Question: How can Australia create legislation that would manage the safe disposal of solar photovoltaic ('PV') modules?

Introduction

Hundreds of millions of solar panels have been installed globally. It is estimated that by 2050 there will be between 60 and 70 million tonnes of photovoltaic ('PV') waste in circulation.[1] Most solar PV modules have not yet reached the end of their expected productive life of 25 years.[2] PV waste is expected to be a huge problem because of the exponential growth of solar. It is the most popular renewable energy in the world[3] and disposal of PV modules into landfill and burning on a large scale is not an option.[4] Australia and Germany have the highest uptake of solar PV power per capita.[5] Even though Germany and the European Union have specific legislation and facilities to deal with recycling, reuse and disposal, there are no waste disposal facilities for solar PV modules in Australia and there is no specific legislation to deal with the waste. The question is, how can Australia create legislation that would manage the safe disposal of solar PV modules? This literature review will evaluate the legislation for safe disposal of PV modules in Europe, the possibilities of recycling and reusing valuable materials from solar PV modules, the economics of establishing recycling and reuse facilities and the current legislation in Australia dealing with hazardous waste.

Six massive solar farms have already been approved for construction around Wellington in NSW.[6] They are part of the new Central-West Orana Renewable Energy Zone.[7] The Suntop[8] and Wellington Solar Farms[9] are already under

[1] C.C. Farrell et al, 'Technical challenges and opportunities in realizing a circular economy for waste photovoltaic materials' (2020) *Renewable and Sustainable Energy Reviews* 128 <https://www.sciencedirect.com/science/article/pii/S1364032120302021>.

[2] Peter Majewski et al, 'Recycling of solar PV panels-product stewardship and regulatory approaches' (2021) *Energy Policy* 149 <https://www.sciencedirect.com/science/article/pii/S0301421520307734>.

[3] Andrew Blakers, 'Solar is now the most popular form of new renewable electricity generation worldwide' *The Conversation* (online, 3 August 2017) <https://theconversation.com/solar-is-now-the-most-popular-form-of-new-electricity-generation-worldwide-81678>.

[4] Peter Majewski et al, n 2.

[5] Ibid.

[6] Manager Strategic Planning Services, Dubbo Regional Council, 'Wellington Renewable Energy Developments – Proposed Planning Agreement Policy for Solar Farms' (Report CCL19/37, 12 March 2019) <file:///C:/Users/Nat/Downloads/Council%20Report%20%20(4).pdf>.

[7] Energy NSW, *Renewable Energy Zones* (Web Page) <https://energy.nsw.gov.au/renewables/renewable-energy-zones>.

[8] Canadian Solar, *Suntop Solar Farm* (Web Page, 2021) <https://suntopsolarfarm.com.au/news-2/>.

[9] Lightsource bp, *Wellington Solar Farm* (Web Page, 2021) <https://www.lightsourcebp.com/au/projects/wellington-solar-farm/>.

construction and over 1 million solar PV modules are already installed. Six million solar PV modules have been approved for use by the NSW Department of Planning in the Wellington district. Each one of the development consents requires the proponents to remove solar PV modules at decommissioning and restore land capability to pre-existing use within 18 months.[10] All are located on prime agricultural land that is used for mixed farming and cropping. No one knows where the solar PV modules are to be removed to, or what is to happen to them once they are removed. Renewable Energy Zones are proposed to be established in Queensland, NSW, Victoria, South Australia and Tasmania and are a high priority initiative for the National Electricity Market.[11]

Toxicity of PV materials

Majewski et al explains that PV materials contain dangerous elements such as lead, cadmium and chromium and if dumped into landfill could leach into and poison the soil as well as the water table. If burnt, harmful carcinogens and tertatogens will be released into the atmosphere and human health adversely effected. The Rural Fire Service forbid volunteer members to enter Solar Farms and put bushfires out. Special breathing equipment and training is required so that potentially toxic fumes and smoke from plastics are not inhaled.[12] Backstrom and Dini found that severely damaged PV modules are capable of producing hazardous conditions and are dangerous.[13] Yang et al went further and found that exposing the PV materials to high heat fluxes in controlled experiments could be very dangerous and can cause death. PV modules mounted on buildings can be even more dangerous when exposed to real fires because they are 5-10 times thicker than the experimental models.[14]

[10] Department of Planning and Environment, *Suntop Solar Farm* (Web Page) <https://majorprojects.planningportal.nsw.gov.au/prweb/PRRestService/mp/01/getContent?AttachRef=SSD-8696-MOD-1%2120191011T041001.703%20GMT>.

