 onwards. As there is no evidence of emissions from this sector declining in the interim, here we remove LUCF emissions in 2020 and 2021 (see §2.2.2) and assume that the sector is zero-sum over the remainder of the century.

3 What role for Carbon Dioxide Removal and Carbon Capture and Storage?

3.1 The case for CDR and CCS

Since the IPCC's first major report in 1990 and the UNFCCC entering into force in 1994[15] [19], the rates of mitigation needed to *"prevent dangerous anthropogenic interference with the climate system"* [11, p.4] have increased substantially. From 2013 the IPCC's reports began to include explicit carbon budgets for various probabilities of different temperatures [2], [6], [7]. These budgets have provided a means to robustly quantify the widening gulf between real action to reduce emissions on the one hand, and political commitments on climate change on the other.

Mitigation modelling has only started to widely embrace CDR and CCS relatively recently, prompted by rapidly depleting carbon budgets and improved understanding of the severity and onset of likely impacts of 1.5°C.

Coincident with the rapid decline in the remaining carbon budgets, improvements in climate science have led to a reduction in the temperature at which 'dangerous' impacts are forecast to occur [21]. This combination of dwindling budgets and a focus on lower temperatures (i.e. a stronger emphasis on 1.5°C) has prompted many mitigation scenario modellers to include increasing levels of future 'carbon dioxide removal' (CDR) and the deployment of 'carbon capture and storage' (CCS) technologies. Within a given carbon budget, the adoption of CDR reduces the necessary rates of mitigation by effectively increasing the available emissions space. The inclusion of CCS has the effect of reducing the carbon intensity of fossil fuel energy (e.g. the grams of CO_2 emitted per kWh of energy produced) and thereby increase the total quantity of fossil fuels that may be combusted for any given carbon budget.

3.2 Why we do not expand the carbon budgets through CDR

Within this report, CDR, both in the form of 'negative emissions technologies' (NETs) and 'nature-based solutions' (NbS), is not used to increase the size of the remaining carbon budgets. This position reflects several key concerns arising from the almost ubiquitous adoption of CDR within high-level emission scenarios. The following subsections provide a succinct account of why, within this analysis, CDR is not used to expand the emission space available for fossil fuel combustion.

3.2.1 NETs: too speculative for inclusion

As of today, NETs are either in the form of small pilot demonstrators capturing just a few thousand tonnes of carbon dioxide[16] [22], [23] or remain in the imagination of modelers and engineers. Despite this, virtually all high-level mitigation analyses assume that in coming decades NETs will be deployed at huge, planetary scale, increasing significantly post-2050 and extending well beyond the end of the century. Certainly, there is merit in a well-funded research and development programme on NETs. Moreover, provided any

promising designs meet stringent ecological and social sustainability criteria, a rapid process of large-scale testing and subsequent deployment should commence.

Negative emissions technology schemes remain at the scale of small pilot schemes. Their deployment at planetary-scale is as yet hard to envisage.

Such deployment of NETs in a small suite of more exotic scenarios would add an important family of model outputs to complement those using existing technologies and understood processes of social change. However, and despite the fledgling state of NETs, their 'unproblematic' use to remove many hundreds of billions of tonnes of carbon dioxide across the century is now pervasive.

3.2.2 BECCS: ecological and sustainability implications

Within existing models and scenarios, the approach that dominates the NETs assumption is bioenergy with carbon capture and storage (BECCS). In this approach the growing of organic material (biomass) absorbs atmospheric CO_2, with the biomass subsequently combusted as fuel in a conventional thermal power station from which the CO_2 is captured and stored rather than emitted.

Ostensibly BECCS confers considerable advantages to models seeking to cost-optimise their responses to climate change, as it substitutes for other mitigation options deemed to have higher marginal costs. However, the scale of mono-cropped[17] biomass necessary to deliver the billions of tonnes of removal through BECCs imposes considerable ecological and societal risks. In important respects, the cure could be as bad if not worse than the disease. One estimate puts the *"loss of terrestrial species* (from high levels of BECCS) *perhaps worse than the losses resulting from a temperature increase of about 2.8°C above pre-industrial levels."* [24]. Another estimate puts the land take associated with the levels of BECCS in many models at between 380 and 700 million hectares [25], equivalent to one-and-a-half times the combined area of the EU's twenty-seven countries, or up to twice the area of India. Further to such high-profile impacts, BECCS at scale also has major implications for water use, land-rights, global shipping and wider transport demands, as well as those associated with the integrity of carbon dioxide storage.

BECCS is not invoked in this report because of its serious ecological and societal risks.

From the perspective of this analysis, the particular details of returning to a global economy powered, in significant part, by the combustion of plant material with the emissions subsequently captured and buried, is largely beside the point. As noted in §3.2.1, this analysis does not explicitly adopt any form of NETs as a means for directly expanding the available carbon budget space for fossil fuels. Nevertheless, as discussed in §3.2.4 below, some form of CDR is indirectly assumed to compensate for warming arising from those residual agricultural emissions that cannot be eliminated.

3.2.3 Forestry as a 'nature-based solution' to rising emissions

Another approach increasingly mooted as having potential to expand the available carbon budget, and thereby reduce the rates of immediate and early mitigation, is the adoption of high levels of forestry. This typically takes the form of afforestation and reforestation, but in analyses that draw on specialist forestry expertise, notably extends to include the regeneration of degraded forests [26].

While there is certainly significant potential for the uptake of carbon dioxide into additional forestry cover, what is critical for this report is that "*the rates and amounts of net carbon uptake are slow and low compared to the rates and amounts of carbon dioxide we release by fossil fuel combustion. Hence, removal of carbon dioxide from the atmosphere does not compensate for the release of fossil fuel emissions*" [26, p. 10]. This key point was reiterated at COP26. Based on the publication of the 'New Insights in Climate Science 2021' [27], Professor Rockström (one of the report's authors) stated clearly "*we need nature-based solutions, but we cannot use them to slow down the pace of emission reductions from fossil fuels*" [28].

Forestation as a 'nature-based solution' to climate change is not invoked in this report because biospheric carbon is not interchangeable with fossil carbon.

Further to this, the simple reduction of the myriad complexities of trees and forests to one of carbon risks missing a much more nuanced suite of climate-related issues that remain, to an important degree, unsettled[18] [29].

For this report the breadth of forestry-related issues – from how terrestrial carbon is always vulnerable to re-emission (i.e. issues of permanence), through to temporal differences in land and fossil-fuel carbon cycles – are considered sufficient reason to exclude NbS from compensating directly for fossil fuels emissions.

3.2.4 CDR to balance residual emissions from agriculture

A key caveat to the role of CDR in relation to carbon dioxide budgets and fossil fuels is that emissions of all long-lived greenhouse gases need to reduce to zero, or warming from any residual emissions must be compensated for. In this regard, the report's authors acknowledge the vital role of some form of CDR in balancing ongoing warming from residual agricultural emissions of nitrous oxide (N_2O) and methane (CH_4). While such emissions can be significantly reduced from their current rate, they cannot be entirely eradicated. With a rising global population, alongside changes in the climate, rainfall patterns, etc, there will very likely be additional demand for fertiliser use to maintain and potentially increase yields. Overall, a combination of much improved agricultural practices and a fundamental shift away from meat consumption is here assumed to result in total global agricultural emissions in

Ongoing emissions of non-CO_2 greenhouse gases (nitrous oxide and methane) cannot be eliminated from agriculture, even with better technology and practices and shifts in diets.

the order of 4 to 7 $GtCO_2e$/year [30], [31] – not too dissimilar to estimates of future CDR.

This report assumes that CDR has a vital role to play in balancing residual (unavoidable) non-CO_2 emissions from agriculture – but not CO_2 from fossil fuels.

Acknowledging the need for significant levels of CDR to address those emissions impossible to eliminate (in contrast to just 'difficult' to decarbonise) highlights the jeopardy of 'double-counting' such removals to offset emissions from fossil fuels. Thus, the fossil fuel phaseout schedules in this report are developed without recourse to future CDR for the energy system.

3.3 Why do we not expand the use for fossil fuels through CCS ?

The prospect of CCS has, since the late 1970s [32], been proposed as a potential means for reducing the emissions per kilowatt hour of fossil-fuel-fired power generation. More recently, it has also been offered as a technology with the potential to unlock the production of 'blue hydrogen'. However, while CCS has remained central to most orthodox system-level mitigation scenarios, in practice the fossil fuels industries have demonstrated very little belief in its long-term prospects, having constructed just a few small pilot schemes over the past two decades.

In 2010 the IEA's CCS Roadmap (as part of its low carbon 'Blue' scenario) [33] envisaged sixty large scale CCS projects by 2020, rising to around 500 by 2030 and over 1800 by 2050. In its 2021 report, the Global CCS Institute noted there were twenty-seven plants operational, with four more currently under construction [34]. Total capture was estimated at a little under 37 $MtCO_2$, or less than 0.1% of total fossil-fuel CO_2 emissions. If those future plants designated by the Global CCS Institute as in a stage of "advanced development" were all to proceed to construction and then full operation, capture rates could rise by an additional 47 $MtCO_2$, bringing the total to a little over 0.2% of current annual fossil fuel emissions. However, these values include both geological storage and the use of captured CO_2 for 'enhanced oil recovery'. Considering only CO_2 actually stored geologically reduces the 37 $MtCO_2$ to a little over 7 $MtCO_2$, or under 0.02% of energy-related CO_2 emitted in 2021. As for the future projects, and again assuming they are proceed to full operation, then in terms of storage, by 2030 the total is set to rise to around 45 $MtCO_2$, or a little over 0.1% of current emissions [35].

Despite bold promises of its potential, CCS on fossil fuels has yet to deliver more than a few million tonnes of CO_2 actually stored.

All of this is far-removed from the long-standing enthusiasm for CCS as a cornerstone of the decarbonisation agenda. Yet, and despite the long history of over-promising and under-delivering [36], this enthusiasm remains unchecked.

3.3.1 CCS: too little too late

The primary remit of this report is reducing emissions in line with not exceeding 1.5°C. This entails rapid decarbonisation, beginning now and being all but complete within one to two decades. Such a tight timeframe is inconsistent with any realistic interpretation of the roadmaps of CCS-based power generation or blue hydrogen production.

The remaining carbon budget for 1.5°C is too small to allow time for CCS to make an impact on fossil fuel emissions.

Furthermore, power generation is the one area of energy supply where very low or zero carbon alternatives actually exist, and at prices that are already competitive. Adding both the significant capital cost of CCS to existing or even new facilities, alongside the major energy penalty of CCS-based generation (i.e. much higher costs/kilowatt hour), further reinforces the cost-competitiveness (and energy security benefits) of renewables.

As such, bolting on what is in effect an inefficient and expensive filter to prolong the life of fossil fuels is very much an 'end-of-pipe' approach, more reminiscent of the last century than the system-level considerations of this century.

3.3.2 The very high lifecycle emissions of CCS

While it may be possible to reduce operational emissions of CO_2 by around 90%, this still leaves a significant residue of CO_2 released to the atmosphere[19] [37]. Given the need for all GHGs to be eliminated globally, with only residual emissions from agriculture remaining, then the high lifecycle emissions associated with CCS (typically 100–300 gCO_2e/kWh [38]) make it unsuitable for all but very marginal roles.

3.3.3 A tonne emitted from CCS is a tonne that cannot be emitted elsewhere

A further consideration in terms of CCS within the energy system is how low- or zero-CO_2 options for power generation are far more advanced than are the alternatives for fossil fuels in other sectors, particularly transport. Consequently, every tonne of CO_2 emitted from a power station (even with CCS) is a tonne that cannot be emitted from transport or industry. Since electricity generation has many more options for easier and earlier decarbonisation, this misappropriation of the scarce carbon budget works against a system-level transition to zero carbon energy.

3.3.4 The potential merits of CCS on cement

CCS will be needed to mitigate ongoing process emissions from cement, for which there is no ready alternative.

The role of CCS in eliminating process emissions from industry, particularly cement manufacture, is subject to different conditions to that for power generation. As it stands, CCS looks set to be a key technology in addressing

the 4% of global CO_2 emissions released from the chemical reactions in cement production.

3.4 CDR and CCS: summary

In short, this report eschews the substitution of deep cuts in emissions today for CDR and CCS tomorrow. Rather, it faces the mitigation challenges head on, navigating the highly constrained space between an equitable and practical distribution of the rapidly dwindling carbon budgets.

SECTION FOOTNOTES

[15] The UNFCCC was adopted at the UN in New York in May 1992, opened for signatures in Rio in June 1992 and finally entered into force in March 1994.

[16] For example, the new (Sept 2021) Orca power plant in Iceland, which captures around 4000 tonnes of CO_2, or the equivalent of around 0.00001% of global CO_2 emissions from fossil fuels. Ostensibly higher levels of actual removal occur at the ADM bioethanol plant in Illinois in the USA. Here in the region of 0.5MtCO_2/yr have been successfully captured and stored, with the operational capacity to increase to 1MtCO_2/yr [60]. However, there is little full life-cycle information available to determine the net levels of CO_2 removal, with the plant's total CO_2 emissions actually rising in recent years (to over 4MtCO_2/yr), likely due in part to the wider activities it undertakes, but also the energy required for the capture and storage. The ADM plant certainly demonstrates how, when rich CO_2 streams exist from biomass processing, it is possible to capture and store the CO_2. However, the application of CCS on the *combustion* of biomass (or indeed fossil fuels) presents a very different engineering challenge (with much lower concentrations of CO_2 and more contaminants), yet it is this approach that dominates the high-level mitigation models.

[17] Or at least a crop with very limited biodiversity.

[18] For example, issues of albedo and 'volatile organic compounds' (VOCs). See [29] for more details.

[19] Sustained capture rates above 90% are theoretically possible, but would very likely go along with a significant increase in both indirect greenhouse emissions and cost.

4 Splitting the global carbon budget between fossil fuel types

This section explains the key methodological assumptions and reasoning used in this analysis to estimate production-specific emissions budgets.

4.1 Rationale for 'production budgets'

This project is primarily concerned with the production side of the emissions equation. At the global level, annual production is in lockstep with annual consumption of fossil fuels. That is to say, fuel is extracted in quantities more or less equal to the market consumption of that fuel. This is largely because of physical and economic limits on storage, whereby there is simply not capacity to store significant surpluses of fossil fuels over and above the national capacity buffers that are held as a matter of course. What limited additional storage facilities exist are filled to capacity by as little as a few months' surplus production for oil and gas [39], or a few weeks for coal [40]. Oversupply therefore leads to falling prices and rapidly scaled down production volumes. The empirical data on annual production and consumption volumes neatly bear out this one-for-one relationship[20].

Fossil fuels cannot be stored in large quantities, so annual production and consumption globally are closely related.

At the global level then, for all practical purposes, fossil fuel production and consumption are equivalent. It is therefore taken as a premise of this work that whatever quantity of fossil fuels is produced in a given year is consumed in that same calendar year[21]. By applying an appropriate emissions factor to each fuel type, one can then calculate the amount of CO_2 that will be released into the atmosphere when the relevant quantity of produced fuel is combusted. Physical restrictions on storing excess production are again relevant here. Since significant surplus production cannot be stored, and apart from the very small fraction of fossil fuels that is diverted to non-energy end uses (and, importantly, that are not combusted at end of life – see §4.1.1 below), it is a matter of inevitability that, once extracted, a fossil fuel will be combusted.

Once extracted, fossil fuels are inevitably combusted.

This being so, the global budgets for CO_2 (Table 1) from fossil-based energy use can be straightforwardly applied to fossil fuel *production* at the global level just as well as to consumption. By translating production volumes into their inevitable emissions outcome using appropriate fuel-specific emissions factors, one can quantify the maximum amount of fossil fuels that may be extracted globally while respecting given temperature-derived carbon budgets [41]–[44].

Global CO_2 budgets for consumption can easily be applied to production.

A complete dataset of the total quantities of each fuel type produced and consumed, in thousands of tonnes of oil equivalent (ktoe), for two-hundred-and-thirteen countries was compiled from the IEA's World Summary Energy Balances 2020 [45]. The most recent year for which a complete dataset was available for both production and consumption of fossil fuels was 2018. It is

this year, therefore, that forms the baseline for all subsequent comparisons and pathway development in this project, unless otherwise stated. The energy equivalent values from the IEA were then converted into their emissions equivalent using IPCC emissions factors[22].

Fossil fuel production is usually expressed in units of energy or volume. Using appropriate emissions factors, these quantities can be converted into their equivalent CO_2 emissions.

