IOP Conference Series:
Earth and
Environmental Science

PAPER • OPEN ACCESS

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To cite this article: A N Madrigal *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1363** 012051

IOP Conf. Series: Earth and Environmental Science **1363** (2024) 012051
doi:10.1088/1755-1315/1363/1/012051

Exploring design thinking processes in circular economy strategies for PV waste management in Australia

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Abstract. Energy from renewable sources such as photovoltaic (PV) panels is increasingly powering small and large-scale installations worldwide. However, the end-of-life (EoL) of PV panels is a challenge. If mismanaged, PV EoL represents a loss of valuable materials and a toxic hazard to the environment and human health. Global R&D towards PV EoL management is commonly focused on recycling. Nevertheless, other options to extend the PVs first lifecycle should be prioritised before it goes into the recycling stream. This paper presents results of research that explores the possibilities for a circular PV EoL management in the Australian context using circular economy strategies such as the ReSOLVE framework and the 10 Rs for circularity. Engaging with key stakeholders, this paper demonstrates that solutions commence from analysing social behaviours of PV manufacture, installation, and decommissioning phases. Additionally, innovations in the built environment such as smart housing standards can impact the efficient use of PVs. The findings from desktop research, interviews with 20 stakeholders from the PV and associated industry in Australia and the validation of the results show that solutions guided by a regulatory framework that have clear second life markets for reuse of PVs and recovered materials (such as manufacturing construction materials with recycled PV glass), having standards and re-certifications in place are urgently needed.

1. Introduction and background.

Energy from renewable sources is steadily increasing as a response to climate change. In Australia, electricity generation from renewables represented 32.5% in 2021, with wind and solar as the predominant type of renewable energy sources [1]. Energy generated from solar panels (also called photovoltaic panels) is expected to experience considerable growth globally in the coming years [2]. Photovoltaic (PV) systems have a significantly lower carbon footprint emission (14-73 g CO_2-eq/kWh) compared to the carbon footprint emission from oil burning (742 g CO_2-eq/kWh) [3].

In Australia, small-scale PV panel installations (residential) have led the renewable energy growth for five years in a row [1], positioning Australia as the country with the highest amount of installed PV per capita in the world [4]. This results in a significant demand for new PV panels. It has been established that the average lifespan of a PV panel is 25-30 years [5, 6] and that the most abundant type of PV panels in the world are crystalline silicon [7]. As of the end of 2022, there were 80 million PV panels installed in Australia with 90% of the installations being silicon panels [8].The demand for new PV panels is already causing functional PV panels to reach early end-of-life (EoL) stages.

As stated in a recent article [9] the lifespan of PV panels is shorter than expected for several reasons; consumer mentality being one of them, as house renovations or expansions often include updating the entire PV system. Additional economic incentives for purchasing new PV panels, such as small-technology certificates (STCs), contribute to PV reaching early EoL [10]. Nevertheless, there is a significant percentage of panel failures related to manufacturing, transportation and PV installation/handling [9, 11].

Production of PV panels requires the use of valuable raw, high-quality materials and high energy-consuming processes. These materials are often lost when PV panels at their end of life (PV EoL) are mismanaged as waste, and they are mostly sent to landfills [12]. PV EoLs can represent a toxic hazard for the environment and human health if the materials embedded, such as lead and cadmium, leak into the soil and contaminate underground water sources [13]. Therefore, researchers around the globe have addressed different pathways to manage PV waste, mostly focusing on PV recycling [5, 13-17]. Scarce number of studies regarding PV waste management solutions are focusing on regulations, policies, and social factors [18, 19].

A previous study has stated that sustainable PV waste management is challenged by the lack of tested and validated large-scale technologies that can manage the various types of PV EoLs [20]. Additionally, few studies have attempted to compare PV waste disposal scenarios. PV waste disposal scenarios studies have focused on PV recycling benefits analysis. The most common approach is through life cycle assessment (LCA) studies; nonetheless, no PV waste disposal comparison studies through full LCA have been conducted [21]. However, a specific study on CE for crystalline PV panels showed that if following a cradle-to-cradle approach in a closed-loop material cycle form, a reduction of 74% can be achieved when climate change impact factor (kg CO2 eq) is considered for recovering PV materials [22]. Furthermore, an early study highlighted that the environmental benefits of recovery of crystalline PV EoL materials can be reflected in the reduction of Global Warming, Terrestrial Ecotoxicity, Freshwater Eutrophication and Human toxicity potential [23]. However, the results of a detailed study in the Australian context highlight that PV recycling includes some environmental consequences that need to be resolved [6]. On this note, recycling processes emit 3 times more kg CO2 emissions than landfilling, but these practices represent 30 times higher greenhouse gas savings [21]. Different options to recycling, such as extending the lifespan of PV panels, could represent a 70% reduction in CO2 emissions if their lifespan is 100 years compared to the current 30 years [12]. PV reuse contributes to reducing carbon dioxide emissions and saves resources otherwise needed for new PV panels production [24].