[11] Infrastructure Australia, *National Electricity Market: Renewable Energy Zones* (Web Page, 26 February 2021) <https://www.infrastructureaustralia.gov.au/map/national-electricity-market-renewable-energy-zone-expansions>.

[12] Adrian Pyrke, *Gunnedah Solar Farm Bushfire Risk Assessment* (Report, 5 April 2018) 2.7 ,3.4 <https://majorprojects.planningportal.nsw.gov.au/prweb/PRRestService/mp/01/getContent?AttachRef=SSD-8658%2120190410T050245.694%20GMT>.

[13] Robert Blackstrom and Dave Dini, 'Firefighter safety and photovoltaic research project' (Research Paper, 2012) <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/8472/1/Firefighter-safety-and-photovoltaic-installations-research-project/10.1117/12.965313.short>.

[14] Hong-Yun Yang et al, 'Experimental studies on the flammability and fire hazards of photovoltaic modules' (2015) 8(7) *Materials*

Globally, most e-waste ends up in landfill with other municipal solid waste ('MSW') or is incinerated with little gas-emission control. Farrell et al[15] explained that landfilling is not sustainable in the long-term for solar PV modules because of the sheer number of modules and the volume of heavy metals such as lead and tin that will leach or contaminate into the soil or groundwater. It was noted that the leaching process results in the generation of toxic nitrogen oxides and creates long-term significant environmental pollution issues.[16]

What happens in Europe

Majewski et al also observed that only Europe has specific regulations for the recycling of solar PV materials.[17] In 2003, Europe developed recycling regulations that aimed to reduce the amount of electronic waste in landfills. The Waste Electrical and Electronic Waste Directives ('WEEE')[18] and hazardous material restriction ('RoHS')[19] were introduced. Under the WEEE legislation producers who wished to enter into the EU market were made legally responsible for managing the end-of-life ('EoL') of the products irrespective of where they were manufactured. The WEEE manages collection, treatment and disposal of products. It also puts restrictions on the design of goods to ease EoL treatments. The WEEE directives were revised in 2012 and specifically included waste PV modules. That meant that 75%/65% (recovery/recycling rate) of waste PV modules by mass were to be recycled during 2016. 80%/75% were to be recycled in 2018 and 85%/80% after 2018.[20] The question arises whether or not this addresses the sheer volume of PV waste without causing an unwanted environmental legacy.

For e-waste from private consumers, companies are required to deposit a certain amount of funds for the EoL treatment of each device sold. This system is called

<https://www.researchgate.net/publication/281736927_Experimental_Studies_on_the_Flammability_and_Fire_Hazards_of_Photovoltaic_Modules>.

[15] C.C. Farrell et al, n 1.

[16] Ibid.

[17] Peter Majewski et al, n 2.

[18] *Directive 2012/19/EU of the European Parliament and of the Council of 19 January 2012 on Waste Electrical and Electronic Equipment (WEEE)* <https://www.eea.europa.eu/policy-documents/waste-electrical-and-electronic-equipment>.

[19] *Directive 2002/95/EC of the European Parliament and of the Council of 1 July 2006 on the Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS)* <https://www.rohsguide.com/rohs-faq.htm#:~:text=RoHS%20stands%20for%20Restriction%20of,products%20(known%20as%20EEE)>.