4.1.1 Non-energy end uses of fossil fuels

Non-energy use refers to those fossil fuels used as raw materials in the manufacture of physical products rather than direct combustion for energy generation (as heat, electricity or motion). Globally, non-energy use averages around 6.4% of total energy supply [46], with the non-energy percentage of oil and gas being slightly higher and coal substantially lower than the aggregate. While this is a non-negligible fraction of the total quantity of fossil fuels extracted each year, it would be misleading to suppose that 'non-energy use' (or sometimes 'non-combustion end use') means that the feedstocks do not ultimately result in CO_2 and other GHG emissions.

It is an open question exactly what portion of non-energy end use fossil fuels are sequestered in stable form as physical products, buildings or infrastructure (such as roads). However, a large proportion of non-energy fossil fuel use is ultimately incinerated at the end of the useful life of the products[23]. Around one quarter of plastics produced annually is incinerated, which releases embedded carbon to the atmosphere[24]. Even the heavy hydrocarbons in road materials such as asphalt and bitumen undergo slow biodegradation in situ, which also gives rise to CO_2 emissions.

As a general principle, this project adopts a pragmatic but precautionary approach to uncertainty, which is appropriate in view of the high uncertainties around earth system feedbacks in the AR6 carbon budgets, and around the consequences of short-term overshoot of given temperature thresholds. Therefore, at the global level, we assume the total quantity of fossil fuel production to be equivalent to the emissions from combusting that same quantity of fossil fuel in any given year. In any case, the proportion of non-energy use fossil CO_2 that remains permanently locked up in durable products is considered too small to materially affect the outcome of the analysis here.

The amount of fossil fuels diverted to non-energy end uses and which remain unburned is negligible from a global carbon budget perspective.

4.2 Phaseout schedules, end dates, pathways and budgets

The remit of this research was to identify appropriate phaseout schedules for oil and gas production in order to comply with specific temperature-constrained emissions budgets. While the concept of an 'end date'[25] can be useful for policymaking, it must be treated with a degree of caution. Put bluntly: the climate is indifferent to the end year for production (or indeed consumption) of fossil fuels; it takes notice only of the cumulative quantity of carbon added to the atmosphere over and above pre-industrial levels. As such,

whether fossil fuels end in 2030 or 2080, what matters is not the end date *per se*, but the total emissions released into the atmosphere up to that point.

When we plot annual emissions associated with production or consumption of fossil fuels on a graph, the line or curve that joins the yearly amounts is known as the emissions pathway (sometimes, emissions trajectory). The pathway is how annual emissions vary (ideally decline) over time until they reach the final zero date, or some other specified end point. In this regard, end dates are a function of the available carbon budget and the rate at which it is depleted over time.

End dates for production (or consumption) mean little without an accompanying budget and pathway.

There is a wide variety of emissions pathways that can lead to the same end date or zero year (see Figure 1 below), but they describe very different cumulative emissions burdens, which in turn have very different consequences for global warming. Thus, the production end dates assessed in this study are relevant to a given climate outcome *only if* the stated pace of emissions reductions (expressed as the pathway) between now and that year is adhered to. If mitigation were to lag in the short term, then the 'end date' would have to come earlier to stay within the overall carbon budget.

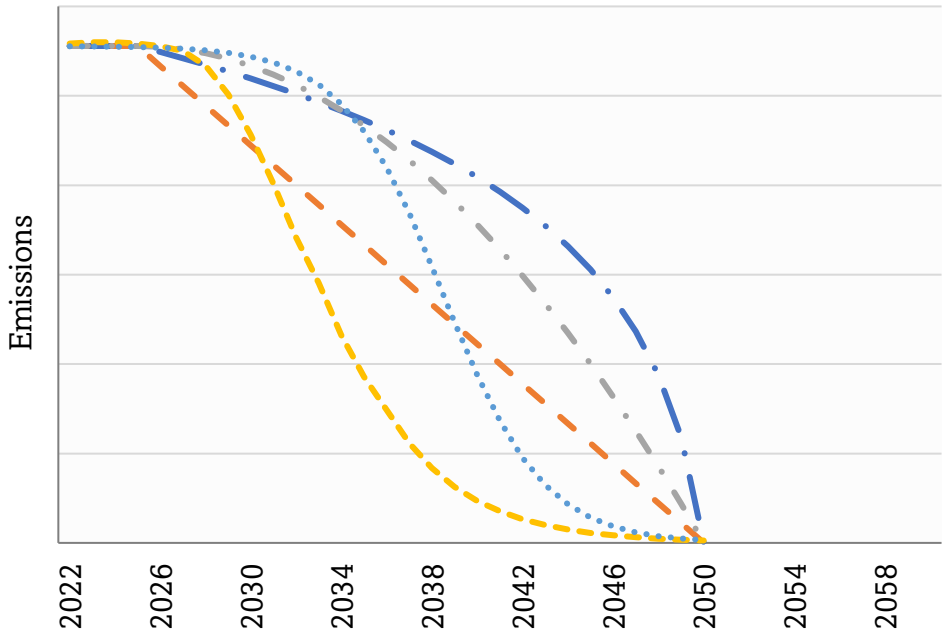


Figure 1: Example of five stylised emissions pathways with the same end year, but with markedly different cumulative emissions.

Strikingly different budgets and pathways can have the same end date. The climate is sensitive only to the cumulative emissions, or budget.

Nevertheless, given the constraints of small and dwindling carbon budgets for desirable probabilities of 1.5°C and 2°C, the variety of *plausible* pathways for emissions from fossil fuel production is limited. That is to say, there is virtually no scope for increasing emissions in the short term without requiring overnight cessation of emissions at the 'eleventh hour'. For the smaller

budgets, there is no scope for anything but immediate deep and rapid reduction in emissions from all forms of production, without bringing the world's energy system to a socially devasting 'hard stop' once the budget is all too quickly consumed.

There are few plausible pathways that are still compatible with 1.5°C. Since we can't end fossil fuel emissions overnight, pathways must show year-on-year reductions.

Thus, the envelope of viable pathways for a given budget with a given zero year is effectively constrained by the imperatives of:

(i) ensuring an ecologically sustainable energy supply for the post-fossil era; and
(ii) ensuring a just transition for those whose livelihoods currently depend on fossil fuel extraction; and
(iii) ensuring viable and ecologically sustainable pathways broadly consistent with the tenets of CBDR-RC.

How these considerations feed into the formation of plausible pathways for ending fossil fuel production is discussed in more detail in section 6 below. There we look at fundamental principles of equity and methods for estimating the differing capacities of producer nations to facilitate a just transition away from fossil fuel production for their societies. For now, it is sufficient to remember that when we get to zero production matters less than how we get there.

4.2.1 Heuristic, not predictive, pathways

The pathways in this report are illustrative rather than precisely prescriptive for individual nations.

Another important point to note about all the pathways presented in this report is that they serve as heuristic tools to understand the relationship between annual emissions (associated with a specified activity) and the global emissions budgets associated with given temperature targets. They are not intended to prescribe precise budgets or pathways for specific nations, but rather to explore the consequences of certain trends and policies.

A key advantage of such relatively simple heuristic pathways is that they render transparent both the problem of fitting production within the remaining global emissions budget, and the assumptions involved in robustly addressing that problem. This stands in contrast to highly complex and inaccessible bottom-up system models.

4.3 Coal budgets – a necessary first step

A key assumption for this analysis was that coal, as the most carbon intensive and least energy efficient fossil fuel type, should be phased out as a higher priority than oil and gas. Coal-fired electricity generation has already been phased out in a number of industrialised, wealthy countries that once relied on it. Building on this, there is now a growing political consensus that in order

to address the climate emergency coal must be phased out as a priority in all countries that continue to use it [8].

To estimate how much emissions budget there is left for oil and gas, we first looked at how quickly coal production could realistically be phased out .

While the main focus of this analysis is oil and gas production, establishing implications of possible phaseout schedules for coal was an important preliminary step in determining the carbon budgets and functional end dates for oil and gas.

4.3.1 Coal production in Developed and Developing Countries

It is important to note that coal is both produced and consumed disproportionately by the poorer countries of the world. Using the categorisation developed in *Factor of Two* for classifying countries as 'Developed' or 'Developing'[26], 72% of coal *production* occurred in the group of Developing nations in our baseline year (2018), with 28% in Developed.

Coal is both produced and consumed disproportionately by developing countries.

As a side-note, this analysis also showed that 74% of coal energy was *consumed* in Developing countries. The small net transfer of coal from Developed to Developing countries notwithstanding, levels of domestic coal production and consumption are closely related for most countries that have any significant proportion of coal in their primary energy mix. Put simply, countries that use a lot of coal tend to be those that have a lot of coal reserves. Coal is much less traded internationally than oil or gas – a simple consequence of its comparatively greater bulk and mass (and hence higher transport costs) than for the quantity of oil or gas with equivalent energy content.

Developing countries' favouring of coal consumption as a 'fuel of choice' may be attributed a range of factors, including: the lack of available and affordable alternatives to coal-fired power generation; limited access to capital for new technology; and the urgent need to increase energy consumption to address issues of poverty.

4.3.2 Coal pathway assumptions

Coal phaseout was pushed as hard as we judged it possible to deliver.

For each of the three temperature-constrained scenarios in this report (§2.3), a pragmatic judgement was made as to the fastest phaseout pathway for coal production in both Developed and Developing country groups. A number of key constraints and considerations that fed into the iterative process of developing the phaseout pathways are described in the following subsections.

4.3.2.1 Relevance of consumption to coal production phaseout schedule

While the explicit focus of this work is on production, in the case of coal the aforementioned close connection between domestic production and consumption was an important factor to consider in developing plausible phaseout pathways. That is to say, because Developing countries with coal

reserves tend to use them principally for their own energy supply, the phaseout pathway has direct and immediate implications for energy *consumption* in those countries and hence their ability to meet the basic development needs of their citizens.

In our analysis, coal is phased out faster for developed countries than for developing countries.

Conversely, very few Developed countries rely heavily on coal production for their domestic energy consumption needs (Poland being a notable exception). The greater economic capacity of Developed countries to implement alternatives to coal to supply their energy needs means that a faster pace of shutdown for coal production in those countries is deemed appropriate.

4.3.2.2 Powering Past Coal Alliance declaration

Members of the Powering Past Coal Alliance (PPCA) have adopted a phaseout timeline for coal power generation in OECD and EU countries by 2030 and in the Rest of the World by 2050[27]. This was based on Rocha et al's [47] estimate of Paris-compatible timelines for ending coal use (Rocha et al also proposed a 2040 phaseout date for China).

Our assumptions about coal production phaseout schedules and end dates track the growing international consensus on phasing out coal's use for power generation.

The PPCA timelines provide a useful backdrop against which to situate the coal production phaseout pathways developed here. However, there are several important methodological differences between the present research and that by Rocha et al, (underpinning the PPCA declaration) that make direct comparison problematic. The foremost divergence is that Rocha et al's analysis and the PPCA itself relates to coal *use* with the main focus being, understandably, on power generation, whereas the focus of this project is explicitly on production.

Second, Rocha et al define the 'phaseout year' as the year in which the reduction in emissions from coal consumption is 90% or more against a baseline year of 2015. This differs subtly but importantly from our 'functional zero year', defined as the first year in which coal (or oil and gas, as the case may be) *production* is less than or equal to 5% of 2018 production. Noting that OECD coal production fell by 10% between 2015 and 2018, the Rocha et al baseline (transposed to production) is around 11% greater than the 2018 one used here[28].

Finally, China, notwithstanding its crucial role as the world's biggest producer and consumer of coal, sits squarely in the Developing countries category and is therefore treated as such in our present analysis, rather than being placed in a separate 'category of one' as in Rocha et al.

4.3.2.3 Sectoral share as a constraint on coal phaseout pathways

Recalling that the climate responds only to cumulative emissions, in developing the phase-out pathway for coal close attention was paid to its share of the global carbon budget, as well as to the remaining budget space for oil and gas. A key constraint was that in no temperature scenario was coal allowed to take up more than its current proportion of production emissions.

For each scenario, we do not allow coal to consume more of the global emissions budget than its current annual share.

	Share of total emissions in 2018	50% 1.7°C scenario	50% 1.5°C scenario	67% 1.5°C scenario
Coal	41%	37%	40%	41%
Oil	38%	41%	39%	38%
Gas	21%	22%	21%	21%

Table 2: Share of global emissions budget by fossil fuel type at baseline and under three temperature-based scenarios.

4.3.2.4 Developing Countries' peak coal production year

Accepting the close correspondence between coal consumption and production for Developing countries, pathway development for that group included a sensitivity analysis of the effect of delaying the year of peak production. Delaying the peak of Developed countries' coal production was found to be an option only in the 1.7°C scenario, with production held constant at 2018 levels until 2025. Under the much tighter constraints of 1.5°C scenarios, any delay in the year of peak production saw coal exceed the limit of 42% of the global budget (4.4.2.3), and by extension substantially reduce the remaining proportion of emissions space for oil and gas. Therefore our coal phaseout pathways in both of the 1.5°C scenarios have peak coal production in 2022 for Developing and Developed country groups alike.

The slightly larger budget for a 50% chance of 1.7°C allows a few more years before developing countries must start winding down their coal production. This is not an option for a 50% or better chance of 1.5°C – reductions must begin immediately.

Once plotted, the coal phaseout pathways rendered 'emergent budgets' for both Developed and Developing country groups (i.e. the cumulative emissions from coal production), as represented by the areas under the curves in Figure 2 below.

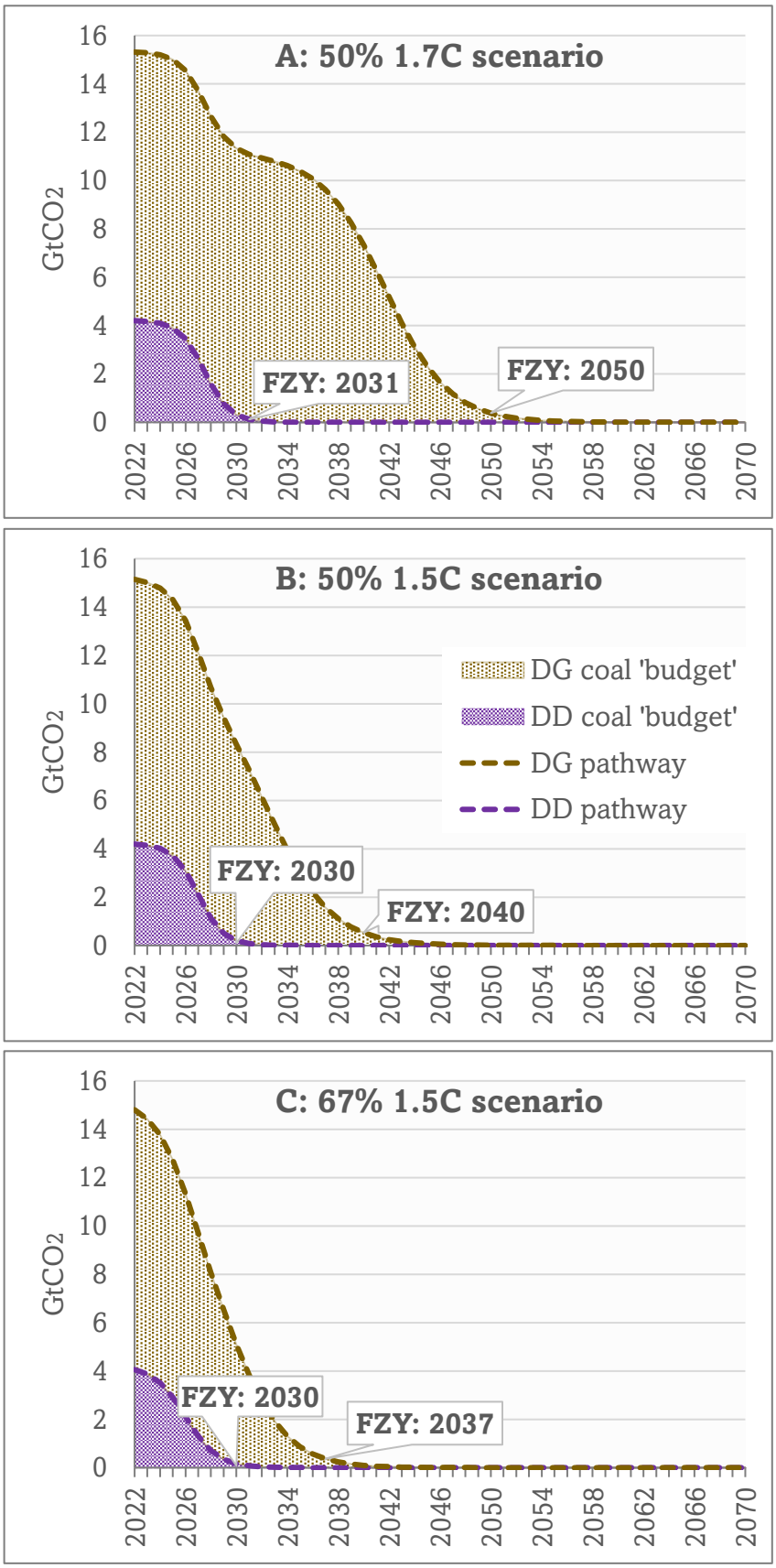


Figure 2: Coal production phaseout pathways and respective 'budgets' for Developed (DD) and Developing (DG) countries under three temperature scenarios.