PV waste management is still a nascent field of R&D in Australia, especially after PV waste landfill bans in South Australia and Victoria in 2011 and 2019 respectively [25], and increased waste levies are no longer making landfills a cheap practice [21]. Different stakeholders such as academia, non-for-profit organisations, private companies, and governments are undertaking R&D on PV waste management. An example of this is the PV PASS program by PV Lab, where information regarding visual inspections and several tests on the panels are being shared with stakeholders to increase PV reliability [26]. Another example is the recent government publication from the Department of Climate Change, Energy, the Environment and Water (DCCEEW), in which a proposal for PV stewardship is presented. DCCEEW's consultation paper describes three target categories for small-scale PV installations, focusing on recycling rates, a free disposal network, and education/ awareness strategies. Nevertheless, large-scale PV installations legacy waste are not included in the proposed scheme's financial or management responsibilities [27].

The current paper follows the research outputs published in a recent paper [10] where the authors explored possible PV waste pathways for the Australian context following circular economy (CE) principles. These principles provide a holistic approach that enables the understanding of PV waste following the three categories described in an ARUP study [28], starting from the production phase through to the use phase until the EoL phase, where PV panels can be recovered. The 10 R ladder for circularity [29] and ReSOLVE framework by Ellen McArthur Foundation were selected in the study to identify several opportunities to reduce PV waste, extend PV panel's first lifecycle and recover valuable materials in PV panel's EoL [10]. The preliminary results suggested a conceptual framework that comprises R ladder actions and stakeholders for determined categories according to the specific lifecycle stage of the PV [10]. These categories are circular design and first use, circular use, and circular recovery. Nevertheless, it is important to note that this conceptual framework requires to be supported by trust-enhancing tools such as case studies, certifications and tailored testing and collecting systems to enable financial flexibility for the recycled/reused PV supply chain. Similar results have been supported on a recent study on CE, applied to PV waste management where it was highlighted that without transparency throughout the CE process, long-term sustainability cannot be guaranteed [22]. Trust-enhancing tools include confidence in digitalisation as a mechanism for information sharing. Using data technologies can enable open access and sharing information regarding the PV product (material passports), which contributes to managing data such as the condition, performance and recyclability of the product, improving its circularity [30].

2. Methods

The conceptual framework presented in the first publication of this study [10] was based on the results of qualitative research methods where twenty semi-structured interviews were undertaken, following a combination of studying peer reviewed literature review and grey literature. The research was guided using design thinking (DT) as a theoretical framework. This paper presents the validation process of the conceptual framework using qualitative research methods (focus group and interview discussions) guided by DT. Focus group method was selected for validation as it was used in a similar study elsewhere recently [30].

The sampling for the validation process consisted of contacting sixteen stakeholders from government, PV and recycling organisations, academics and installers based on their experience/interest with PV waste or e-waste management. Some of the participant had been involved in previous interviews in the same project and expressed interest in being involved in ongoing research. A total of eight stakeholders agreed to participate via online, four in the focus group discussion and four in the individual interview discussions. In both discussion types, the stakeholders were given access to a Miro board where they could find decision flow diagrams based on circular design (figure 1), circular use (figure 2) and circular recovery (figure 3) solutions. To prepare the stakeholders for the interview and focus groups, they were sent a brief summary of the research prior. Access to the figures 1-3 during the interview or focus group process not only allowed the respondents to visualize the process, it also gave them the opportunity to peruse the diagrams in their own time during the sessions. These diagrams were developed post the first interview stage and analysis, leading to development of options for end of life of PVs in Australia. Questions were posed during the online sessions with access to post it notes on Miro, so respondents could use both verbal and text options for communication. Participants were also provided access after the focus group for a limited time, should they wish to go back to the diagrams and comment either on their own or in discussions with their organisation or other team members.