[20] Ibid.

business to consumer regulation ('B2C'). Besides e-waste from private households, producers are also responsible for e-waste from other sources such as business to business equipment. If the equipment was purchased prior to the introduction of the WEEE legislation, the producer must offer a reasonable option for its return and disposal.[21]

Farrell et al concurred with Majewski et al, but went further and explained the waste hierarchy adopted in Europe.[22]

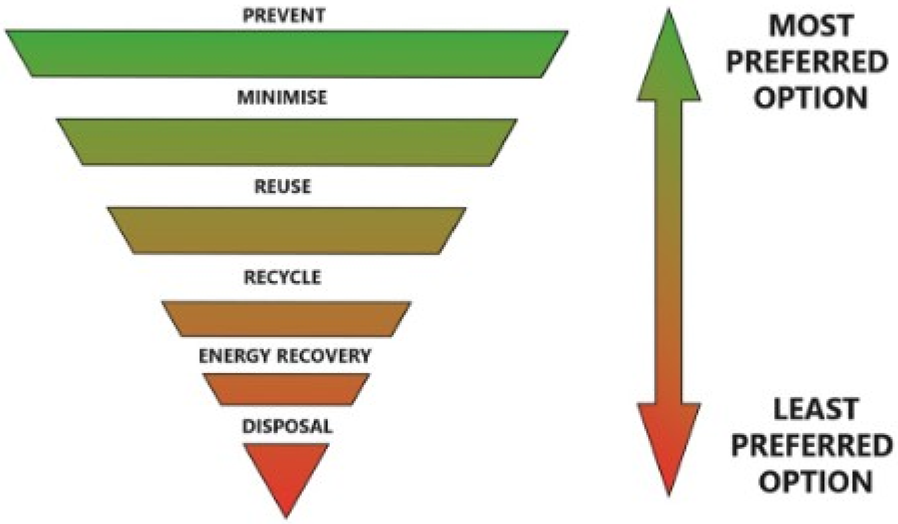

Fig. 1. The waste management hierarchy adopted in Europe.

Figure 1 shows that disposal of waste into landfilling is the worst option, followed by energy recovery, recycling, reuse and minimisation, prevention through efficient design is the best option. To move up the waste hierarchy, the concept of designing products for ease of recycling, recovery of materials and minimisation/prevention of hazardous materials must be considered to comply with EU laws and regulations. Farrrell et al acknowledges that the RoHS directive has had a positive effect on PV design by lowering the amounts and types of materials used in PV construction regardless of their exemption from the RoHS 2 directive.[23]

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[21] Ibid.
[22] Farrell et al, n 1.
[23] Ibid.

Latunussa et al[24] showed that the regulatory framework is less than perfect in Europe because PV modules that are collected for recycling are then transported to one of 350 recycling sites in Europe. Each site does not have the same recycling expertise or specification. Some sites transport PV materials to other sites for specialist recycling and some of the material may be landfilled. For example, PV waste generated from different places in Italy is transported and loaded into a treatment plant called SASIL located in the Piedmont region. Upon arrival the aluminium frame is removed as well as the cable/junction box. The PV module is then put through a high temperature process to separate solar glass from the PV sandwich layer. The glass will go through an optical separation process to obtain clean glass for recycling and the sandwich pieces will be transported 200km away to an authorised incinerator where the polymer part is burnt and energy recovered. The remaining ash is sent back to the treatment plant and transferred into a sieving process in order to recover the aluminium mixture from the ash. The residual ash is further treated so that silicon metal can be extracted. The acid residuals from the extraction process are recirculated and are then treated with electrolysis to recover silver and copper. The final waste sludge from this process is then transported to landfill. The recovered materials are expected to be substitutes for primary materials and will have avoided the production of these materials.[25]

Mahmoudi, Huda and Behnia[26] found that even though the OECD shares its eco-social problems and collaborates to find solutions, recycling and recovery has its upsides and downsides if it is not handled properly.[27] One of the advantages is that as PV waste moves across borders into other OECD countries, energy recovery levels for the whole cost-recovery treatment are considerably reduced and the recycling process does result in better environmental outcomes. The majority of OECD countries are from Europe but those countries in Europe which are not members of the OECD and where there is not a sound regulatory framework for waste management and do not have the WEEE required facilities

[24] Cynthia E.L. Latunussa et al, ‘Case study: Life cycle assessment of photovoltaic waste treatment’ in *Analysis of Material Recovery from Silicon Photovoltaic Panels* (Report No.EUR 27797 EN, March 2016) 29-32 <https://www.researchgate.net/publication/301693669_Analysis_of_Material_Recovery_from_Silicon_Photovoltaic_Panels>.
[25] Ibid.
[26] Sajjad Mahmoudi, Nazmul Huda and Masud Behnia, ‘Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels’ (2021) *Resources, Conservation and Recycling* 164 <https://www.sciencedirect.com/science/article/pii/S0921344920304626>.
[27] Ibid.