NB: FZY = Functional Zero Year (<5% of 2018 baseline). See endnote 29 for note on the distinctive pathway shape in panel A (50% 1.7°C scenario).

4.4 Oil and gas budgets

The cumulative emissions totals from the coal phaseout pathways were then subtracted from the global carbon budgets (for the respective temperature scenarios) leaving a budget for oil and gas production combined.

Global budgets for oil and gas production over the rest of the century were obtained by subtracting coal emissions from the overall global budgets (based on IPCC AR6).

Further disaggregation into oil and gas separately was not undertaken in this analysis, because:

(i) most producer nations with one fuel (oil or gas) also have the other, and it was not deemed sensible to be prescriptive about which fuel type producer nations should prioritise.

(ii) it was decided to limit the number pathways and variables to ensure clarity of presentation and communication.

(iii) compelling reasons for favouring one fuel over the other, relative to their current shares, could not be found. See Appendix 1: Key sensitivities for more details of limitations and alternative assumptions.

Oil and gas are therefore treated in combination (summing to the non-coal emissions budget) in all scenarios in this report.

	Budget ($GtCO_2$) : 50% 1.7°C scenario	**Budget ($GtCO_2$): 50% 1.5°C scenario**	**Budget ($GtCO_2$): 67% 1.5°C scenario**
Coal	249	145	108
Oil & Gas	422	215	154

Table 3: global CO_2 production budgets for coal and oil & gas (combined) in three core scenarios.

NB: budgets as of January 2022.

These oil and gas budgets are then taken as the starting point for the disaggregation to groups of producer nations (§6).

SECTION FOOTNOTES

[20] For this project's baseline year of 2018, the amount of each of the three primary fossil fuel types produced was within 1% of the amount consumed globally, according to the IEA's World Summary Energy Balances 2019. Specifically, global coal production was 1.2% *below* consumption; global oil production was 0.6% above consumption; and global natural gas production was 1.1% above consumption.

[21] This is an expedient simplification: clearly a barrel of oil or tonne of coal extracted in say mid-December of one year may not enter the fuel supply chain and reach its final point of end use (combustion) until the following year. However, from one year to the next this 'carry over' simply cancels out, as the historical records on global production and consumption show.

[22] IPCC default emission factors for stationary combustion in the energy industries (tCO_2 / toe): bituminous coal 3.96; crude oil 3.07; natural gas 2.35 [61].

[23] Combustible non-energy products include plastics, lubricants, waxes, solvents, adhesives, paints, paper coverings and packaging [41].

[24] The amount of plastics recycled worldwide is low at around one fifth of annual production, while just over half ends up in municipal landfills or as litter. Most plastics do not break down in nature, so landfilled plastic is unlikely to release CO_2 directly [46].

[25] The terms 'end date', 'end year', 'phaseout year' or 'zero year' are used variously throughout the literature and dialogue on decarbonisation. They are treated synonymously in this report, except where otherwise specified.

[26] Countries were assigned to either 'Developed' (DD) or 'Developing' (DG) categories firstly according to their status as Annex 1 or non-Annex, with a refinement and subsequent reallocation from DG to DD of a small number of oil-rich, wealthy, non-Annex 1 nations whose HDI score exceeded the mean value for Annex 1 nations. This reallocation produced the new categories 'DD2' and 'DG2' in *Factor of Two*, which are the categories adopted here. Appendix C of *Factor of Two* contains the full country list; the categories of the producer countries relevant here can be found in Appendix 2: key data at the end of this report.

[27] In a post-SR1.5 update to the 2016 Rocha et al study, Yanguas Parra et al [62] found that, for compatibility with 1.5°C goals, coal use must be ended by 2030 in OECD (basically Developed) countries and by 2040 at the latest in non-OECD (Developing) countries. The 10-year earlier end date for Developing countries has yet to be adopted into the PPCA declaration.

[28] The coal phaseout pathways developed in this analysis reached functional zero years not later than the Rocha et al / PPCA phaseout years in all but one case. The exception was the Developed countries' coal pathway under the 67% chance of 1.7°C scenario, which reaches functional zero in 2031. However, against a 2015 baseline and 90% reduction phaseout threshold as per Rocha *et al*'s analysis, that pathway's phaseout year would be 2030.

[29] The coal pathways for a 50% chance of 1.7°C are slightly different from the pathways for the 1.5°C budgets, in that Developing countries' emissions from coal production are held constant from 2022 until 2025, when they begin their decline – essentially a delayed peak year. This gives the characteristic 'humped' shape of the stacked area chart of the budgets in Panel A of Figure 2. Under 1.5°C global budgets there was insufficient leeway to allow this delayed peak year for Developing countries' coal.

5 Dividing the global carbon budget between producer nations

Summary: this section explains the rationale and the methodology for grouping countries, before going on to present the five groups.

5.1 'Location independence': international trade of oil and gas

Oil and gas are more widely traded than coal. Constraining a country's production need not mean a corresponding immediate constraint on their use of oil and gas.

Whereas §4.4 identified the typically close correspondence between the country of production and country of consumption in the case of coal, national energy data demonstrates this is not true of oil or gas. Oil in particular is a widely-traded global commodity and is relatively cheap to move from port to port. Gas is traditionally more costly to move across and between continents, since pipelines are expensive to construct, in significant part because of the high capital cost of constructing pipelines and associated infrastructure. However, the growth of liquefied natural gas (LNG) production and marine transportation by tanker have led to increasing 'commodification' of the international gas market. International trade in gas has grown as a consequence, although it remains a markedly less traded fuel than oil.

For these reasons, production of oil and gas is taken to be largely independent of consumption. This is important when considering access-to-energy and the development implications of the phaseout pathways presented here[30]. Since oil and gas are widely traded (more so oil than gas), a country's energy needs are effectively indifferent to where the oil or gas is produced. This 'location independence' forms an important premise of this analysis. Countries will still be able to access oil and gas on the international market, at least to the extent that oil and gas continues to be available (ultimately constrained by the oil and gas budgets and the accompanying phase-out pathways). In short, constraining production of some nations more than others does not lead, necessarily, to a corresponding limitation on their access to oil and gas[31].

5.2 Oil and gas phaseout pathways and equity

The principle of equity dictates that developed countries, with the greatest abilities to decarbonise, should make both bigger and sooner emissions reductions than developing countries.

The principle of 'common but differentiated responsibilities and respective capabilities' (CBDR-RC) makes plain that Developed Countries, with greater socio-economic capacity to mitigate, should make both bigger and earlier steps to decarbonise than Developing Countries (with less capacity) Moreover, the principle requires that Developed Countries provide financial support to enable Developing Countries to implement effective mitigation while continuing to pursue sustainable development and poverty eradication.

While usually applied to the consumption or energy use side of the equation, CBDR-RC can reasonably be taken to apply to the production side too. The key difference in applying CBDR-RC to production is that, whereas all

countries are consumers of fossil fuels (therefore have emissions associated with energy use), only a minority of countries are producers of fossil fuels.

Equity can be applied to production phaseout schedules, to reflect differing abilities or capacities to make a just (or fair) transition for oil and gas industry workers.

Considering only producer countries, CBDR-RC can be reasonably interpreted as requiring those nations with the greatest capacity for a just transition away from oil and gas production doing so earlier and more rapidly than those nations with less capacity to make a just transition.

With this as a guiding principle, we quantify the 'capacity' to make a just transition for oil and gas producing nations and to classify them accordingly. It may also be noted that much of the production in the 'Global South' is carried out by 'Northern' multinational corporations, such that many of the benefits accrue outside the country of extraction. While our analysis focuses on managing the transitional impacts in-country, further research could usefully differentiate between production by foreign companies, domestic private sector and state-owned companies [48], [49].

95% of global oil and gas production occurs in just 33 countries.

Of total global oil and gas production, 95% takes place in just thirty-three producer nations. However, there are many developing countries lower down the list of producers, in which oil and /or gas production makes an important contribution to their national economy, while not being internationally significant in quantity. It was therefore decided to extend the list to capture the top eighty-eight producer nations, thereby accounting for 99.97% of all oil and gas production.

5.3 Quantifying capacity to make a just transition

Seeking to quantify countries' capacities to make a just transition away from oil and gas production, several approaches were explored. Muttitt and Kartha compared producer countries along dimensions of overall capacity to fund a just transition (expressed as GDP per capita) and their level of dependence on income from oil and gas production (expressed as the share of government spending budget derived from oil production) [50].

A similar approach was considered here, but data on the second metric was lacking for the full list of producer countries in this analysis. In addition, government spending alone was considered to capture only part of the full extent of a country's 'dependence' on production, and one that was largely contingent on individual country's tax regimes and structuring of their national oil companies.

Hence, the net was cast wider in seeking a metric that would capture a fuller picture of how intrinsic oil and gas production are to a country's present economy, taking into account jobs supported in auxiliary sectors as well as

those directly employed in the upstream extraction industry itself. Since no such comprehensive dataset was found to exist, it was determined to obtain from scratch country by country values for the percentage share of GDP contributed by the oil and gas production sector. This was done by structured web-search, whereby reputable internet sources for each producer country's share of GDP from oil and gas were sought and, where possible, cross referenced.

5.3.1 'Non-oil GDP per capita' – a useful metric of capacity

For our analysis we developed a new measure of countries' capacities to transition away from oil and gas production, based on the contribution of oil and gas to national GDP.

Ultimately, values for GDP from oil and gas were found or inferred for sixty of the eighty-eight producer nations in this study. The remaining twenty-eight nations, for which no useful data could be found, collectively comprise only 1.7% of global oil and gas production. In each case where no useful quantitative data could be obtained, there was sufficient reason to consider the relevance of extraction to the economy in question to be very minor indeed (less than 1%). As such, a generous allowance of 1% contribution to GDP from oil and gas was applied to each country for which no data was recorded.

See column 8 of Table 7 in Appendix 2: Key data for the complete list of values. See §10.1.6 in Appendix 1: Key sensitivities for details of the caveats relating to this dataset.

The percentages of GDP from oil and gas production were then applied to each nation's GDP per capita (purchasing power parity, current USD) to give the share of GDP per capita that effectively is independent of a country's production industries. This value, which we refer to as 'non-oil (and gas) GDP per capita', is adopted here as the metric of a country's capacity to fund a just transition even without benefit of its production related national income. As a per capita figure, in essence it represents each country's relative 'net-capacity' to fund a just transition once its entire GDP share from oil and gas production is discounted.

Table 4 shows the top thirty-three countries according to production volumes as a share of the global total oil and gas production in our baseline year (i). This is juxtaposed against the thirty-three countries with the highest proportion of GDP from oil and gas (ii) and the thirty-three countries with the highest non-oil GDP per capita at PPP, 2019, current international dollars (iii). This partial snapshot of the full list of eighty-eight nations represents all producer nations with non-oil GDP per capita above the mean. The right-hand two columns (iv and v) indicate whether a country in the list of non-oil GDP per capita (iii) also appears in the lists (i) and (ii), and if so its ranking in those lists.

Rank	(i) Top 33 producers by share of global oil & gas production[32]		(ii) Top 33 producers by share of national GDP from oil & gas (dependence)[33]		(iii) Top 33 producers by non-oil GDP/capita, PPP, 2019, current $ (capacity)[34]		(iv) Top 33 by % of global production?	(v) Top 33 by dependence on O&G?
1	United States	17.9%	Iraq	65%	Ireland	$90,894	No	No
2	Russia	14.8%	Congo	65%	United States	$60,098	Yes (1)	No
3	Saudi Arabia	8.5%	Brunei	60%	Denmark	$59,139	No	No
4	Canada	5.4%	Equatorial Guinea	60%	Netherlands	$58,922	No	No
5	Iran	5.1%	Libya	60%	Austria	$58,098	No	No
6	China	4.1%	South Sudan	60%	Qatar	$57,065	Yes (9)	Yes (11)
7	Iraq	3.1%	Saudi Arabia	50%	Norway	$56,678	Yes (10)	Yes (29)
8	UAE	3.0%	Gabon	50%	Germany	$55,664	No	No
9	Qatar	2.8%	Angola	50%	Australia	$51,131	Yes (17)	No
10	Norway	2.5%	Azerbaijan	44%	France	$49,199	No	No
11	Kuwait	2.1%	Qatar	40%	United Kingdom	$48,020	Yes (21)	No
12	Brazil	2.0%	Kuwait	40%	UAE	$46,618	Yes (8)	Yes (19)
13	Algeria	2.0%	Trinidad & Tobago	40%	Canada	$46,385	Yes (4)	No
14	Nigeria	1.7%	Oman	36%	Bahrain	$46,234	No	Yes (32)
15	Mexico	1.7%	Timor-Leste	36%	South Korea	$44,127	No	No
16	Kazakhstan	1.6%	Turkmenistan	35%	Italy	$43,775	No	No
17	Australia	1.5%	Algeria	30%	Japan	$43,273	No	No
18	Venezuela	1.4%	Chad	27%	New Zealand	$43,125	No	No
19	Indonesia	1.3%	UAE	27%	Israel	$41,368	No	No
20	Malaysia	1.2%	Venezuela	25%	Estonia	$36,941	No	No
21	United Kingdom	1.1%	Yemen	24%	Poland	$34,278	No	No
22	Egypt	1.1%	Egypt	24%	Hungary	$33,984	No	No
23	Oman	1.0%	Iran	23%	Romania	$30,931	No	No
24	Turkmenistan	1.0%	Ecuador	21%	Croatia	$29,626	No	No
25	Angola	1.0%	Malaysia	20%	Turkey	$29,426	No	No
26	Libya	0.9%	Russia	19%	Kuwait	$27,611	Yes (11)	Yes (12)
27	India	0.9%	Papua New Guinea	18%	Chile	$24,719	No	No
28	Argentina	0.8%	Uzbekistan	16%	Saudi Arabia	$24,608	Yes (3)	Yes (7)
29	Colombia	0.7%	Norway	14%	Brunei	$24,413	No	Yes (3)
30	Azerbaijan	0.7%	Kazakhstan	13%	Kazakhstan	$23,662	Yes (16)	Yes (30)
31	Uzbekistan	0.7%	Indonesia	12%	Malaysia	$23,234	Yes (20)	Yes (25)
32	Thailand	0.5%	Bahrain	11%	Russia	$22,988	Yes (2)	Yes (26)
33	Trinidad and Tobago	0.4%	Brazil	10%	Argentina	$22,123	Yes (28)	No

Table 4: Top thirty-three producer nations ranked according to: (i) share of global oil & gas production; (ii) share of GDP/capita from oil and gas; (iii) non-oil GDP/capita.