Following the process for innovation in DT, the five steps: "*Define the problem; Need finding and Synthesis; Ideate; Prototype and Test"* [31] were followed throughout the research project (except for *Test* as it would involve running a pilot for circular PV waste management). The validation process was intended to evaluate the proposed solutions with the stakeholder's input to inform a pilot for circular PV waste management.

3. Finding and analysis

IOP Conf. Series: Earth and Environmental Science **1363** (2024) 012051 doi:10.1088/1755-1315/1363/1/012051

The validation process showed that an approach that addresses waste management per stage of the lifecycle can effectively reduce the amount of PV waste. Decision flow diagrams in figures 1-3 show the current scenario in contrast with the possible scenarios if solutions based on 10 Rs for circularity and ReSOLVE framework were adopted. In the current scenario, panels have little opportunities for reuse or recycling and end up in land fill. Scenario A (figure 2) presents the enabling factors for a circular use of PV panels, stressing the need for PV waste education, maintenance, and attentive installations/uninstallation processes. Scenario B (figure 3) presents the possibilities within a circular recovery scenario for PV panels that have been decommissioned. Based on testing results and supported by certifications, the panels can be directed to specific streams to extend the lifespan of the materials or the panel itself.

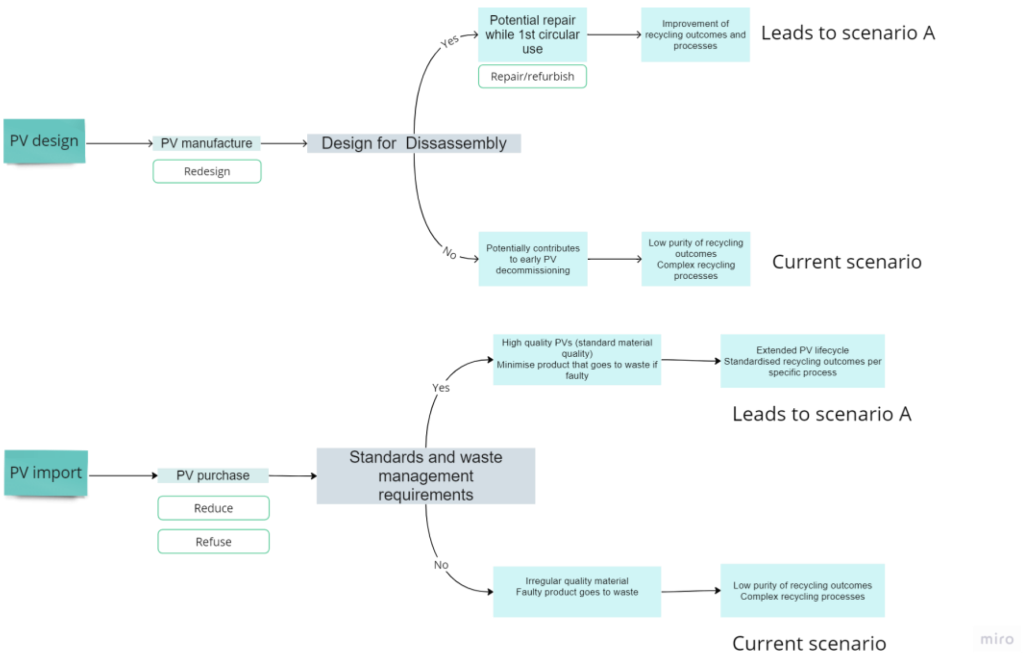

Figure 1. New panels in the Australian market. Source: Authors

Majority of the PV panels in Australia are manufactured overseas. Hence, suggestions that involve circular design are only suitable for a couple of Australian companies manufacturing solar panels. Therefore, figure 1 summarises the opportunities for PV design and PV imports. Design for disassembly enables the opportunity to repair or refurbish specific areas of a panel which may allow the entire panel to be functional for a longer period. Nonetheless, it was raised that design for disassembly may affect the lifespan of the panel if the sturdiness of the panel is compromised.

As PV circular design is challenging to apply in an Australian context, attention must be directed to PV imports. Quality and technical information of the PV panels that are imported into the country are critical for the rest of the PV lifecycle. The challenge remains in the technical capacity to develop confidence, transparency and information-sharing mechanisms through digital tools such as panel passports. Additionally, international agreements on manufacturing standards and waste management plans are necessary to start diverting faulty PVs from the moment of purchase. Refusing to import low-quality panels increases the probability of the panels having a longer lifespan. Reducing the demand for new PV panels by improving construction parameters through passive house, smart house design and renovation standards can add to minimise PV waste.