and infrastructure that meet high environmental standards, costs increased substantially and environmental damage was exacerbated. A massive PV waste reduction can occur when a secondary raw materials market is created. PV products can maintain their value for an extended period of time.[28]

Recycling and Re-using in Europe

Germany has been the pioneer in PV recycling technology in Europe. Latunussa et al reported the results of a pilot study known as the Freiberg Pilot System conducted in Germany and released in 2010.[29] The aim of the system was to find the most environmentally-friendly way to reprocess PV solar cells. The focus of the pilot project was to minimise the use of toxic etching solutions. The trial has been running since 2002 and found that silicon could be recovered in an environmentally-friendly way but there were insufficient quantities of PV waste to make the process viable. There are however, some companies such as Deutsche Solar and PV CYCLE that adapt decentralised strategies by doing material recovery and then sending the recovered materials to specific recyclers. It should be noted that Deutsche Solar is known as a pioneer of the silicon recycling industry but its recycling operations were terminated because of the high cost of treatment and the low quantities of PV waste input.[30]

The extraction and separation of cadmium, tellurium and copper from PV module scrap was investigated by Fthenakis and Wang. It was found that a dilute aqueous solution of hydrogen peroxide and sulfuric acid was sufficient to completely leach out cadmium and tellurium from PV modules. The same method successfully removed cadmium and tellurium from actual manufacturing scrap and copper was partially extracted. The reason for the investigation was that if spent modules and manufacturing scrap were classified as hazardous, their handling and disposal would cost about twenty times more than non-hazardous waste. The experiments showed that a separation of 99.99% of cadmium was accomplished from actual manufacturing waste at an estimated capital and materials cost of about 2 cents per watt for a 10 MW/year recycling facility.[31]

[28] Ibid.
[29] Cynthia E.L. Latunussa et al, n 21 [26].
[30] Ibid 26-27.
[31] V.M. Fthenakis and W.Wang, 'Extraction and separation of Cd and Te from Cadmium Telluride Photovoltaic manufacturing scrap' (2006) 14 *Progress in Photovoltaics and Applications*

Pagnanelli et al surmised that different types of PV modules had to be treated differently to successfully extract waste from them. For crystalline silicon panels a lot of effort has been put into the recovery of silicon cells because of the high cost of silicon. The main drawback was the cost of recovery because the process could not be automated. For thin film panels research had concentrated on delamination of the modules or grinding, decoating of the substrate, extraction and refining of the metals. Despite all these efforts, no innovative technology for treating different kinds of PV panels in an automotive way at the same plant had been developed. Pagnanelli et al researched a new treatment of different kinds of panels at the one plant. Crushing, sieving, thermal treatment of the coarse fraction and chemical treatment of the fine fraction were all considered. It was discovered that both silicon-based panels and cadmium/tellurium panels could all be treated at the same plant with an overall recycling rate of 91%.[32]

Azeumo et al,[33] pointed out that the main problem with PV waste is its poor biodegradability. Great volumes can be landfilled if it is not treated correctly. It was found in laboratory experiments that physical and chemical processes could be used. The physical process was aimed at the recovery of glass, metals and the polyvinyl fluoride film. 76% of the glass was recovered in the experiment and 100% of the metals. The chemical process was aimed at identifying the best conditions which allow the dissolution of the ethyl vinyl acetate ('EVA'). The best conditions to dissolve EVA in less than 60 minutes in laboratory conditions was the use of toluene as a solvent at 60°C combined with the use of ultrasound at 200W. The pre-treatment at 200°C appeared to be useless.[34]

Alternatively, Fiandra et al proposed a new two step process to separate and recover glass, silicon and metals. It consists of two different sequential treatments; a simple mechanical delamination of the backsheet and a thermal treatment of the remaining PV waste. The proposed recovery process meets the requirements of economic and environmental sustainability. It obtains a higher

<https://onlinelibrary.wiley.com/doi/epdf/10.1002/pip.676>.

