# Enabling a Responsible Second-Hand Market for Photovoltaic Systems in Australia

**Institute for Sustainable Futures**

June 2023

UTS Institute for Sustainable Futures

## Research Team


- Hengky Salim
- Nick Florin
- Rachael Wakefield-Rann
- Benjamin Madden


## Citation

Salim, H., Florin, N., Wakefield-Rann, R., Madden, B. (2023). Enabling a responsible second-hand market for photovoltaic systems in Australia. Report prepared by the Institute for Sustainable Futures, University of Technology Sydney.

## Acknowledgements


This project was made possible thanks to funding from the NSW Environment Protection Authority Circular Solar grants program.

This research is part of a broader project led by PV Industries Pty Ltd.

The authors would like to acknowledge the contributions of Elsa Dominish and Kriti Nagrath (UTS ISF) and also thank the expert interviewees and survey respondents for participating in this research project.


www.epa.nsw.gov.au www.pvindustries.com.au

**Disclaimer**

The authors have used all due care and skill to ensure the material is accurate as at the date of this report. ISF and the authors do not accept any responsibility for any loss that may arise by anyone relying upon its contents.




**Institute for Sustainable Futures**
University of Technology Sydney
PO Box 123 Broadway, NSW, 2007
www.isf.uts.edu.au

# Executive Summary

## Introduction and approach

**For many product categories, reuse, and remanufacturing at end of life represent the most resource and energy efficient option. While currently lacking, reuse could become an integral part of a circular economy solution for photovoltaic (PV) systems in Australia. Evidence suggests that many PV systems are being decommissioned earlier than intended (i.e. before 10-12 years). It is therefore likely that some used components could be effectively reused.**

A typical PV system includes PV panels, inverters, racking/mounting systems, cabling and may include an energy storage system (ESS). The market and potential pathways for second-hand PV systems are not fully understood, as there has been limited research focused on this to date.

Existing online marketplaces that test, repair, and refurbish PV systems are still immature and primarily located in Europe and North America. There is also evidence of unregulated PV panel exports to low- and middle-income countries. There is a risk that defective PV systems are being dumped in countries where electronic waste management policies and infrastructure are lacking. Presently, the Technical Guidelines on Transboundary Movements of Electrical and Electronic Waste and Used Electrical and Electronic Equipment (EEE) which recommend regulation and prohibition of exporting waste and used electronics is currently non-legally binding for Basel Convention signatory countries.

The lack of domestic second-hand market development in Australia is caused by a diversity of challenges ranging from regulatory, economic, and technological challenges.

A better understanding of the opportunities, challenges, and enablers for reuse is an important first step for planning and development to help create a responsible second-hand market for PV systems. Responsible reuse means that companies are conducting proper testing, repair, and/or refurbishment of second-hand PV systems, ensuring compliance with the latest installation standards (e.g. AS/NZS 5033 for PV panels).

This research seeks to support the development of a responsible second-hand market for PV systems by assessing market opportunities, highlighting challenges and enablers, as well as providing strategic policy recommendations.

This study is part of the broader project through the New South Wales (NSW) Environmental Protection Authority Circular Solar Grants Program led by PV Industries Ltd that aims to evaluate circular economy opportunities for PV systems in NSW. The project includes developing safe handling procedures; establishing a collection and logistics network for urban and regional NSW; optimising high-value recycling approaches; activating new end-markets for recovered glass; and investigating future market opportunities for reuse. The latter is the focus of this report.

**"There needs to be an integrated approach from stakeholders across the PV system supply chain to address the diverse challenges in establishing a responsible second-hand market for PV systems."**

## Key findings

This section summarises the significant findings from each part of the report: characterising decommissioning activities; existing second-hand markets in Australia, Europe, and North America; and challenges and enablers to establish responsible second-hand markets.

### Characterising decommissioning activities

Decommissioning activities (e.g. age of decommissioned PV systems, failures and damages, and performance testing to determine “reusability”) were characterised for three main PV system components: PV panels, ESSs, and inverters.

#### PV panels

Many PV panels are being decommissioned early (before 10-12 years). Reasons include failure of or damage to one part of the system or upgrades to a higher capacity system. Early-stage failures of PV panels can be categorised as: 1) infant (<5 years), which includes failure of junction boxes, string boxes, charge controllers, cabling, and ground mounting system; and, 2) mid-life failures (5-12 years), which include degradation of the anti-reflective coating of the glass layer, discoloration of the ethylene vinyl acetate (EVA), delamination, cracked solar cells, junction boxes, and cabling. Lastly, rough handling during transport after decommissioning can also result in damages to panels.

Customers and manufacturers (under warranty claims) also generally replace the entire PV system even when there are only a few damaged panels, especially those systems equipped with string inverters. Thus, it is highly likely that PV panels in good condition are being decommissioned, which presents an opportunity for reuse.

Five existing studies looking at the percentage of reusable PV panels are inconclusive. This is likely to be attributed to the absence of a common definition or criteria for “reusability” and standardised testing procedures and approaches to produce consistent results.

#### Energy storage systems

There is more interest in reusing electric vehicle (EV) batteries for ESSs than reusing ESSs as currently there are limited EOL ESSs being decommissioned given the immaturity of this market. ESSs can accommodate lower battery efficiency levels compared to EV applications, which are often retired when the capacity declines to 70-80% of original capacity. These decommissioned EV batteries can either be reused directly if they meet the minimum performance and safety standards or be refurbished by replacing defective battery cells or components for a new application.