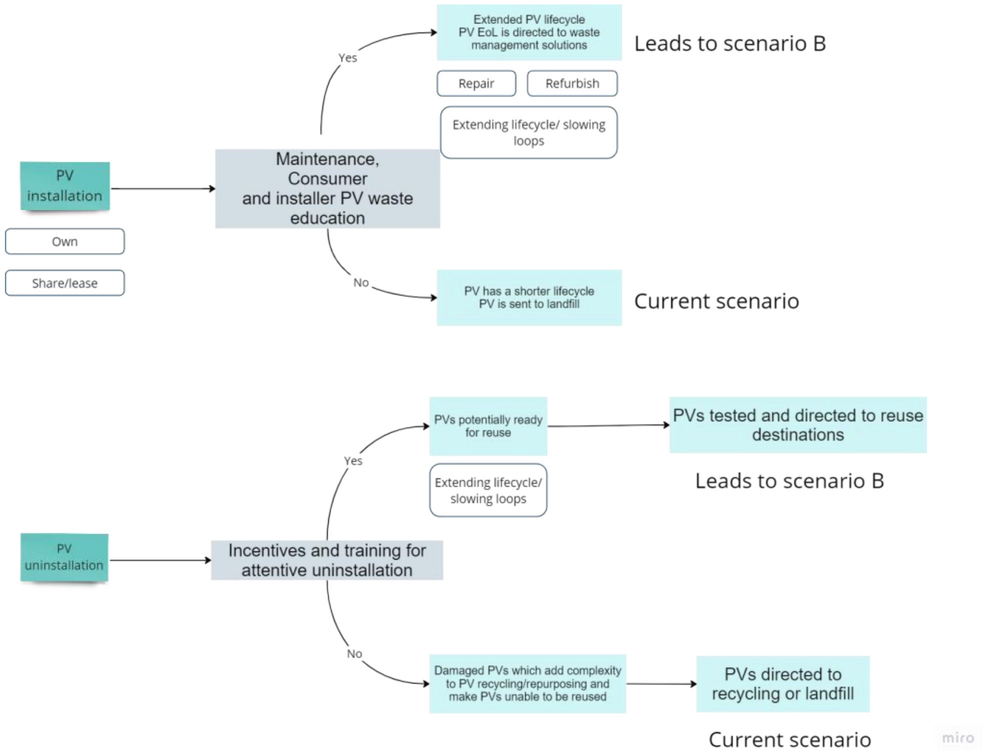

Figure 2. Scenario A. First use of panels. Source: Authors

Figure 2 visualises how the current decision-making processes determine the installation and uninstallation of the PV panels, which affects PV performance and EoL management. Providing EoL management plans from the moment of installation can guide consumers towards which actions to take in case the panel is faulty. The interview process showed that installers and retailers are the first contact point for consumers when a panel installation is faulty or is to be removed. Hence, EoL management plans should highlight procedures for attentive uninstallation/repair/refurbish and possible service providers for these solutions. Validation participants agreed on training and incentives for attentive uninstallation as key factors for a circular PV waste management. However, challenges emerge in the current scenario of PV uninstallation. Only a minimal amount of PV panels ends up in recycling destinations; stakeholders argue that more panels are going to informal reuse destinations overseas mainly due to financial reasons. This situation is expected to change with the updates in the Basel Convention [32]. Additionally, sharing or leasing models can imply regular maintenance requirements, which promotes extending the lifespan of PV installations. On this note, standards and consumer behaviour are crucial in determining the fate of PVs. Results of the interview process showed that currently, one of the major causes of PV waste is the renovation of PV installations.