[32] Francesca Pagnanelli et al, 'Physical and chemical treatment of end of life panels: An integrated automatic approach viable for different photovoltaic technologies' (2017) *Waste Management* 59 <https://www.sciencedirect.com/science/article/pii/S0956053X16306699>.

[33] Maurianne Flore Azeumo et al, ' Photovoltaic module recycling, a physical and chemical recovery process' (2019) *Solar Energy Materials and Solar Cells* 193 <https://www.sciencedirect.com/science/article/pii/S0927024819300510#:~:text=Sunicon%20recycling%20technology%20is%20applied,thermal%20and%20an%20etching%20process.&text=In%20the%20second%20step%20an,22%5D%2C%20%5B23%5D>.

[34] Ibid.

mass recovery and a lower environmental impact than conventional methods. About 90% of the PV panel can be recovered. Importantly, less PV waste is thermally treated and energy costs are reduced. The main innovation of this process concerns the removal of the fluorinated polymeric layers from the modules without their degradation.[35]

Ardente et al considered the resource efficiency of future PV panels. Base-case recycling has a low efficiency and in some cases is not in line with regulatory targets. Alternatively, high-efficient recycling can meet these targets and at the same time recover silicon, glass and silver which are usually lost in the base-case process. The benefits of high-efficient recycling means that fewer resources are depleted from the natural environment. The article also points out that thermal treatments are necessary to achieve high-efficiency in recycling but have to be carefully assessed. Air pollutants such as hydrogen fluoride can be released from combustion of halogenated plastics in the panel's backsheet. The delocalisation of some treatments and the use of pyrolysis in thermal processing should also be considered. Compulsory labelling of solar PV panels by manufacturers could help identify fluorine free waste and assist in sorting it for optimal recycling.[36]

Farrell et al, found that pyrolysis offers the best potential for the optimum recovery of material from crystalline silicon PV modules. These modules have had a 80-90% market share over the last 40 years and will constitute the bulk of the impending waste stream. The modules are composed of glass, metal, semi-conductor and polymer layers in a strongly bound laminate. Re-use and recycling is difficult because of this design. Pyrolysis is efficient in removing the bulk of the backsheet and the ethylene vinyl acetate encapsulant. It provides a clean separation of the layers without the need for hazardous chemicals.[37]

Zhao et al conducted experiments that showed that high voltage pulse technology could be used to extract valuable components of solar modules such as silicon and silver after the PV modules were crushed. As the number of pulses and voltage was increased high voltage pulses broke down the other components and the

[35] Valeri Fiandra et al, 'Silicon photovoltaic modules at end-of-life: Removal of polymeric layers and separation of materials' (2019) *Waste Management* 97 <https://www.sciencedirect.com/science/article/pii/S0956053X19300753>.
[36] Fluvio Ardente, Cynthia E.L. Latunussa and Gian Andrea Blengini, 'Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling' (2019) *Waste Management* 91 <https://www.sciencedirect.com/science/article/pii/S0956053X19302909>.
[37] C.C. Farrell et al, n 1.

selectivity for silicon and silver increased. With an increased electrode gap, the selectivity of glass and silicon was slightly changed, while that of silver was increased. The experiments also showed that high voltage pulse crushing can effectively enrich and recover the silver in waste PV panels and provide convenience for subsequent sorting.[38]

Klugman-Radziemska and Kuczynska-Lazewska agreed that recycling helps to reduce the consumption of valuable raw materials, reduce production costs and reduced environmental impacts. Their research showed that the total impact of PV production can be reduced by as much as 58% energy cost by using recycled silicon. Greenhouse gases were reduced by 42%. In the analysed recycling process several processes were used to recover silicon wafers. New photovoltaic cells were produced from the recovered wafers that proved to be a lower energy cost to produce and nearly twice as environmentally friendly. The biggest difference was seen in the fossil fuels category and a relatively small difference was observed in the radiation category.[39]