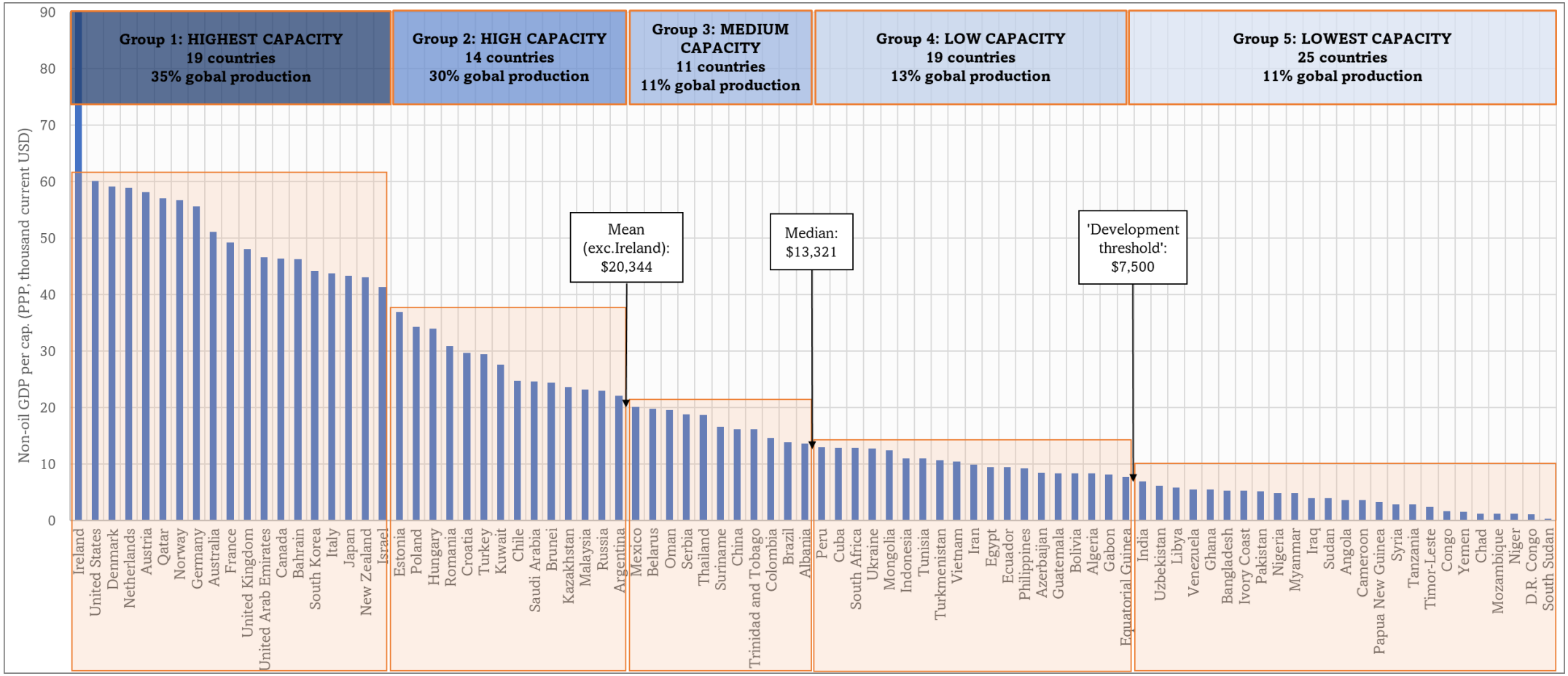


Figure 3: Grouping of producer countries by non-oil GDP/capita

5.4 Ranking and grouping countries by non-oil GDP/capita

Non-oil GDP per capita of the top eighty-eight producer countries is shown in Figure 3, arranged in descending order left to right. Superimposed on the data columns in the Figure are groupings 1 to 5, reflecting subsets of producer countries with broadly comparable values for non-oil GDP per capita. Although in some cases the difference between the bottom of one group and the top of the next is less than the differences within the groups, the boundaries were not imposed arbitrarily.

We split the top 88 oil and gas producing countries into five groups according to the size of their economies excluding the contribution from oil and gas.

Two of the four crucial breakpoints for country groupings are based on simple arithmetic averages: the mean and median. Of these the mean is the most salient, since countries whose non-oil GDP/capita is below the mean are taken to have less capacity than average (for all producer nations) to enable a just transition. This key observation informs a pivotal assumption in the next methodological step, whereby production phaseout pathways are developed for each country group reflecting their capacity to transition relative to the mean (see §6.2).

In short, countries whose non-oil GDP/capita is above the mean are expected to transition away from oil and gas production faster than countries below the mean, with countries below the median value taking longer than countries between the mean and the median.

In addition to the mean and median values, a third breakpoint was introduced at a level of GDP per capita intended to reflect the 'global poverty line', set at $7,500 to coincide with the default 'development threshold' in Holz et al's Climate Equity Reference Calculator [51]. Countries whose non-oil GDP/capita is below this threshold are assumed to have the least capacity to transition away from oil and gas production and will follow slower phaseout pathways than the other four groups.

Finally, the fourth division (between the highest capacity groups, one and two) was placed at the observed inflection point in the side-by-side rankings in Figure 3, where a somewhat larger jump occurs in the values between Estonia and Israel than between their next closest country.

SECTION FOOTNOTES

[30] For example, country A produces 1 $GtCO_2$ equivalent of oil each year but consumes only 0.5 $GtCO_2$ equivalent of oil in the same period. Country B produces 0.5 $GtCO_2$ worth of oil but consumes 2 $GtCO_2$ worth each year. Global trade in oil and oil products balances out these surpluses and deficits.

[31] This analysis does not look in detail at how the energy consumption emissions pathways of countries, whether they be producers or non-producers, fit within temperature-constrained global budgets. Note: throughout this report, where the word *consumption* is used it refers to the use of fossil fuels as distinct from the *production* of fossil fuels. It is not intended in the sense of 'consumption emissions accounting' (as distinguished from 'territorial emissions accounting' or 'production accounting'), which refers to a method of including the emissions embedded in goods produced overseas within national end-use emissions inventories.

[32] Source: Extracted from [40]. See Table 7 in Appendix 2: key data for complete dataset of all eighty-eight producer nations.

[33] See Table 8 in Appendix 2: key data for a full list of sources.

[34] Source: authors' own calculations based on GDP/capita (PPP, 2019, current international dollar), WEO subject code PPPPC [59], and values for share of national GDP from oil and gas (list ii in Table 4). See Appendix 2 for complete dataset of eighty-eight producer nations.

6 Disaggregating production budgets among producer nations

This section explains how production budgets and phaseout schedules were developed for the country groupings above, including the mechanism by which rebalancing and delayed phaseout for the poorest countries was applied.

6.1 Establishing the starting position

A 'grandfathered budget' is each group's share of the remaining global budget based on its current percentage of total annual emissions.

For each of the country groupings 1 to 5 in Figure 3, the percentage of global oil and gas production in the baseline year (2018) was obtained. Based on these percentages, each group's 'grandfathered'[35] share of the emissions budget for oil and gas (§4.4) was calculated for each temperature scenario. The grandfathered budgets can be expressed as the number of years remaining at baseline levels of production (hereafter 'years of current production'), which serves as a useful unit of exchange in developing the phaseout pathways for the different groups.

As the grandfathered budgets are based on each group's current (or rather baseline year) share of annual production, all five country groups have an equal number of years of current production (particular to each temperature scenario) in their de facto 'starting position'.

However, the average capacity to enable a just transition (expressed as non-oil GDP per capita) of the highest capacity countries (Group 1) is estimated at fourteen times that of the lowest capacity countries (Group 5). Thus, phaseout pathways that preserved the status quo would clearly be highly inequitable, strongly favouring the wealthy Groups 1 and 2 and disfavouring poorer Groups 3, 4 and 5.

We made equity-based adjustments to each group's 'grandfathered budget' according to their respective capacities to make a just transition.

Therefore this stage of our analysis seeks to address the unfairness inherent in the status quo by developing pathways that allow longer for poorer nations to phaseout their oil and gas production than the richer nations.

6.2 Capacity weightings

In order to make proportionate adjustments to the de facto starting position, 'share of aggregate absolute deviation' was selected as an adequate mathematical proxy for each group's 'relative capacity to enable a just transition'. In essence this proxy functions as a 'capacity weighting' that can be used to redistribute the oil and gas budget to render new phaseout pathways more equitable than the status quo.

In practical terms, capacity weightings were calculated as follows.

(i) The absolute deviation was obtained for each group[36].

(ii) The absolute deviations of groups above the mean were summed (i.e. Groups 1 and 2).
(iii) Likewise, for groups below the mean (i.e. Groups 3, 4 and 5).
(iv) The capacity weighting for Groups 1 and 2 was their respective share of the sum of absolute deviations above the mean.
(v) The capacity weighting for Groups 3, 4 and 5 was their respective share of the sum of absolute deviations below the mean.

Therefore,

$$\text{CW G1\&2} = (x-\mu) / \Sigma_{1,2}(x-\mu)$$
$$\text{CW G3,4\&5} = (|x-\mu|) / \Sigma_{3,4,5}(|x-\mu|)$$

Where: x is the 'group mean non-oil GDP/capita' of each group 1 to 5 and μ is the 'mean of group means'.

We used each group's average value for capacity to transition to determine a simple ratio to redistribute the remaining global budget for oil and gas production.

	Number of countries	% total O&G production	Mean non-oil GDP/cap	Absolute deviation	Capacity Weighting
Group 1 **Highest capacity**	19	35%	$50,495	$28,661	0.83
Group 2 **High capacity**	14	30%	$27,753	$5,919	0.17
		Above mean ↑	**↓ Below mean**		
Group 3 **Medium capacity**	11	11%	$17,086	-$4,748	0.14
Group 4 **Low capacity**	19	13%	$10,230	-$11,604	0.34
Group 5 **Lowest capacity**	25	11%	$3,605	-$18,229	0.53

Table 5: Capacity weightings of five groups of oil and gas producing countries according to share of aggregate absolute deviation.

6.3 Rebalancing the budgets: equity-based adjustments to the status quo

Redistribution of years of current production was then undertaken, with groups above the mean 'donating' budget space to groups below the mean. Here the capacity weighting serves as a ratio regulating the iterative process of redistribution. Thus, for each year of current production donated from the grandfathered Group 2 budget, 4.8 years of current production is donated by Group 1 (reflecting the ratio of the above-mean groups' capacity weightings, 4.8:1 being equivalent to 83:17).

The donated budget from Groups 1 and 2 is then summed and redistributed among Groups 3, 4 and 5 according to their respective capacity weightings (i.e. at the ratio of 14% to Group 3, 34% to Group 4 and 53% to Group 5).

In our temperature-constrained scenarios, the wealthier (most capable) producers in Groups 1 and 2 'donate' budget to the poorer producers in Groups 3, 4 and 5.

The extent of redistribution applied was the outcome of extensive deliberation and iteration by the research team, client and external stakeholders. Construction of a simple mathematical model permitted calibrated, stepwise increases of redistribution (governed by the capacity weightings), while monitoring the outcomes with respect to the pathway gradient (i.e. rate at which production is being closed down) and functional end dates consistent with the rebalanced budgets for each group.

The rebalanced budgets and pathways presented here are premised on a constant percentage redistribution of the sum of the above-mean groups' grandfathered budgets. That is, in each temperature scenario, a constant 20% of the combined grandfathered budgets of the above-mean Groups 1 and 2 is redistributed amongst the below-mean Groups 3, 4 and 5. Donation and benefit alike are governed by groups' respective capacity weightings.

Groups 1 and 2 donate 20% of their combined budget to the poorer Groups 3, 4 and 5.

Holding the percentage of above-mean budget redistribution constant means that the absolute amount of reallocated budget declines as the overall global budget tightens (for increasing probabilities of lower temperatures). Sensitivity analysis was conducted to explore the effects of increasing and decreasing the percentage of above-mean budget redistribution, and of varying the percentage inversely to the global budget (that is, smaller global budgets saw bigger percentage redistributions). Lower constant percentage reductions produced infeasibly early end dates for below-mean groups, while higher percentages gave infeasibly early end dates for above-mean groups under the tighter global budgets.

The budgetary adjustments in this part of our analysis are therefore an exploration of scenarios that are less inequitable than the starting position, or status quo. However, equitable rebalancing proves to be increasingly difficult under the tighter global budgets; indeed it becomes impossible if a budget with a good chance of 1.5°C is selected.

The differential pathways and their implications are discussed fully in §7.4. In summary: the higher the probability of 1.5°C sought, the more inequitable the budgets and pathways for poorer nations that fall within the bounds of 'feasibility' for all. This unavoidable inequitability strengthens arguments for financial reparations from developed to developing countries.

			(1) Headline AR6 global budget GtCO2 (2) Remaining from Jan 2022	Years of current production: grand-fathered	Donated Group 1&2 budget GtCO2	Donated share of Group 1&2 combined budget	Years current of production: rebalanced budget	Funct-ional zero year	Reduction 2030	Reduction 2035	Reduction 2040	Reduction 2045	Reduction 2050
50% 1.7C	**COAL**	DD	(1) 850 (2) 671					2031	92%	~	~	~	~
		DG peak						2025	~	~	~	~	~
		DG						2050	1%	7%	34%	79%	~
	OIL & GAS	Group 1		19.4	55	20%	13.2	2045	20%	52%	83%	~	~
		Group 2		19.4			18.1	2050	5%	20%	53%	83%	~
		Group 3		19.4			22.6	2054	1%	6%	23%	57%	85%
		Group 4		19.4			26.2	2058	0%	2%	9%	31%	67%
		Group 5		19.4			30.6	2062	0%	1%	3%	11%	35%
50% 1.5C	**COAL**	DD	(1) 500 (2) 361					2030	~	~	~	~	~
		DG peak						2022	~	~	~	~	~
		DG						2040	27%	73%	~	~	~
	OIL & GAS	Group 1		9.9	29	21%	6.6	2034	74%	~	~	~	~
		Group 2		9.9			9.3	2039	43%	85%	~	~	~
		Group 3		9.9			11.6	2043	28%	64%	89%	~	~
		Group 4		9.9			13.5	2045	18%	50%	82%	95%	~
		Group 5		9.9			15.9	2050	14%	35%	66%	87%	~
67% 1.5C	**COAL**	DD	(1) 400 (2) 261					2030	~	~	~	~	~
		DG peak						2022	~	~	~	~	~
		DG						2037	56%	92%	~	~	~
	OIL & GAS	Group 1		7.1	20	20%	4.8	2031	~	~	~	~	~
		Group 2		7.1			6.6	2034	76%	~	~	~	~
		Group 3		7.1			8.2	2037	53%	91%	~	~	~
		Group 4		7.1			9.5	2038	39%	86%	~	~	~
		Group 5		7.1			11.2	2042	28%	69%	93%	~	~

Table 6: Key model parameters and outputs across the three temperature scenarios, including functional zero years for all groups and fuels.

NB: DD = Developed countries / DG = Developing countries (see §4.3.1)

6.4 Fitting pathways to the rebalanced budgets

Like the grandfathered de facto budgets, the rebalanced budgets for each group produced by the redistribution model can be expressed as 'years of current production'. While the climate is agnostic as to how those budgets are 'spent' over time, there are of course many practical constraints on the shape of realistic phaseout pathways.

Oil and gas budgets can be expressed as 'years of current production', but a pathway shape is needed to understand how fast the budget will be used up.

The simplest stylised pathway would follow equal annual reductions – a straight line from current production to zero. Such a stylisation has limited value as a heuristic in practical terms, since it makes no allowance for system inertia or mitigation ramp-up rates. To keep to such a pathway, reductions must begin at maximum pace[37] as soon as the starting gun is fired and continue uniformly until the last barrel of oil is extracted.

In an attempt to offer more useful illustrative pathways, those we offer here incorporate a degree of system inertia and gradual ramp-up of mitigation (as much as this is possible within the constraint of the group budget in question). The simplest version of this is a sigmoidal curve, symmetrical around a straight-line pathway with the same budget (or area).

The end date – or functional zero year – for each pathway is the year in which production falls to 5% of the starting value (baseline).

As in the case of coal production pathways in §4.4, the point at which our oil and gas pathways is considered to have reached zero is the first year in which production is less than or equal to 5% of the baseline 2018 value. This is the pathway's 'functional zero year'.

More technical details of how the sigmoidal pathways were constructed can be found in §10.1.8 in Appendix 1. For present purposes it is enough to note that, for a given budget, the functional zero year is sensitive to an exogenous gradient value. As a simplifying assumption, the pathways presented in this part of the report all take the lowest gradient value possible in order to give the latest functional zero year within budget[38].