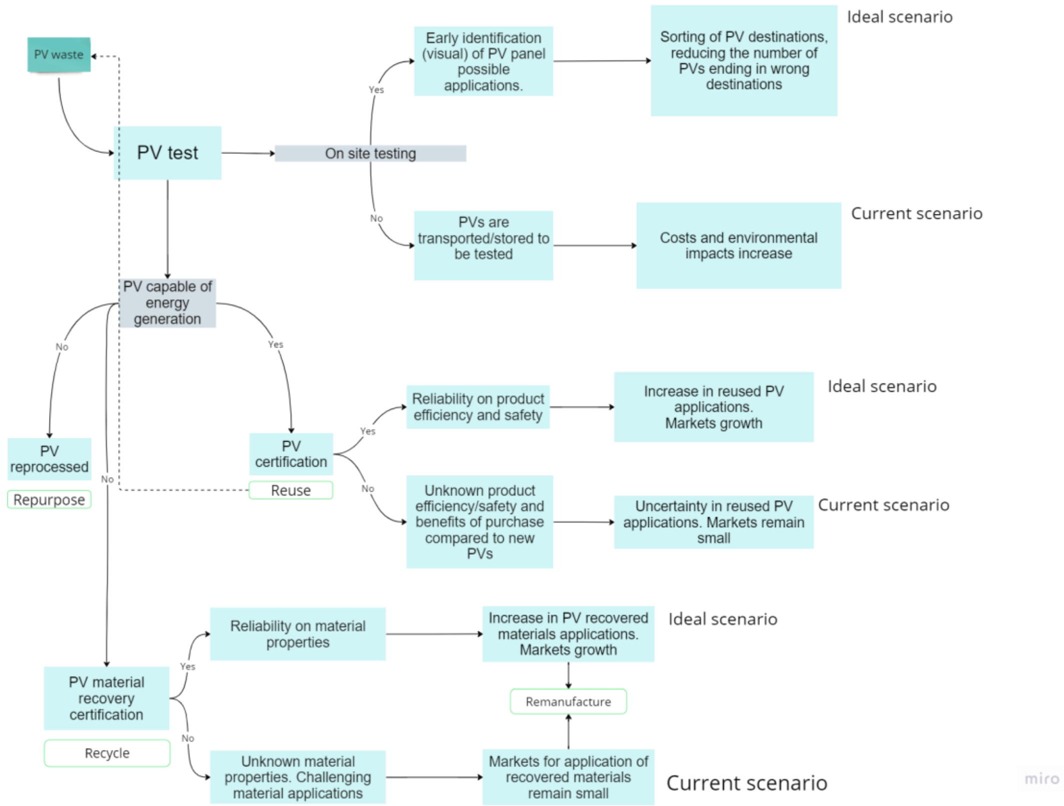

Figure 3. Scenario B. Second use of panels. Source: Authors

Figure 3 depicts the possibilities for second use of PV panels, which is translated into an ideal scenario for a circular PV waste management. Testing panels is the first step to determine the destination of the panels. On-site PV testing can reduce costs, environmental impacts and time in sorting if the panel is fit to reuse, repurpose or recycle destinations. Participants taking part in the validation agreed on the importance of testing and added that tests that go beyond visual tests, as PV Pass program [26], are required to have adequate test results. Most of the comments were directed to the current situation in the Australian context, where second-life markets for recovered PV panels have not been established as manufacturing is mostly taking place overseas. This situation adds complexity for PV recyclers as, at the moment, the profit of recycling a PV panel is focused mainly on glass and aluminium recovery (with inherent challenges). Quality and certification of recovered materials will drive emerging second-life markets. PV waste flow addressing scale issues is another factor that adds to the PV recycling profitability challenge.

4. Conclusions

The validation process showed that technical and social factors need to be addressed simultaneously if a circular PV waste management is sought. Technical challenges can be found at every stage of the PV lifecycle, though, these can be addressed with accurate collaborations and enough financial support. A significant enabler for the transition towards a circular management relies in the design of regulations and policies that respond to tailored requirements of scale, location and technical capacity to process PV waste. Social challenges can be addressed using information sharing tools (digital tools) that prompt transparency throughout the PV supply chain. Sharing information and building reliability mechanisms such as re-certifications and warranties can improve the trust in circular PV waste management. Recertification of safe second use PV panels remains the biggest challenge. A significant observation from a participant from the PV industry highlighted that as PV waste management in Australia is composed of relatively small group of companies/services compared to those in the European context, collaborations and agreements should be attainable. Agreements between installers and PV waste services should take place to reduce the number of PVs going to landfills. Nevertheless, education needs to be considered upfront, as consumers (for small and large scale) make the decision in upgrading their PV system and purchasing quality PV panels. Smart house designs which require lower energy demand can help to reduce the energy consumption and therein the number of solar panels required.

Acknowledgments

The authors acknowledge the support provided by the researchers in the IC3P platform, the focus group and individual interview participants. We also acknowledge funding from the Victorian Higher Education State Investment Fund in supporting this research.

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