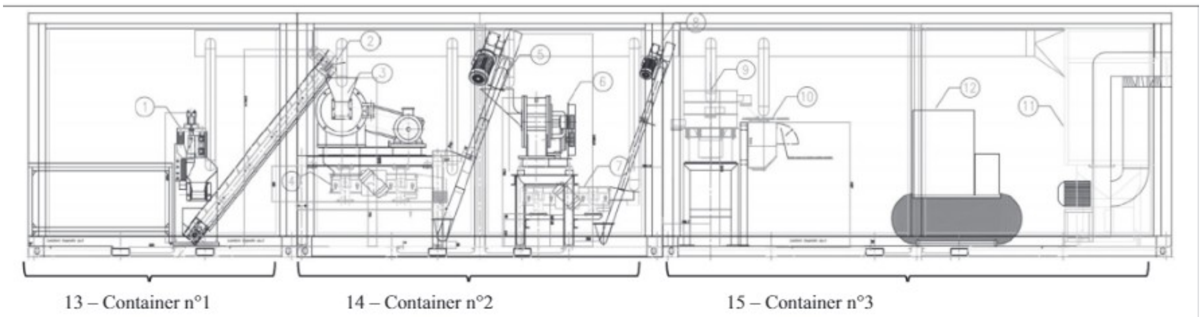
Mobile Waste Facility

Del Pero et al analysed the potential of a mobile mechanical treatment plant.[40] The process, the machinery installed in the system and their functions were described. The system boundaries included construction and operation of the device as well as recycling and incineration performed outside the plant. The results showed that impacts are concentrated on the operation stage mainly due to energy consumption involved in milling and separation activities.

[38] Pengfei Zhao et al, ‘A novel and efficient method for resources recycling in waste photovoltaic panels: High voltage pulse crushing’ (2020) *Journal of Cleaner Production* 257 <https://www.sciencedirect.com/science/article/abs/pii/S0959652620304893>.

[39] Ewa Klugmann-Radziemska and Anna Kuczynska-Lazewska, ‘The use of recycled semiconductor material in crystalline silicon photovoltaic modules production – A life cycle assessment of environmental impacts’ (2020) *Solar Energy Materials & Solar Cells* 205 <https://www.sciencedirect.com/science/article/pii/S0927024819305884>.

[40] Francesco Del Pero et al, ‘Innovative device for mechanical treatment of end-of -life photovoltaic panels: Technical and environmental analysis’ (2019) 95(1) *Waste Management* <https://www.sciencedirect.com/science/article/pii/S0956053X19304246>.



PRE-TREATMENT	GLASS SEPARATION	SILICON SEPARATION	COPPER & POLYMERIC FRACTION SEPARATION	AUXILIARIES
Removal of Aluminum frame, electrical cables and junction box (not represented in the picture) **PANEL SHEARING** 1. Shearing machine	2. Conveyor 3. Hammer mill 4. Vibrating screen	5. Conveyor 6. Hammer mill 7. Vibrating screen	8. Conveyor 9. Three-stages circular separator	10. Dust aspiration system 11. Filtering system 12. Compressed air generator 13. Container n°1 14. Container n°2 15. Container n°3

Figure 2 – Layout and machineries of the PV-MOREDE system[41]

Figure 2 shows the layout and various machineries used in the process. The separation stage involved the use of a manipulator to separate electrical cables and connector boxes. The aluminium frame was placed on an expander device and removed. After preparation the remaining parts of the PV panel were placed on a shearing machine and cut into 100 x 100mm pieces. Further fragmentation was achieved during the glass, silicon and copper polymeric fraction stages and other auxiliaries were required to complete the process. The analysis of different operation steps reveals that pre-treatment gives the highest contribution, followed by glass and silicon separation with the lowest quota attributable to copper and polymeric fraction separation. The comparison of results with fixed recycling facilities shows that a mobile system has considerable environmental benefits and lowers transport costs.[42]

Hazardous Waste Legislation in Australia

The object of the Hazardous Waste Act [43] is to regulate the export, import and transit of hazardous waste to ensure that exported, imported or transited waste is managed in an environmentally sound manner so that human beings and the environment, both within and outside Australia, are protected from the harmful

[41] Ibid 539.
[42] Ibid.
[43] *Hazardous Waste (Regulation of Exports and Imports) Act 1989* (Cth) s 3(1).

effects of the waste. The aims of the Act are to give effect to Article 11 of the *Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal*.[44] Article 11 stipulates that parties may enter into bilateral, multilateral or regional agreements or arrangements regarding transboundary movement of hazardous wastes or other wastes provided that such agreements or arrangements do not derogate from the environmentally sound management of hazardous wastes and other wastes as required by the Convention.[45] Polyvinylfluoride ('PVF') and polyvinylidenefluoride ('PVDF') are listed as cured waste resins under B3010 of the Convention.[46]