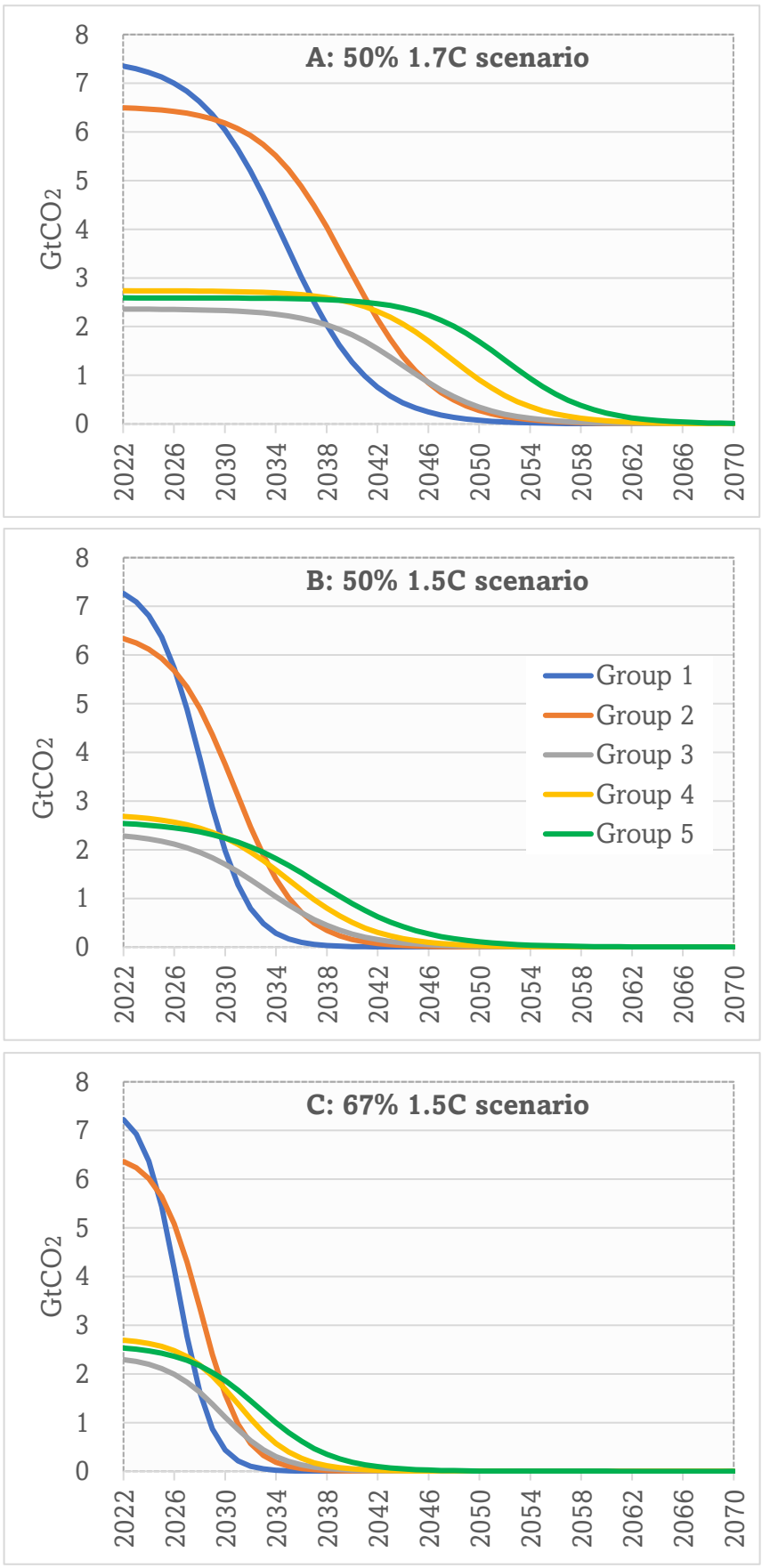


Figure 4: Combined oil & gas phaseout pathways for five groups of countries under three core temperature scenarios.

SECTION FOOTNOTES

[35] Grandfathering is a system of budget allocation whereby a country's or group's historical level of resource use (i.e. emissions space) is used to set its share of future budget entitlement [63]. In this analysis, we use each group's 2018 production emissions to set its de facto grandfathered share of the global oil and gas budgets.

[36] Ireland's non-oil GDP/capita is a conspicuous outlier and was therefore excluded from the mean of Group 1.

[37] That is reduction in 'tonnes of production/year'. The actual percentage reduction, relative to the previous year, actually increases year on year for a straight-line gradient.

[38] The range of possible values for sigmoidal pathway gradients is 0.1 to 1.0. In full, the rubric for setting the gradients was that the lowest value within budget should be selected, down to a lower limit of 0.3. While not in all cases incompatible with certain larger budgets, pathways with a gradient lower than 0.3 have very long tails (hence, in extreme cases, grossly delayed functional zero years), which were deemed to be inconsistent with the ethos of rapid international mitigation effort.

7 Discussion and conclusions

7.1 Overview

This report has focussed specifically on phaseout schedules for oil and gas producing nations. The schedules are aligned with tight and quantified carbon budgets and informed by the equity considerations embedded within the principle of "Common but Differentiated Responsibility and Respective Capabilities" (CBDR-RC).

The three global budgets that have guided the analysis are taken to reflect the commitment enshrined in the 2015 Paris Agreement to hold *"the increase in the global average temperature to well below 2°C … and to pursue efforts to limit the temperature increase to 1.5°C."*. In addition, they also capture the shift in emphasis towards 1.5°C, evident in the IPCC's SR1.5 report [2], the G7 Communique [4] and COP26 [5].

Discussion focusses on our 'central scenario', with a 50:50 chance of not exceeding 1.5°C

The headline budget adopted as the central scenario for this report is for a 50% chance of not exceeding 1.5°C. This central scenario is flanked by a less demanding, 'lower ambition' scenario with a 50% chance of 1.7°C (i.e. "well below 2°C") and a more challenging, 'higher ambition' scenario with a 63% chance of not exceeding 1.5°C.

In 2022, all of these budgets have profound implications for the future of fossil fuel production. However, they embody significant differences in phaseout schedules. Considering the largest of the budgets, 50% of 1.7°C (i.e. equivalent to an 83% chance of not exceeding 2°C), and updated to the start of 2022, this value equates to eighteen years of current fossil fuel production. At the other end of the budget range, the 63% chance of not exceeding 1.5°C, gives just seven years of production, increasing to a decade for a 50:50 chance of 1.5°C.

For a 50% chance of not exceeding 1.5°C, less than 10 years' worth of emissions space remains at current levels of production.

7.2 Findings for coal

Working from these budgets and with a focus on detailing oil and gas phaseouts across the eighty-eight producer nations, it was first necessary to develop a coarse-level schedule for phasing out coal production. This was undertaken in relation to "developed" and "developing country parties" (consistent with the language and designation within the Paris Agreement).

Two key coal-related characteristics evident in compiling the fossil fuel database (production and consumption) that informed this report were:

(i) coal is disproportionately favoured by those nations undergoing rapid industrialisation; and

(ii) there is a close link between national production and consumption of coal.

This second point has direct implications for the proportion of coal that is extracted and subsequently traded on the world market, which is much smaller than for oil and, to a lesser degree, gas.

Collectively, these two characteristics provide a strong steer that there needs to be a clear distinction drawn between the phaseout schedules of coal within "developed" nations and within "developing" nations. However, given the very tight and rapidly dwindling carbon budget associated with this report's emphasis on 1.5°C, even within developing nations the move away from coal needs to be rapid.

Early in the analysis, acknowledging the much higher carbon intensity of coal (i.e. more CO_2 is emitted per unit of energy than from either oil or gas) led to a decision that none of the scenarios should see the coal use, as a proportion of all fossil fuel energy, increase. The implication of this for a 50% or better chance of 1.5°C, led to coal scenarios where production needed to end by 2030 for developed countries and 2040 for developing countries. Any reasonable pathway of coal's use beyond these dates would see it taking up more of the remaining global carbon budget than its current share. Were this to be permitted in a carbon budget-constrained scenario, there would be less emissions space for oil and gas, which would have significant impact on the access to energy for sectors that rely on these fuels – especially transport.

For a 50% chance of not exceeding 1.5°C, coal production needs to be phased out in developed countries by 2030 and in developing countries by 2040.

On the face of it, this conclusion simply reinforces a common understanding that there needs to be an urgent and rapid shift away from coal production. However, quantifying such a shift in relation to a 50% chance of 1.5°C, with a strong emphasis on equity, makes clear just how stark this 'urgency' really is. For developed nations, coal production needs to fall by 50% within five years and be effectively eliminated by 2030. For developing nations, there is some relative leeway. Nevertheless, coal production has to begin an immediate decline, reducing by half within a decade with all extraction ceased by 2040.

7.3 Findings for oil and gas

Having established coal production pathways, with attendant total cumulative emissions, for each of the three global carbon budgets, the remaining non-coal budget was considered in relation to oil and gas production. Here, and as explained in §4.4, oil and gas were brought together as a single energy source, rather than addressed separately.

A central concern in apportioning the oil and gas budget between the eighty-eight producer nations was the issue of equity. Acknowledging that there are several interpretations of such equity within the literature, what quickly

became apparent was just how little emissions space remained within which equity could be considered. Constrained by a breadth of factors, ranging from data availability to the physical constraints of the remaining oil and gas budget, we settled on a metric for 'capacity to make a just transition' that achieved a workable balance, but still with fairness at its core.

Oil and gas producing nations differ greatly in their dependence on income from production. Some of the poorest producers have very little income other than from oil and gas.

Probing the production and economic data for oil and gas revealed that nations' reliance on revenue from the sector differs by an order of magnitude. Although striking in itself, this observation painted only a partial picture. Some nations, despite being small producers, have little economic revenue beyond that from oil and gas production (for example, South Sudan, Equatorial Guinea, Congo-Brazzaville and Gabon).

At the other end of the spectrum, some larger producers have such diverse and vibrant economies that the oil and gas revenue is arguably more of a 'nice to have' (for example, United Kingdom, Canada, Australia and, even the USA[39],). Still others are large producers with oil and gas revenue forming a major proportion of their economy, but with very high non-oil-and-gas income too (for example, Qatar, United Arab Emirates[40] and Norway).

Wealthier producers tend to have much more diversified economies, even when they are major producers of oil and gas.

Bringing all of this together, we chose the non-oil-and-gas facet of national GDP (measured in PPP per capita) as a measure of capacity to rapidly phase out oil and gas production and restructure economies without the associated revenue. Using this measure, it was possible to test different redistributions of the production emissions budgets between groups of nations, endeavouring to find a balance between equity and a judgement of what was deliverable. This process of iteration was undertaken for each of the three headline carbon budget constraints.

The specific reference to 'groups of nations' here is key. As detailed in §7.5, the available data were partial, had different or missing dates and was very often poorly specified. Nevertheless, set against other similarly partial datasets, we considered the non-oil-and-gas proportion of GDP the most appropriate proxy for capacity while taking account of equity. To assuage some of our concerns with the quality of the data, we chose to collate nations into five groups. Within each group, the data was averaged to provide generic group characteristics, which subsequently informed the redistribution of the budget allocations between the groups (see §6.2). This approach inevitably loses some national specificity, but in doing so it lends an element of robustness to otherwise ambiguous and partial data.

Wealthier producers are still wealthy even once their revenue from oil and gas is removed.

What quickly became evident from the completed dataset of non-oil-and-gas GDP per capita (PPP), was how those wealthy nations that are major producers, typically remain wealthy even once the oil and gas revenue is

removed. In contrast, several of the smaller producers have economies so deeply locked into oil and gas production that they have very little financial capacity to reconfigure their economies once the oil and gas inputs are removed.

This assessment of capacity was a key determinant in testing what level of carbon budgets could be redistributed between the different groups (see §6.3 for details of how this was done). However, and as emphasised earlier, the physical limits of the remaining carbon budgets placed a significant constraint on the levels of redistribution possible; this was particularly evident for the two 1.5°C budgets.

For a 50% chance of 1.5°C, the wealthiest producers (Group 1) need to end production of oil and gas by 2034, while the poorest producers (Group 5) have until 2050.

For our central scenario (50% chance of 1.5°C), the final redistribution that balanced equity with delivery sees oil and gas production in the wealthiest (Group 1) nations reduce by 50% in just six years, and cease by 2034. For the poorest nations most dependent on oil and gas revenue (Group 5), the date for a 50% drop in production extends out to 2037, with complete phaseout by 2050

7.4 Implications of the findings

7.4.1 Phaseout ambition must increase

The fossil fuel phaseout schedules that emerge from our analysis are, for all three temperature scenarios, far removed from proposals forthcoming from the governments of virtually all producer nations.

The very few exceptions include the proposed ending of oil and gas production by France (a minor producer, 0.01% of global oil and gas) in 2040 and by the State of California in 2045. However, these undertakings are only compatible with our lowest ambition temperature scenario, and fall far short of what would be necessary for 1.5°C. Denmark's (0.1% of global production) pledge to phaseout in 2050, would be five years too late to be compatible with the lowest ambition scenario. It bears repeating that it is the pathway to the final end date that is of key importance to respecting the overall temperature-related budget. Achievement of the end date does not alone constitute conformity with the budget, and may actually relate to total emissions far in excess of what is permitted.

Our findings suggest that the current proposals by governments of virtually all oil and gas producing nations place the world on course for exceeding 1.5°C.

7.4.2 No room to expand production in any scenario

Of graver concern than pledges of weak end dates, is that most oil and gas producing countries are planning to increase production in the short term. [52]. This is diametrically opposed to the production pathways identified in this report. Peak production needs to be now, followed, with immediate effect, by the rapid phaseout of existing production.

For a 50% or better chance of 1.5°C, our analysis shows that all producer countries must peak their production immediately and begin an uninterrupted decline. Expanding production in wealthier producers would either shift poorer producers (in fact all producers) onto more steeply declining pathways with earlier end dates, or put the temperature commitments beyond reach.

For context, in our central scenario (50% chance of 1.5°C) – even with the relatively weak version of equity applied here[41] – production in poorer nations needs to come down by between one sixth (for Group 5, the very poorest producers) and almost a third (for Group 3, below average capacity) by 2030. This already represents a significant loss of short-term income opportunity for the countries least able to tolerate such losses.

For a 50% or better chance of staying below 1.5°C, production must start to reduce everywhere. There is no room in a 1.5°C budget for any expansion of oil and gas production.

In this light it is clear that, should wealthy producers (Groups 1 and 2, responsible for two thirds of global oil and gas) expand their production, then either the global carbon budget is breeched (causing greater climate impacts), or the already challenging transition for poorer producers is grievously exacerbated (undermining their development).

It is worth noting that any expansion by poorer producers (Groups 3, 4 and 5, responsible for one third of global oil and gas) would also force their 'group-mate nations' onto steeper phaseout pathways with earlier end dates (thus exacerbating economic hardship), or again jeopardise the overall global budget.

Only in the weaker ambition scenario associated with a 50% chance of 1.7°C is there scope for the poorest producers to effectively flatline their production until the early 2040s. But such leeway is possible if and only if the wealthier producers (Groups 1 and 2) eliminate their production during that same twenty-year period.

In summary, should any group or groups of nations opt for expansion of production, rather than following the pathways illustrated in Figure 4, then the corresponding end dates would be forfeit and steeper reduction curves would be required of all. With even a weak interpretation of equity, the achievement of any of the three temperature-probability scenarios in this analysis would be fatally undermined by an increase in oil and gas production.

7.4.3 Need for financial transfers

While differentiated phaseout timelines, such as those developed in this analysis, are an important means to recognise producer nations' differing capacities to conduct a just transition, they do not fully (or evenly mostly)

deliver equity. As noted in §6.3, equity has to be weighed against the need to configure pathways that are 'feasible for all'. In the tighter '50% of 1.5°C' budgets, there was insufficient emission space, and therefore time, for poorer producers (Groups 4 and 5) to phase out their production without severely hampering their socio-economic development needs. This inequitable situation could only be alleviated by releasing additional budget through the almost overnight 'switching off' of production in the wealthier producers (Group 1); a requirement that is infeasible both practically and politically.

There is not enough space left in a 1.5°C global budget to be fully equitable in the treatment of the poorest producers through later phaseout dates alone.

Furthermore, as noted in §7.3, many of poorest producers are the most heavily reliant on income from the oil and gas sector. With low levels of economic diversification such poor nations face a much more difficult transition away from the hydrocarbon 'resource curse' [53]–[55] than do those, typically wealthier, producers with diverse economies.

It will be especially difficult for the poorest, oil-dependent countries to phase out production by the 2040s or 2050, yet this is exactly what is required of them for a 50% or better chance of 1.5°C. Therefore the provision of international financial support will be crucial, in addition to the differentiation of end dates for production developed in this report [56]. Note that the upscaling of climate finance necessary to enable those transitions is separate from and additional to the issue of reparations for loss and damage arising from climate impacts already being suffered and those yet to arise from a warming world.

Financial transfers will be essential to help poorer producers transition from oil and gas production quickly enough to stay below 1.5°C.

SECTION FOOTNOTES

[39] Oil and gas revenue may contribute 8% of the US GDP, but the economy is so diversified, mature and large that relative to the non-oil GDP of virtually all other producer nations the phasing out of oil and gas revenue would still leave a substantial and thriving economy. To put some numbers on this, with the 8% removed, the US has a GDP/capita of over $60k, the second highest globally. Another perspective here, is that with US oil and gas revenue removed, the US still has a GDP/capita that is one third above that of the OECD and the EU (both with oil and gas revenue included) and three-and-a-half times that of the global and Chinese average (again, with including oil and gas revenue).