Ogunseitan points out that the Basel Convention is designed to make it more difficult and less cost effective to transfer hazardous junk electronic waste across national boundaries. The guidelines acknowledge the difficulties faced by government authorities to assess and differentiate bonafide used electronic equipment shipped for repair, refurbishment, resale, or humanitarian-aid reuse from defunct electronic e-waste destined for environmental disposal and unsafe scrap mining.[47] Should solar PV modules be added to the list, it will mandatory that recycling/re-use facilities be established in Australia and other PV waste disposed under the terms of the Basel Convention. Export of waste EoL PV modules will not be an option unless strict environmental standards are met.

Mathur, Gregory and Hogan explain that governance of solar energy systems in Australia is defined by the Renewable Energy Act[48] and administered through the Clean Energy Regulator Schemes. The objects of the Renewable Energy Act are to encourage electricity generation through renewable resources, to reduce greenhouse gas emissions and to ensure that renewable energy sources are ecologically sustainable.[49] When the solar system breaks down, each of its subsections has a different waste trajectory. PV waste can be classified either as a pollutant and is hazardous or as a commodity and therefore a potential economic resource. The regional waste co-ordinator in the NT for example, could be placed

[44] Ibid s 3(2)(a) & (b).
[45] *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal* (adopted on 22 March 1989, came into force 5 May 1992) art 11 <https://www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf>.
[46] Ibid [83].
[47] Oladele A Orgunseitan, 'The Basel Convention and e-waste: translation of scientific uncertainty to protective policy' (2013) 1(6) *The Lancet* <https://www.thelancet.com/journals/langlo/article/PIIS2214-109X(13)70110-4/fulltext>.
[48] *Renewable Energy (Electricity) Act 2000* (Cth).
[49] Ibid s 3(a),(b) &(c).

in a difficult position if a contractor wanted to dump PV modules in landfill. There is no specific legislation to rely on and PV modules are not regarded as hazardous. It may be that they could be re-used as shade by the local council but the cost of hazardous waste extraction could be prohibitive when they reach their EoL.[50]

Islam et al point out that in Australia, waste policies for solar PV modules are at the state and territory levels and local councils form their own strategies to align with the overall state guidelines. The result of this study shows that the highest waste solar PV in NSW will be generated at Murrumbidgee, Berrigan, Balranald and Bogan Councils. Out of 129 councils in NSW, the model identified 78 optimised locations for collection points and three major recycling facilities would be needed at Newcastle, Narrandera and Wagga Wagga Councils.[51]

Economic Considerations in Australia

McDonald and Pearce found that the economic motivation to recycle most PV modules was unfavourable and there were not any appropriate energy and environmental policies. This was especially true for PV containing hazardous materials. Some solar manufacturing companies had voluntarily recycled solar PV modules but such initiatives were driven by environmental responsibility rather than economic benefit. It was concluded that unless recycling is regulated in the future, it is unlikely that voluntary recycling will continue and hazardous wastes will begin to enter local waste streams. It is most important that regulation of recycling does not provide a competitive advantage to the more environmentally destructive forms of electricity generation.[52]

Mahmoudi, Huda and Behnia supported these views and explained that severe challenges are likely to emerge in Australia from the early 2030s. A lack of holistic strategy concerning environmental impacts of disposal scenarios and the failure to enact a comprehensive local council policy and regulations were of concern. Findings from the analysis indicated that the domestic treatment proposed for

[50] Deepika Mathur, Robin Gregory and Eleanor Hogan, 'Do solar systems have a mid-life crisis? Valorising renewables and ignoring waste in regional towns in Australia's Northern Territory' (2021) *Energy Research & Social Science* 76 <https://www.sciencedirect.com/journal/energy-research-and-social-science/vol/76>.

[51] Md Tasbirul Islam et al, 'Reverse logistics network design for waste solar photovoltaic panels: A case study of NSW councils in Australia (2021) 39(2) *Waste Management Resources* <https://pubmed.ncbi.nlm.nih.gov/33023422/>.

[52] N.C. McDonald and J.M. Pearce, 'Producer responsibility and recycling solar photovoltaic modules' (2010) 38(11) *Energy Policy* <https://www.sciencedirect.com/science/article/pii/S0301421510005537>.

Australia was feasible and included high profit margins and at the same time made a considerable reduction on environmental burdens and resource losses. The analysis was profitable when 20,000 tonnes of waste was treated each year. If only 10,000 tonnes of treated waste was achieved the plant did not show profitability. A special tax exemption during the loan lifetime could assist in making the plant profitable.[53]

Mathur, Sing and Sutherland found that the development of effective processing technologies to isolate valuable materials will help divert PV waste away from landfill while reducing dependence on primary resources and enhancing economic sustainability. One limitation of the research paper was the lack of economic data for recovered materials.[54]

Kim and Park suggest that an appropriate system for the monitoring, collection and storage of PV waste needs to be arranged before the volume becomes high enough for recycling to be economically viable. International co-operation could be a way to maintain the level of recycling as well as modifying the PV modules to make them easier to recycle.[55]

Salim et al conducted a literature review in Australia to elicit stakeholder perceptions on drivers, barriers and enablers to EoL management of PV panels and battery energy storage systems. This was backed up by a questionnaire survey. It appeared that all stakeholders addressed triple bottom line issues but research/education institutions put more emphasis on economic and environmental factors. They reported the lack of profitability, unavailability of regulations and incentives, as well as a lack of awareness of safe disposal options, as being the most significant issues. Only government respondents recognised the current lack of on-shore recycling infrastructures as a critical barrier. Introducing a product stewardship scheme, implementing business models for collection, providing economic incentives, as well as developing recycling technologies and

[53] Sajjad Mahmoudi, Nazmul Huda and Masud Behnia, ‘Environmental impacts and economic feasibility of end-of-life photovoltaic panels in Australia: A comprehensive assessment’ (2020) *Journal of Cleaner Production* 260 <https://www.sciencedirect.com/science/article/pii/S095965262031043X>.

[54] N. Mathur, S Singh and J.W. Sutherland, ‘Promoting a circular economy in the solar photovoltaic industry using life cycle symbiosis’ (2020) *Resources, Conservation & Recycling* 155 <https://www.sciencedirect.com/science/article/pii/S0921344919305555>.

[55] Hana Kim and Hun Park, ‘PV waste management at the crossroads of circular economy energy transition: The case of South Korea’ (2018) `10(10) *Sustainability* <https://www.researchgate.net/publication/328159196_PV_Waste_Management_at_the_Crossroads_of_Circular_Economy_and_Energy_Transition_The_Case_of_South_Korea>.

infrastructures were regarded as the most important enablers. Evaluating consumer perceptions to pay for the de-installation of PV modules is also worth investigating so that appropriate models can be developed.[56]

Conclusion

This literature review has cited literature that dealt with legislation for safe disposal of PV modules in Europe, the possibilities of recycling and reusing valuable materials from solar panels, the economics of establishing recycling and reuse facilities and the current almost non-existent legislation in Australia dealing with hazardous waste. Significant weather events, demolition of buildings on which solar PV panels are installed, and future solar PV innovations can sharply increase the amount of unwanted waste. It is therefore essential to have legislation in place which regulates waste, that helps to develop stewardship responsibilities and encourages industry to reuse and recycle components.[57] One cannot wait until there are 20,000 tonnes of PV module waste in Australia to make recycling profitable. Safe disposal legislation is needed now. Voluntary recycling will not succeed in the long-term and every effort needs to be made to keep hazardous waste at a minimum. It may well be that the most profitable treatment facility will be a mobile facility that can be moved to where the bulk of the EoL PV modules are. Effective legislation would need to take this possibility into account and ensure that environmental damage is kept to a minimum. The European model has much to recommend but needs to be adapted to Australian conditions.

[56] Hengky K. Salim et al, 'End-of-life management of solar photovoltaic and battery energy storage systems: A stakeholder survey in Australia' (2019) *Resources, Conservation and Recycling* 150 <https://www.sciencedirect.com/science/article/pii/S0921344919303398>.
[57] Peter Majewski et al, n 2.

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