[40] Whilst the economies of Qatar and UAE remain highly dependent on oil and gas revenue, the past twenty years have also seen some significant diversification of their economies. Both countries now have substantial economic return from manufacturing and heavy industry, as well as thriving financial and tourism sectors. In the case of UAE, there are important differences in the economic make-up of its seven emirates, with, for example, Dubai now much more diversified from oil than Abu Dhabi.

[41] Weak insofar as the attempt to achieve an equitable rebalancing of the budgets was constrained by judgements about feasible rates of real-world energy system transitions.

8 Glossary

AFOLU	agriculture, forestry and other land use
BECCS	bioenergy with carbon capture and storage
capacity	the ability of a producer nation to conduct a just transition away from fossil fuel production
capacity weighting (CW)	a measure of relative capacity developed in this report, based on GDP/capita excluding oil and gas (measured in PPP)
carbon budget	the amount of CO_2 that can be emitted while staying below a given amount of global warming
CBDR-RC	common but differentiated responsibilities and respective capabilities – the principles of equity embedded in the UNFCCC and Paris Agreement
CCS	carbon capture and storage – capturing CO_2 at point of emission and storing it in geological strata
CDR	carbon dioxide removal – extracting carbon dioxide from the atmosphere after it has been emitted by technological or biological means
CH_4	methane, a potent greenhouse gas, significantly from agriculture and fossil fuel production
CO_2	carbon dioxide, the principal greenhouse gas from fossil fuels
DACCS	direct air carbon capture and storage, a form of CDR
Developed countries (DD)	UNFCCC Annex 1 parties plus oil-rich countries with GDP/capita and HDI values above the mean of Annex 1 nations
Developing countries (DG)	UNFCCC non-Annex 1 parties minus oil-rich countries with GDP/capita and HDI values above the mean of Annex 1 nations
GDP	gross domestic product, a broad measure of a country's economic output
$GtCO_2$	gigatonnes of carbon dioxide (billion tonnes)
HDI	Human Development Index, a composite measure of the relative health and prosperity of a country's population
IAM	integrated assessment model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
just transition	a shift away from fossil fuel production accompanied by social and economic interventions to secure workers' livelihoods
ktoe	kilotonnes of oil equivalent, a unit of energy for fossil fuels
LNG	liquefied natural gas
LUCF	land use change and forestry
$MtCO_2$	million tonnes of CO_2
mtoe	million tonnes of oil equivalent, a unit of energy for fossil fuels
N_2O	nitrous oxide, a potent GHG, largely unavoidable from AFOLU
NbS	nature-based solutions, (such as forestation), a biological form of CDR
NETs	negative emissions technologies (such as DACCS), another form of CDR

NO-GDP	non-oil-and-gas GDP, a measure developed in this report of the size of a country's economy without income from oil and gas
PPCA	Powering Past Coal Alliance
PPP	purchasing power parity, an adjustment to GDP to allow international comparisons
UNFCCC	United Nations Federation Convention on Climate Change

9 References

[1] United Nations Framework Convention on Climate Change, *Decision 1/CP.21, Paris Agreement, document FCCC/CP/2015/10/ Add.1. Paris: United Nations*. 2015.

[2] IPCC, "Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change," 2018. [Online]. Available: https://www.ipcc.ch/sr15/

[3] Working Group 1 of the IPCC, "Climate Change 2021, The Physical Science Basis, Summary for Policymakers," 2021. doi: 10.1260/095830507781076194.

[4] G7, "G7 Climate and Environment Ministers' Meeting Communiqué. London, United Kingdom. 20-21 May 2021," no. May, pp. 1–27, 2021, [Online]. Available: https://www.env.go.jp/press/files/jp/116305.pdf

[5] UkCOP26.org, "COP26 keeps 1.5C alive and finalises Paris Agreement - UN Climate Change Conference (COP26) at the SEC – Glasgow 2021." https://ukcop26.org/cop26-keeps-1-5c-alive-and-finalises-paris-agreement/ (accessed Feb. 23, 2022).

[6] IPCC, "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge University Press, Cambridge, UK, and New York, USA, 2013. [Online]. Available: https://www.ipcc.ch/report/ar5/wg1/

[7] IPCC, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge University Press, In Press, 2021. [Online]. Available: https://www.ipcc.ch/report/ar6/wg1/

[8] United Nations, "UN Chief Calls for Immediate Global Action to Phase Out Coal | UNFCCC," 2021. https://unfccc.int/news/un-chief-calls-for-immediate-global-action-to-phase-out-coal (accessed Feb. 18, 2022).

[9] PPCA, "Declaration | Powering Past Coal Alliance," 2017. https://www.poweringpastcoal.org/about/declaration (accessed Feb. 18, 2022).

[10] K. Anderson and J. Jewell, "Debating the bedrock of climate-change mitigation scenarios," *Nature 2021 573:7774*, vol. 573, no. 7774, pp. 348–349, Sep. 2019, doi: 10.1038/d41586-019-02744-9.

[11] R. Pollin and B. Callaci, "The Economics of Just Transition: A Framework for Supporting Fossil Fuel–Dependent Workers and Communities in the United States:," *https://doi.org/10.1177/0160449X18787051*, vol. 44, no. 2, pp. 93–138, Jul. 2018, doi: 10.1177/0160449X18787051.

[12] K. Perry, "Realising Climate Reparations: Towards a Global Climate Stabilization Fund and Resilience Fund Programme for Loss and Damage in Marginalised and Former Colonised Societies," *SSRN Electronic Journal*, pp. 1–24, 2020, doi: 10.2139/ssrn.3561121.

[13] J. A. Lowe and D. Bernie, "The impact of Earth system feedbacks on carbon budgets and climate response," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 376, no. 2119, May 2018, doi: 10.1098/RSTA.2017.0263.

[14] R. Andrew and G. Peters, "The Global Carbon Project's fossil CO2 emissions dataset," Oct. 2021, doi: 10.6084/M9.FIGSHARE.16729084.V1.

[15] P. Friedlingstein *et al.*, "Global Carbon Budget 2021," *Earth System Science Data Discussions*, vol. 2021, pp. 1–191, 2021, doi: 10.5194/essd-2021-386.

[16] K. Anderson, J. F. Broderick, and I. Stoddard, "A factor of two: how the mitigation plans of 'climate progressive' nations fall far short of Paris-compliant pathways," *Climate Policy*, vol. 20, no. 10, pp. 1290–1304, 2020, doi: 10.1080/14693062.2020.1728209.

[17] IEA, "Technology roadmap: Low-Carbon Transition in the Cement Industry," 2018.

[18] IEA, "Iron and Steel Technology Roadmap: Towards more sustainable steelmaking," 2020. [Online]. Available: https://www.iea.org/reports/iron-and-steel-technology-roadmap

[19] United Nations, "What is the United Nations Framework Convention on Climate Change? | UNFCCC." https://unfccc.int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change (accessed Feb. 16, 2022).

[20] United Nations, *United Nations Framework Convention on Climate Change*. 1992. doi: 10.35935/edr/31.2513.

[21] J. B. Smith *et al.*, "Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) '"reasons for concern."'" [Online]. Available: www.pnas.orgcgidoi10.1073pnas.0812355106

[22] Climeworks.com, "Orca is Climeworks' new large-scale carbon dioxide removal plant." https://climeworks.com/roadmap/orca (accessed Feb. 16, 2022).

[23] The Economist, "The world's biggest carbon-removal plant switches on | The Economist." https://www.economist.com/science-and-technology/2021/09/18/the-worlds-biggest-carbon-removal-plant-switches-on (accessed Feb. 16, 2022).

[24] P. Williamson, "Emissions reduction: Scrutinize CO2 removal methods," *Nature*, vol. 530, no. 7589, pp. 153–155, 2016, doi: 10.1038/530153a.

[25] P. Smith *et al.*, "Biophysical and economic limits to negative CO2 emissions," *Nature Climate Change*, vol. 6, no. 1, pp. 42–50, 2016, doi: 10.1038/nclimate2870.

[26] E. W. Littleton *et al.*, "Dynamic modelling shows substantial contribution of ecosystem restoration to climate change mitigation," *Environmental Research Letters*, vol. 16, no. 12, p. 124061, Dec. 2021, doi: 10.1088/1748-9326/AC3C6C.

[27] Future Earth, The Earth League, and WCRP, "10 New Insights in Climate Science 2021," Stockholm, 2021. Accessed: Feb. 15, 2021. [Online]. Available: https://doi.org/10.5281/zenodo.5639539

[28] UN Climate Change, *Johan Rockström at #COP26: 10 New Insights in Climate Science*, (2021). [Online Video]. Available: https://youtu.be/iW4fPXzX1S0?t=415

[29] G. Popkin, "How much can forests fight climate change?," *Nature*, vol. 565, no. 7739, pp. 280–282, Jan. 2019, doi: 10.1038/D41586-019-00122-Z.

[30] T. Searchinger, R. Waite, C. Hanson, and J. Ranganathan, "World Resources Report. Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050," Washington, DC, USA, 2019. [Online]. Available: https://agritrop.cirad.fr/593176/1/WRR_Food_Full_Report_0.pdf

[31] A. Bows-Larkin *et al.*, "Importance of non-CO2 emissions in carbon management," *Carbon Management*, vol. 5, no. 2, pp. 193–210, Mar. 2014, doi: 10.1080/17583004.2014.913859.

[32] C. Marchetti, "On geoengineering and the CO2 problem," *Climatic Change*, vol. 1, no. 1, pp. 59–68, 1977, doi: 10.1007/BF00162777.

[33] IEA, "Technology Roadmap: Carbon Capture and Storage in Industrial Applications," Paris, 2011. [Online]. Available: www.iea.org/reports/roadmap-carbon-capture-and-storage-in-industrial-applications

[34] Global CCS Institute, "The Global Status of CCS: 2021," Australia, 2016. [Online]. Available: https://www.globalccsinstitute.com/wp-content/uploads/2021/11/Global-Status-of-CCS-2021-Global-CCS-Institute-1121.pdf

[35] E. Martin-Roberts, V. Scott, S. Flude, G. Johnson, R. S. Haszeldine, and S. Gilfillan, "Carbon capture and storage at the end of a lost decade," *One Earth*, vol. 4, no. 11, pp. 1569–1584, Nov. 2021, doi: 10.1016/J.ONEEAR.2021.10.002.

[36] N. Wang, K. Akimoto, and G. F. Nemet, "What went wrong? Learning from three decades of carbon capture, utilization and sequestration (CCUS) pilot and demonstration projects," *Energy Policy*, vol. 158, p. 112546, Nov. 2021, doi: 10.1016/J.ENPOL.2021.112546.

[37] IEAGHG, "Towards zero emissions CCS from power stations using higher capture rates or biomass," 2019. [Online]. Available: https://climit.no/app/uploads/sites/4/2019/09/IEAGHG-Report-2019-02-Towards-zero-emissions.pdf

[38] T. Gibon, A. Arvesen, and E. G. Hertwich, "Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options," *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 1283–1290, Sep. 2017, doi: 10.1016/J.RSER.2017.03.078.

[39] B. Cahill, "The Oil Inventory Challenge," *Center for Strategic and International Studies*, 2020. https://www.csis.org/analysis/oil-inventory-challenge (accessed Feb. 11, 2022).

[40] Global Times, "As power shortages in China ease, India is still grappling with supply bottlenecks." https://www.globaltimes.cn/page/202110/1237262.shtml (accessed Feb. 11, 2022).

[41] Carbon Tracker Initiative, "Unburnable Carbon: Are the World's Financial Markets Carrying a Carbon Bubble?," 2011. https://carbontracker.org/reports/carbon-bubble/ (accessed Feb. 22, 2022).

[42] M. Meinshausen *et al.*, "Greenhouse-gas emission targets for limiting global warming to 2 °C," *Nature 2009 458:7242*, vol. 458, no. 7242, pp. 1158–1162, Apr. 2009, doi: 10.1038/nature08017.

[43] C. McGlade and P. Ekins, "The geographical distribution of fossil fuels unused when limiting global warming to 2 °C," *Nature 2015 517:7533*, vol. 517, no. 7533, pp. 187–190, Jan. 2015, doi: 10.1038/nature14016.

[44] D. Welsby, J. Price, S. Pye, and P. Ekins, "Unextractable fossil fuels in a 1.5 °C world," *Nature 2021 597:7875*, vol. 597, no. 7875, pp. 230–234, Sep. 2021, doi: 10.1038/s41586-021-03821-8.

[45] International Energy Agency, "World Energy Balances (2021 Edition). UK Data Service." [Online]. Available: https://dx.doi.org/10.5257/iea/web/2021

[46] ScienceBasedTargets.org, "Annex A - Non-energy uses of petroleum and gas products," 2020. [Online]. Available: https://sciencebasedtargets.org/wp-

content/uploads/2020/08/OG-Annex-A-Non-energy-uses-of-petroleum-and-gas-products-2.pdf

[47] M. Rocha *et al.*, "Implications of the Paris Agreement for coal use in the power sector," 2016. [Online]. Available: www.climateanalytics.org/publications

[48] J. T. Roberts and B. C. Parks, "Ecologically Unequal Exchange, Ecological Debt, and Climate Justice: The History and Implications of Three Related Ideas for a New Social Movement," *International Journal of Comparative Sociology*, vol. 50, no. 3–4, pp. 385–409, 2009, doi: 10.1177/0020715209105147.

[49] J. Martinez-Alier, "The environmentalism of the poor," 2002. [Online]. Available: https://www.unrisd.org/80256B3C005BCCF9/(httpAuxPages)/5EB03FFBDD19EA90C1257664004831BD/$file/MartinezAlier.pdf

[50] G. Muttitt and S. Kartha, "Equity, climate justice and fossil fuel extraction: principles for a managed phase out," *Climate Policy*, vol. 0, no. 0, pp. 1024–1042, 2020, doi: 10.1080/14693062.2020.1763900.

[51] C. Holz, E. Kemp-Benedict, T. Athanasiou, and S. Kartha, "The Climate Equity Reference Calculator," *Journal of Open Source Software*, vol. 4, no. 35, p. 1273, 2019, doi: 10.21105/joss.01273.

[52] SEI, IISD, ODI, E3G, and UNEP, "The Production Gap Report 2021," 2021. [Online]. Available: http://productiongap.org/2021report

[53] N. Alsharif, S. Bhattacharyya, and M. Intartaglia, "Economic Diversification in Resource Rich Countries: Uncovering the State of Knowledge," *CSAE Working Paper WPS/2016-28*, vol. 44, no. 0, pp. 1–50, 2016.

[54] P. Stevens, G. Lahn, and J. Kooroshy, "The Resource Curse revisited," *Griffith Review*, vol. 28, no. August, pp. 47–63, 2015.

[55] Martin Hvidt, "Economic diversification in GCC countries: past record and future trends. (Kuwait Programme on Development, Governance and Globalisation in the Gulf States).," London, 2014. Accessed: Mar. 02, 2022. [Online]. Available: http://eprints.lse.ac.uk/55252/

[56] Civil Society Review, "A Fair Shares Phase Out: A Civil Society Equity Review on an Equitable Global Phase Out of Fossil Fuels.," Manila, London, Cape Town, Washington, et al., 2021. [Online]. Available: http://civilsocietyreview.org/report2021/

[57] UN Climate Change, "Speech: Mia Mottley, Prime Minister of Barbados at the Opening of the #COP26 World Leaders Summit - YouTube." https://www.youtube.com/watch?v=PN6THYZ4ngM (accessed Feb. 26, 2022).

[58] Our World in Data, "World population by region." https://ourworldindata.org/grapher/historical-and-projected-population-by-region (accessed Mar. 09, 2022).

[59] IMF, "World Economic Outlook Database, April 2021." 2021. [Online]. Available: https://www.imf.org/-/media/Files/Publications/WEO/WEO-Database/2021/WEOApr2021all.ashx

[60] R. Simon, Y. Erbay, C. Henderson, and R. Taylor, "Review of International Delivery of Negative Emission Technologies (NETs)," Edinburgh, 2021. Accessed: Mar. 10, 2022. [Online]. Available: http://dx.doi.org/10.7488/era/1684

[61] IPCC, "IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy. Chapter 2: Stationary combustion.," 2006. [Online]. Available: http://link.springer.com/10.1007/BF00914340

[62] P. A. Yanguas Parra, G. Ganti, R. Brecha, B. Hare, M. Schaeffer, and U. Fuentes, "Global and regional coal phase-out requirements of the Paris Agreement : Insights from the IPCC Special Report on 1.5 ° C," *Climate analytics*, no. September, pp. 1–3, 2019.

[63] M. Damon, D. H. Cole, E. Ostrom, and T. Sterner, "Grandfathering: Environmental Uses and Impacts," *https://doi.org/10.1093/reep/rey017*, vol. 13, no. 1, pp. 23–42, Sep. 2020, doi: 10.1093/REEP/REY017.

[64] P. Dumas, C. Hanson, J. Ranganathan, T. Searchinger, and R. Waite, "Creating a Sustainable Food Future," *WRI - World Resources Institute*, vol. 1, no. 1, pp. 1–564, 2019, [Online]. Available: www.SustainableFoodFuture.org.

10 Appendix 1: Key sensitivities

10.1 Limitations and alternatives

Any assessment of pathways to eliminate fossil fuel emissions is subject to multiple assumptions. Our approach throughout this report has been to adopt a well-reasoned, sequential logic starting from peer-reviewed global carbon budgets and progressing via a sequence of observations and arguments (essentially assumptions) about key factors that influence the rate of depletion of these global budgets. Sections 2 to 6 of this report give detailed information about all of these assumptions. For rigour and transparency, we summarise them again here and offer brief commentary on how the outcomes of the analysis might be affected were alternative assumptions to be applied.

10.1.1 Selection of scenario set

Global emissions budgets form the bedrock on which the rest of the pathway analysis stands. Budgets for a 50% chance of 1.7°C, and 50% and 67% chances of 1.5°C reflect temperature and probability outcomes that the authors and client agreed appropriately represented the imperatives of the Paris Agreement to hold "the increase in the global average temperature to *well below* 2°C … and to pursue efforts to limit the temperature increase to 1.5°C." While, arguably, 67% chance goes further than 'pursuing efforts' to 1.5°C, it was considered a valid representation of both increasing high-level rhetoric on 1.5°C, and of the earlier and more serious impacts of 1.5°C that have emerged in the years since Paris.

Should a lower probability of staying at or below 1.5°C (or indeed 1.7°C) be deemed appropriate, then clearly bigger budgets and less strenuous mitigation pathways would ensue. However, such an assumption would categorically be at odds with calls from climate-vulnerable nations in the Global South to increase ambition on 1.5°C (see for example [57]), and with the scientific consensus on the severity of impacts of exceeding 1.5°C.

10.1.2 Application of precaution (ESFs, CDR, LUCF)

The assumptions made in this analysis about uncertainties regarding the effects on the global carbon budget of earth systems feedbacks (ESFs), carbon dioxide removal (CDR) and land use change and forestry (LUCF) are best characterised as conservative. That is to say, the global budgets are not downsized to reflect the potential for around 145 $GtCO_2$ of additional feedbacks for 1.5°C budgets (±97 $GtCO_2$ of ESFs per degree Celsius of warming, see §2.2.1) in a 'worst case scenario'. At the same time, we do not expand the global carbon budgets by applying planetary-scale quantities of NETs, or by assuming that the land use sector will compensate for emissions of CO_2 over and above the carbon budgets.

Should a stronger framing of precaution be preferred, one might factor in the additional feedbacks identified in AR6. This would mean that, to retain a 50% chance of 1.5°C, it would be necessary to follow a pathway slightly below the one offered here for 67% chance of 1.5°C. In other words, removing 145 $GtCO_2$ of additional feedbacks from the 50% chance of 1.5°C budget would leave rather less than in the 67% chance of 1.5°C budget (361 $GtCO_2$, for a 50% chance,

would come down to around 216 $GtCO_2$ – i.e. 45 $GtCO_2$ less than the budget for a 67% chance of 1.5°C).

With regard to CDR, a more bullish (less precautionary) approach might advocate for greater inclusion of CO_2 removal through (amongst others) reforestation, afforestation, BECCS, DACCS and so on. Setting aside the arguments in §3.2 for why, with specific reference to fossil fuel CO_2, this analysis rejects such a move, it is worth remembering that any available CDR should be counted first against unavoidable emissions from agriculture. Only then, and if there are surplus levels of 'removal', should the NETs component of CDR be considered in relation to fossil fuels, for which ready alternatives exist (through a combination of energy supply and demand management).

To recap: in this analysis we assume that any CO_2 released from deforestation and the broader land use sector (including agriculture)[42] will be compensated by sequestration of CO_2 through LUCF over the course of the century. Simultaneously, we optimistically assume that residual emissions of non-CO_2 GHGs from agriculture will be reduced to around 4 to 7 $GtCO_2e$/year by mid-century and hold constant thereafter. In other words, this analysis does not reject CDR, rather it indirectly assumes that any warming from non-CO_2 agricultural emissions will be compensated by some form of CDR.

Should a case be convincingly made for deliverable CDR over and above that assumed here for agriculture, it would have the effect of increasing the probability of a given phaseout pathway being compatible with its respective temperature threshold. For example, if in addition to the CDR necessary to compensate for non-CO_2 warming, there were a further 100 $GtCO_2$ of verifiable and permanent CDR, then this would effectively 'relax' the pathway for a 67% chance of staying below 1.5°C to that of the 50% pathway.

10.1.3 Process emissions

This analysis followed the approach in *Factor of Two* [16], extrapolating the cement industry growth rate in IEA's Cement Technology Roadmap out across the rest of the century. A key assumption was that cement, as an essential material in the construction of zero-carbon energy networks everywhere and other essential infrastructure in developing countries, will continue to be so for several decades to come. However, as noted in §2.2.3, the slowdown in growth rate assumed in the IEA Roadmap is highly optimistic, with no precedent in the post-WW2 era. For this reason we applied a slower rate of decline in cement process emissions in our 1.7°C scenario, (resulting in 100 $GtCO_2$ overhead in the 1.7°C scenario, as opposed to a 60 $GtCO_2$ overhead in the more constrained 1.5°C scenarios). This more precautionary 100 $GtCO_2$ overhead for cement is incompatible with the 50% and 67% 1.5°C budgets. But the more optimistic 60 $GtCO_2$ overhead could, of course, be applied to the 1.7°C scenario. This would mean an additional 40 $GtCO_2$ for our fossil fuel scenarios, equating to one more year of oil and gas production (at current levels). However, this would be at the expense of a major reduction in cement availability to developing countries.

10.1.4 CCS on fossil fuels

In §3.3 we discuss the rationale for not assuming any relaxation of the production emissions budgets on the basis of carbon capture and storage on fossil fuel use. In view of the slow rate of delivery of CCS projects – which, importantly, is *much* slower than touted by the fossil fuel industry – it is our judgement that CCS can contribute virtually nothing towards achieving 1.5°C-compatible pathways. Such pathways require complete decarbonisation of the energy system in developed countries by the early 2030s (see Table 6 and panels B and C of Figure 4).

Without invoking rates of CCS development and roll-out that are beyond anything discussed in the literature, then, only scenarios incompatible with 1.5°C have the flexibility to accept any contribution from CCS. That being so, increased deployment of CCS could allow marginally more fossil fuel use (and by extension production) within 1.7°C-and-warmer scenarios. However, the ongoing track-record of under-delivery in CCS does not support the positing of large-scale deployment even within the 2030s to 2040s phaseout timeframe of 1.7°C scenarios. Thus, the extra budgetary flexibility afforded is likely to be minor (a few gigatonnes of CO_2 at best) over the timeframe of concern for 1.7°C. The difference to phaseout pathways and end dates for oil and gas production from this additional CCS would be similarly trivial, measured in extra months of production (at baseline levels) rather than years.

10.1.5 Coal phaseout parameters

The phaseout pathways for coal production are sensitive to several key assumptions, as follows.

(i) The end year for production for Developed and Developing producer nations;
(ii) The peak year for production in both Developed and Developing nations;
(iii) The phaseout trajectory or pathway shape for Developed and Developing nations (which determines their relative share of the total coal budget);
(iv) The percentage share of the overall global carbon budget that was allowed to be consumed by coal production.

See Table 6 for the key input parameter values, and Table 2 for the outcome of those values with respect to the relative share of the global budget given to coal, oil and gas.

The underpinning analysis for coal was iterative insofar as the interplay of these parameters was configured to represent the fastest feasible phaseout of coal in both Developed and Developing producers. Coal pathway development was subject to deliberative judgement by the authors, client and civil society consultees regarding real-world limitations on rates of transition in both Developed and Developing nations' coal production.

The resulting coal pathways for 1.5°C scenarios are immensely challenging; we assume that Developed countries cease coal production by 2030-1 and Developing countries end by 2037-40. Since our coal assumptions were taken to be maximally demanding, alternative assumptions regarding parameters (i)–(iv) above would likely have the effect of relaxing the rate of phaseout of coal production. Note that our 1.7°C scenario is the only one in which coal occupies less of the total global carbon budget than its current share (in the baseline year). In both 1.5°C

scenarios coal is effectively held at its current share of cumulative emissions. This is because faster phaseout was considered implausible without major constraints on access to energy in Developing countries (the major users and producers of coal) on the one hand, or ignoring real world inertia in energy system transformation by pushing Developed countries to end coal in less than eight years on the other. To argue for a faster trajectories or earlier end dates than reflected in the 1.5°C pathways here, one would have to give an account of how these access-to-energy and inertia-based constraints could be overcome. Conversely, to assign slower trajectories or later end dates for coal production (or later peak production in Developing countries) than in the 1.5°C scenarios, one would have to justify giving more budget space to coal than its baseline share (41%), with all the energy efficiency penalties that brings.

In the case of the 1.7°C scenario, there is a little more flexibility. Should the immensely challenging 1.5°C coal phaseout pathways be applied to the 1.7°C budget, it would increase space for oil and gas and postpone their production end dates by a few years for each country group. However, this would be at the cost of substantially limiting access to energy (especially in the short-term) in Developing countries, a constraint out of kilter with the overall pace of reductions in the 1.7°C scenario.

10.1.6 Capacity parameters

The estimation of producer nations' relative capacities to make a just transition away from oil and gas production is based on several key assumptions.

First, the list of producers includes only countries with currently operational oil and/or gas production facilities. As such, potentially soon-to-be producers such as Namibia, Mozambique et al are not considered within the phaseout schedules in this report. This is a limitation of available data and project time, not to mention that the precarious political and security situations of some aspiring producers makes estimation of likely future output too speculative for inclusion at present.

Second, to differentiate the eighty-eight currently operational producers (with at least 0.5 mtoe output of oil and/or gas per year), this report developed a novel metric of 'non-oil-and-gas GDP', adjusted for PPP/capita (see §5.3.1). Compiling this dataset was subject to several limitations, not least the fact that there is no universal standard for reporting the contribution of oil and gas production (or indeed any industry sector) to GDP. Hence, data were gathered from a variety of internet sources (see Table 8). These sources were inevitably heterogeneous with respect to system boundaries (estimates for some countries included both direct and indirect revenue from the sector, others direct only, still others potentially referred only to economic rents); time period (often indeterminate); and aggregation with other extractive industries (such as coal, mineral ores etc).

Other proxies for capacity to transition were explored in the early stages of our analysis, including economic rents and the share of government budget from oil and gas revenues. These were rejected as being too narrow to capture the full extent of economic dependency on

hydrocarbon production, not to mention offering scarcely more complete datasets than non-oil GDP. Nevertheless, adopting an alternative proxy for capacity would doubtless have the effect of moving some producers up or down the rankings in Figure 3. However, while a different proxy would change the composition (or membership) of the groups, it would not affect the allocation of emissions budget between groups.

10.1.7 Country grouping parameters

The ordering of producers into groups sharing broadly similar levels of capacity to transition away from oil and gas production is subject to the following key assumptions.

First, 2019 was selected as the reference year for GDP/capita (PPP), being the most recent year for which an almost complete dataset exists. National GDPs can vary not insignificantly from year to year, especially for oil and gas producing countries subject to the forces of global supply and demand. As such, choosing a different reference year for GDP/capita would affect the relative position of producers in the rankings shown in Figure 3. Similarly, choosing a different PPP adjustment to GDP/capita (such as 'constant 2017 international dollars' rather than 'current international dollars') would also affect some countries' ordinal position in the overall ranking.

Second, the break points for country groupings were based on mathematical averages (mean and median) of the non-oil GDP dataset, plus the development threshold at $7,500. Clearly, different groupings would emerge if alternative boundaries were set. The level of the development threshold is the most obvious candidate for further exploration. Indeed some reviewers (of an earlier draft of this report) suggested an additional lower break point might be applied to subdivide the large group of lowest capacity countries (Group 5), and render even more subtly differentiated phaseout schedules for the poorest and 'very poorest' producers.

Further to this, consideration was given to breaking Groups 1 and 5 into two more subgroups each, but was rejected for two reasons. First, project constraints limited the number of iterations possible in the analysis that builds on these groupings. Second, the inherent imprecision in the underlying data for the oil and gas share of GDP (see §10.1.6 above) means that further subdivision would risk placing undue emphasis on the exact values of non-oil GDP rather than on relative values. With access to more precise data on the contribution of oil and gas to the GDP of all eighty-eight producer nations, budgets and pathways could be derived for each country separately. However, researching and compiling such a dataset from scratch would require substantial further research, considerably beyond the scope of the present work.

As with the sensitivities around capacity parameters, fine tuning the grouping parameters is relevant only to the precise outcomes for individual countries (insofar as it assigns them to a particular group); it does not affect the differentiation between pathways for those groups.

10.1.8 Differential phaseout parameters

The final step of our analysis disaggregated the budgets for oil and gas to five groups of producers according to their grandfathered starting positions, before attempting to rebalance these shares in accordance with the equity principles of CBDR-RC. The key parameters in this process are as follows.

(i) Use of each group's share of aggregate absolute deviation as the basis for the capacity weightings. As always, alternative proxies or metrics would yield slightly different country rankings and groupings. For example, the proportion of 'excess' national income above the global poverty threshold could be used to determine weightings. In principle this would accord a higher budgetary reallocation benefit to the poorest countries (which have negative 'excess' in relation to the poverty line). Such a re-weighting would work well with more finely delineated groups, or indeed country-by-country, based on better data on non-oil GDP. However, given the acknowledged imprecision of the non-oil GDP data and the need for a manageable number of discrete groups, it was deemed more appropriate to take group means and shares of aggregate absolute deviation as broadly capturing the relative capacity characteristics of each group.

(ii) The extent of budgetary reallocation between groups was capped at 20% of the combined grandfathered budgets of Groups 1 and 2. This was held constant across all three scenarios. The outcome of this, as noted in §6.3, is that the differentiation between phaseout pathways becomes less equitable as the budgets get tighter for higher probabilities of 1.5°C. It goes almost without saying that altering this reallocated percentage would have noticeable outcomes for the end dates for all five groups, with a greater percentage yielding earlier end dates for Groups 1 and 2 and later end dates for Groups 3, 4 and 5.

It is worth noting that the 20% value emerged from an iterative and deliberative process of calibrated pathway adjustments, with 'feasibility for all' groups being the final arbiter of selection. For a 50% or better chance of 1.5°C, a 20% reallocation renders end dates for Groups 1 and 2 in the 2030s, with 74% and 43% reduction by 2030 respectively. Applying a greater percentage reallocation would bring the Group 1 end date to within a handful of years from now. Applying a smaller percentage reallocation would place the pathways further from a reasonable interpretation of CBDR-RC, and require even more emphasis on financial transfers and reparations from wealthy to poor producers.

(iii) Phaseout end dates on the logit-based, sigmoidal pathways shown in Figure 4 are sensitive to an exogenous gradient value[43]. Put simply, the lower (or shallower) the gradient, the later the end date for a given budget. A simplifying assumption was made across the board for all pathways[44] to set the gradient as low as possible down to a lower limit of 0.3. Higher gradients would render more 'front-loaded' pathways with earlier end dates. Since such pathways consume a greater share of the emissions space in the early years, they rely heavily on steeper rates of reduction soon after. Therefore more evenly-paced phaseout schedules were preferred wherever possible to increase likelihood of compliance. Gradients lower than 0.3 render pathways with very long tails of production (especially for Groups 4 and 5), with small quantities of production

extending into the later decades of the century. In such pathways, these small but lingering quantities of production were considered antithetical to the wider interests of global decarbonisation.

(iv) End dates are sensitive to the value taken to mark 'functional zero'; in this report we used 5% of baseline production. Clearly, setting the bar of elimination higher by selecting a lower remaining percentage of baseline production would suggest later end dates for the same pathway. However, given the diminishing returns from dwindling amounts of oil and gas, 5% reflects the likelihood of a final 'coup-de-grâce' closure of the last few facilities in a producer country. Setting the bar of elimination lower with a higher remaining percentage would suggest earlier end dates for the same pathways.

SECTION FOOTNOTES

[42] Sometimes referred to by the acronym AFOLU, for agriculture, forestry and other land use.

[43] Logit-curve based pathways were constrained to cumulative group budgets using:

y =L/(-K*(1+EXP(A1-x0)))

where L = the curve's maximum y-value (production emissions in the baseline year)
x0 = the x-value of the sigmoid midpoint (obtained from number of years of current production in budget)
K = the steepness or gradient of the curve (constant, set as low as possible down to 0.3)

[44] The sole exception being the gradient of Group 5's pathway in the central scenario, (50% chance of 1.5°C), which was set at 0.25 (a single decrement lower than 0.3) to better reflect the strong preference amongst civil society reviewers for a later end date (for the same cumulative budget) for this poorest group of producers.

11 Appendix 2: Key data

Table 7: Key data on eighty-eight producer nations.

COLUMN 1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Producer country	**Deve-loped or Deve-loping**	**Total oil & gas prod'n mtoe (2018)**	**% of global O&G prod'n (2018)**	**Popul-ation, millions (2017)**	**GDP/cap 2019, PPP (current int.$)**	**Oil & gas % of GDP**	**Non-oil GDP/cap. 2019 (PPP, current $)**	**Producer Group in this report**
Ireland	DD	3	0.03%	4.8	91,812	ND	90,894	1
United States	DD	1404	17.87%	325.1	65,254	8%	60,098	1
Denmark	DD	10	0.12%	5.7	60,379	2%	59,139	1
Netherlands	DD	29	0.37%	17.0	59,517	1%	58,922	1
Austria	DD	2	0.02%	8.8	58,685	1%	58,098	1
Qatar	DD	219	2.79%	2.7	95,108	40%	57,065	1
Norway	DD	193	2.46%	5.3	65,905	14%	56,678	1
Germany	DD	8	0.10%	82.7	56,226	ND	55,664	1
Australia	DD	115	1.46%	24.6	52,712	3%	51,131	1
France	DD	1	0.01%	64.8	49,696	ND	49,199	1
United Kingdom	DD	88	1.12%	66.7	48,603	1%	48,020	1
United Arab Emirates	DD	232	2.95%	9.5	63,590	27%	46,618	1
Canada	DD	422	5.37%	36.7	51,481	10%	46,385	1
Bahrain	DD	22	0.29%	1.5	51,948	11%	46,234	1
South Korea	DD	1	0.01%	51.1	44,573	ND	44,127	1
Italy	DD	10	0.12%	60.7	44,218	ND	43,775	1
Japan	DD	3	0.03%	127.5	43,710	ND	43,273	1
New Zealand	DD	5	0.06%	4.7	43,689	1%	43,125	1
Israel	DD	8	0.10%	8.2	41,786	ND	41,368	1
Estonia	DD	5	0.06%	1.3	38,480	4%	36,941	2
Poland	DD	5	0.06%	38.0	34,624	ND	34,278	2
Hungary	DD	3	0.03%	9.7	34,327	ND	33,984	2
Romania	DD	12	0.15%	19.7	31,244	ND	30,931	2
Croatia	DD	2	0.02%	4.2	29,925	ND	29,626	2
Turkey	DD	3	0.04%	81.1	29,724	ND	29,426	2
Kuwait	DD	165	2.09%	4.1	46,018	40%	27,611	2
Chile	DG	1	0.02%	18.5	24,969	ND	24,719	2
Saudi Arabia	DD	665	8.47%	33.1	49,216	50%	24,608	2

Producer country	Deve-loped or Deve-loping	Total oil & gas prod'n mtoe (2018)	% of global O&G prod'n (2018)	Popul-ation, millions (2017)	GDP/cap 2019, PPP (current int.$)	Oil & gas % of GDP	Non-oil GDP/cap. 2019 (PPP, current $)	Producer Group in this report
Brunei	DD	16	0.21%	0.4	61,032	60%	24,413	2
Kazakhstan	DG	128	1.63%	18.1	27,292	13%	23,662	2
Malaysia	DG	93	1.19%	31.1	29,043	20%	23,234	2
Russia	DD	1165	14.83%	145.5	28,450	19.2%	22,988	2
Argentina	DG	65	0.83%	43.9	22,997	4%	22,123	2
Mexico	DG	131	1.67%	124.8	20,796	4%	20,068	3
Belarus	DD	2	0.02%	9.5	19,984	ND	19,785	3
Oman	DD	82	1.04%	4.7	30,654	36%	19,619	3
Serbia	DG	1	0.02%	8.8	19,027	ND	18,837	3
Thailand	DG	43	0.54%	69.2	19,234	3%	18,657	3
Suriname	DG	1	0.01%	0.6	16,768	ND	16,600	3
China (inc. HK)	DG	325	4.13%	1421.0	16,659	3%	16,160	3
Trinidad & Tobago	DG	34	0.44%	1.4	26,920	40%	16,152	3
Colombia	DG	56	0.71%	48.9	15,345	5%	14,577	3
Brazil	DG	160	2.04%	207.8	15,454	10%	13,847	3
Albania	DG	1	0.01%	2.9	14,534	6%	13,648	3
Peru	DG	18	0.22%	31.4	13,328	3%	12,995	4
Cuba	DG	4	0.05%	11.3	13,028 †	ND	12,898	4
South Africa	DG	1	0.01%	57.0	12,962	ND	12,832	4
Ukraine	DG	19	0.24%	44.5	13,442	5%	12,752	4
Mongolia	DG	1	0.01%	3.1	12,558	ND	12,433	4
Indonesia	DG	102	1.30%	264.7	12,483	12%	10,985	4
Tunisia	DG	4	0.05%	11.4	11,075	ND	10,964	4
Turkmenistan	DG	79	1.01%	5.8	16,438	35%	10,685	4
Vietnam	DG	21	0.27%	94.6	10,535	ND	10,430	4
Iran	DG	401	5.11%	80.7	12,858	23%	9,901	4
Egypt	DG	83	1.06%	96.4	12,445	24%	9,458	4
Ecuador	DG	28	0.35%	16.8	11,924	21%	9,420	4
Philippines	DG	4	0.05%	105.2	9,356	ND	9,263	4
Azerbaijan	DG	55	0.70%	9.8	15,076	44%	8,443	4
Guatemala	DG	1	0.01%	16.9	8,487	ND	8,402	4

Producer country	Deve-loped or Deve-loping	Total oil & gas prod'n mtoe (2018)	% of global O&G prod'n (2018)	Popul-ation, millions (2017)	GDP/cap 2019, PPP (current int.$)	Oil & gas % of GDP	Non-oil GDP/cap. 2019 (PPP, current $)	Producer Group in this report
Bolivia	DG	19	0.24%	11.2	9,064	8%	8,339	4
Algeria	DG	155	1.98%	41.4	11,895	30%	8,326	4
Gabon	DG	10	0.13%	2.1	16,272	50%	8,136	4
Equatorial Guinea	DG	14	0.18%	1.3	19,286	60%	7,715	4
India	DG	67	0.85%	1338.7	6,992	2%	6,887	5
Uzbekistan	DG	53	0.68%	32.0	7,382	16%	6,201	5
Libya	DG	70	0.89%	6.6	14,599	60%	5,840	5
Venezuela	DG	110	1.40%	29.4	7,344	25%	5,508	5
Ghana	DG	10	0.13%	29.1	5,688	4%	5,472	5
Bangladesh	DG	23	0.30%	159.7	5,330	1%	5,298	5
Ivory Coast	DG	3	0.04%	26.4	5,318	ND	5,264	5
Pakistan	DG	23	0.30%	207.9	5,204	ND	5,152	5
Nigeria	DG	136	1.73%	190.9	5,353	10%	4,817	5
Myanmar	DG	16	0.20%	53.4	5,054	5%	4,817	5
Iraq	DG	241	3.07%	37.6	11,379	65%	3,983	5
Sudan	DG	4	0.06%	40.8	4,310	8%	3,965	5
Angola	DG	78	0.99%	29.8	7,346	50%	3,673	5
Cameroon	DG	5	0.06%	24.6	3,801	4%	3,664	5
Papua New Guinea (*)	DG	11	0.14%	8.4	4,022	18%	3,316	5
Syria	DG	4	0.05%	17.1	2,900 ‡	ND	2,871	5
Tanzania	DG	1	0.01%	54.7	2,841	ND	2,812	5
Timor-Leste (*)	DG	6	0.08%	1.2	3,703	36%	2,370	5
Congo	DG	18	0.23%	5.1	4,600	65%	1,610	5
Yemen	DG	2	0.02%	27.8	2,057	24%	1,561	5
Chad (*)	DG	8	0.10%	15.0	1,654	27%	1,208	5
Mozambique	DG	4	0.05%	28.6	1,302	8%	1,198	5
Niger	DG	1	0.01%	21.6	1,276	7%	1,187	5
D.R. Congo	DG	1	0.01%	81.4	1,130	ND	1,118	5
South Sudan	DG	7	0.08%	10.9	862	60%	345	5

DD = Developed; DG = Developing; ND = no data available, 1% default value assumed.

Data sources for Table 7 were as follows:

- Column 2 classification follows that established in *Factor of Two* [16]. In this report, DD is equivalent to *Factor of Two*'s DD2, i.e. Annex-1 nations plus those non-Annex 1 oil-rich states with GDP/capita and HDI values above the mean of developed nations. DG is equivalent to *Factor of Two*'s DG2.
- Column 3 energy data extracted from International Energy Agency, World Summary Energy Balances [45], except those marked (*) from U.S. Environmental Information Agency.
- Column 5 population data from OurWorldinData.org [58].
- Column 6 GDP/capita (PPP) from IMF World Economic Outlook [59]. † Cuba value is for 2016. ‡ Syria value is for 2015.
- Column 7 contribution of oil and gas to national GDP: drawn from multiple online sources, as shown in Table 8 below.

Table 8: sources for contribution of oil and gas to national GDP

Ireland	No data
United States	https://www.naturalgasintel.com/natural-gas-oil-found-to-support-sizeable-chunk-of-u-s-gdp-including-pennsylvania/
Denmark	https://ens.dk/en/our-responsibilities/oil-gas/economy-oil-and-gas
Netherlands	https://www.cbs.nl/en-gb/news/2019/22/natural-gas-revenues-almost-417-billion-euros
Austria	No data
Qatar	https://www.nationsencyclopedia.com/economies/Asia-and-the-Pacific/Qatar-OVERVIEW-OF-ECONOMY.html
Norway	https://oilprice.com/Latest-Energy-News/World-News/Oil-Gas-Share-Of-Russias-GDP-Dropped-To-15-In-2020.html
Germany	No data
Australia	https://www.upstreamonline.com/finance/oil-and-gas-industry-270-billion-boost-to-australias-economy/2-1-1025044
France	No data
United	https://www.ofgem.gov.uk/sites/default/files/docs/2020/02/oguk_evidence_economic_report_2019.pdf
United Arab	https://www.statista.com/statistics/1105966/uae-oil-and-gas-sector-gdp/
Canada	https://oilprice.com/Latest-Energy-News/World-News/Oil-Gas-Share-Of-Russias-GDP-Dropped-To-15-In-2020.html
Bahrain	https://globaledge.msu.edu/countries/bahrain/economy
South Korea	No data
Italy	No data
Japan	No data
New Zealand	https://www.stuff.co.nz/business/110700136/new-report-estimates-oil-and-gas-ban-will-cost-taranaki-30bn
Israel	No data
Estonia	https://icds.ee/wp-content/uploads/2015/Jordan_Kearns_-_Trends_in_Estonian_Oil_Shale_Utilization_Oct_2015.pdf
Poland	No data
Hungary	No data
Romania	No data
Croatia	No data
Turkey	No data

Kuwait	https://www.opec.org/opec_web/en/about_us/165.htm
Chile	No data
Saudi Arabia	https://oilprice.com/Latest-Energy-News/World-News/Oil-Gas-Share-Of-Russias-GDP-Dropped-To-15-In-2020.html
Brunei	https://globaledge.msu.edu/countries/brunei/economy
Kazakhstan	https://oilprice.com/Latest-Energy-News/World-News/Oil-Gas-Share-Of-Russias-GDP-Dropped-To-15-In-2020.html
Malaysia	https://www.internationalinvestor.com/malaysia/sectors/oil-gas/summary/
Russia	https://oilprice.com/Latest-Energy-News/World-News/Oil-Gas-Share-Of-Russias-GDP-Dropped-To-15-In-2020.html
Argentina	https://eiti.org/argentina
Mexico	https://eiti.org/mexico
Belarus	No data
Oman	https://www.brookings.edu/blog/order-from-chaos/2021/01/13/one-year-into-his-reign-omans-sultan-must-renegotiate-the-social-contract-and-prioritize-diversification/
Serbia	No data
Thailand	Various sources pointing to less than 3%
Suriname	No data
China (inc.	https://data.stats.gov.cn/english/easyquery.htm?cn=C01
Trinidad and	https://www.cia.gov/the-world-factbook/countries/trinidad-and-tobago/
Colombia	https://eiti.org/es/implementing_country/17
Brazil	https://www.iioa.org/conferences/16th/files/Papers/Guilhoto Oil Business BR Guilhoto et al.pdf
Albania	https://eiti.org/albania
Peru	https://eiti.org/files/documents/vii_informe_nacional_eiti_peru_2017-2018.pdf
Cuba	No data
South Africa	No data
Ukraine	https://eiti.org/fr/implementing_country/26
Mongolia	No data
Indonesia	https://www.thejakartapost.com/news/2020/03/02/analysis-unlocking-indonesia-s-500b-oil-and-gas-revenue-opportunity.html
Tunisia	No data
Turkmenistan	https://www.trade.gov/country-commercial-guides/turkmenistan-market-overview
Vietnam	No data, other than rapidly declining.
Iran	https://tradingeconomics.com/iran/gdp
Egypt	https://www.trade.gov/country-commercial-guides/egypt-oil-and-gas-equipment
Ecuador	https://www.icontainers.com/us/2020/03/23/ecuador-main-imports-and-exports/
Philippines	Various sources pointing to steep decline with natural gas reserves exhausted by 2027
Azerbaijan	https://www.privacyshield.gov/article?id=Azerbaijan-Market-Overview
Guatemala	No data
Bolivia	https://www.eia.gov/international/analysis/country/BOL
Algeria	https://theodora.com/wfbcurrent/algeria/algeria_economy.html
Gabon	https://www.mordorintelligence.com/industry-reports/gabon-oil-and-gas-market
Equatorial	https://www.eia.gov/international/analysis/country/GNQ
India	https://statisticstimes.com/economy/country/india-gdp-sectorwise.php
Uzbekistan	https://www.export.gov/apex/article2?id=Uzbekistan-Oil-and-Gas-Industry
Libya	https://www.opec.org/opec_web/en/about_us/166.htm
Venezuela	https://www.investopedia.com/ask/answers/032515/how-does-price-oil-affect-venezuelas-economy.asp
Ghana	https://eiti.org/ghana
Bangladesh	http://203.112.218.65:8008/WebTestApplication/userfiles/Image/GDP/GDP_2015-16_p.pdf
Ivory Coast	Various sources pointing to small but growing fraction.

Pakistan	No data
Nigeria	https://www.statista.com/statistics/1165865/contribution-of-oil-sector-to-gdp-in-nigeria/
Myanmar	https://www.statista.com/statistics/1062945/myanmar-gdp-contribution-energy-sector/
Iraq	http://documents.worldbank.org/curated/en/771451524124058858/pdf/125406-WP-PUBLIC-P163016-Iraq-Economic-Monitor-text-Spring-2018-4-18-18web.pdf
Sudan	https://www.researchgate.net/publication/259484744_Oil_and_Agriculture_in_the_Post-Separation_Sudan
Angola	https://theodora.com/wfbcurrent/angola/angola_economy.html
Cameroon	https://eiti.org/es/implementing_country/20
Papua New	https://eiti.org/ru/implementing_country/46
Syria	No data
Tanzania	No data
Timor-Leste	https://eiti.org/timorleste
Congo	https://globaledge.msu.edu/countries/republic-of-congo/economy
Yemen	https://reliefweb.int/sites/reliefweb.int/files/resources/yseu14_english_final_1.pdf
Chad (*)	https://globaledge.msu.edu/countries/chad/memo
Mozambique	https://eiti.org/files/documents/itie_mocambique_9o_relatorio_i2a_consultoria_versao_inglesa_002.pdf
Niger	https://www.savannah-energy.com/operations/niger/country-overview/
D.R. Congo	https://eiti.org/democratic-republic-of-congo
South Sudan	https://www.oecd-ilibrary.org/south-sudan_5jfvt664hzmp.pdf?itemId=%2Fcontent%2Fcomponent%2Faeo-2017-58-en&mimeType=pdf