Decommissioned EV batteries present different efficiency levels, faults, and damages associated with unique degradation patterns impacted by milage, temperature, rate of charge or discharge, and involvement in car accidents. Each battery needs to be inspected and tested using a consistent procedure to determine its reusability.

A further barrier to EV battery reuse is variability in EV battery design, including different chemistries, battery cell sizes and format (e.g., cylindrical, prismatic, and pouch), control systems, and thermal management systems. This creates compatibility issues when swapping new battery cells and may inhibit automated refurbishment process.

#### Inverters

Inverters are considered to be the least reliable components of a PV system and inverter faults are a major factor contributing to PV system failures. Studies focusing on identifying causes of failures in inverters (especially in micro-inverters) and likely lifetime durations remain limited. However, one study noted inverter failures are typically caused by failures in capacitors and semiconductor devices. Typical inverter warranties (i.e., 10 years) are relatively short compared to performance warranties for PV panels (i.e., around 25 to 30 years).

We are not aware of any study characterising the reusability of decommissioned inverters. However, there is a concern in reusing older generation inverters as they may not meet the requirements of current product standards. For example, in Australia, the inverter standards were updated in 2020 after the identification of power system security risks that were not captured by the previous standard.

## Existing second-hand markets

Existing second-hand markets in Australia, Europe and North America were reviewed considering domestic markets and export to low- and middle-income countries:

1. **Domestic market**: Australian domestic second-hand PV markets are less developed compared to Europe and North America. However, even in these more developed markets, domestic trading of second-hand PV systems is largely conducted without sufficient performance and safety testing. Only around 15 companies are active in the responsible PV panel reuse sector. In Europe alone the volume traded is only around 300MW per year. In terms of battery reuse, many EV manufacturers in Europe and North America have formed joint ventures with energy generation companies and battery refurbishment and recycling companies to offer refurbished ESSs.
2. **International exports**: Export of PV panels to low- and middle-income regions such as Africa, Middle East, and Southeast Asia occurs from Australia, Europe, and North America to meet demands for accessible and affordable renewable energy generation. These exports are conducted without prior testing, repair, and/or refurbishment on these panels. Based on the Technical Guidelines on Transboundary Movements of Electrical and Electronic Waste and Used Electrical and Electronic Equipment (EEE), export of used PV panels, EV batteries, and inverters should be prohibited unless they are destined for direct reuse with documentation evidencing that performance and safety testing or and necessary repair or refurbishment has been or will be undertaken. This guideline is currently not legally binding for Basel Convention signatory countries.

## Challenges and enablers to responsible second-hand markets

Factors currently inhibiting the establishment of responsible second-hand PV system markets in Australia and across international supply chains were reviewed and the potential enablers were identified:

1. **Definition and criteria for reusability:** There is no agreed upon definition or criteria for reusable PV systems in Australia or globally. The existing AS50377:2022 standard which outlines requirements for reusing electronics is not product-specific which means technical guidelines are needed to provide industries with detailed procedures for evaluating PV system reusability. Definitions and criteria could be adapted from the Technical Guidelines on Transboundary Movements of Electrical and Electronic Waste and Used EEE.
2. **Standards and regulatory requirements**: Existing installation and product standard requirements (e.g., AS/NZS 5033 which requires PV panel compliance with IEC 61215 and IEC 61730 standards, IEC 61270:2017 for ESSs, and AS/NZS 4777.2 for inverters) in the market are currently inhibiting reuse of second-hand PV systems in the domestic Australian market. Second-hand PV systems currently do not comply with these standards and a potential enabler is to update existing standards to include second-hand PV systems. In the absence of commonly accepted IEC standard in Australia, voluntary industry standards can also increase the value of second-hand PV systems. Voluntary industry standards are currently available for reusing EV batteries for ESSs.
3. **Customer quality assurance**: There is a lack of information related to performance, ownership, and repair history, that can help customers make an informed decision when purchasing second-hand PV systems. Second-hand marketplaces should disclose information that demonstrate quality, reliability, and safety of these components. As far as we are aware, warranty for second-hand PV systems is not offered in Australia because there is no quality assurance process in place. Providing shorter-term or limited warranties to customers could boost customer confidence in buying second-hand PV systems.
4. **Circular design considerations**: Existing design for PV panels and batteries do not allow easy repair and refurbishment processes. For example, PV panel construction means solar cells cannot be easily accessed for repair and diversity in battery design with different chemistries, cell formats, welding

methods, and adhesives limits standardised approaches for repair and refurbishment. Research and development to investigate opportunities for circular design could promote standardise design, modular design approaches, use of components that can be easily replaced, first life data provisions, and automated disassembly. The development of a ‘repairability index’ would help consumers differentiate PV systems with greater repairability.

5. **Collection and transport**: There is a risk of breakage of potentially reusable PV panels during transport and decommissioning owing to rough handling. There needs to be training, guidelines or the development of new reverse logistics protocols to ensure workers are practicing safe handling, stacking, and transport methods that do not undermine opportunities for reuse.

6. **Economic feasibility for reuse**: Second-hand PV systems are not price competitive with new systems with the price for new systems continuously declining over many years. This is further compounded by the fact that customers cannot access small scale technology certificate (STC) rebates when deploying second-hand systems. Lowering testing, repair, and refurbishment costs can be achieved via improved circular design, improved field-testing capabilities, and promote more repairable systems in the market. Furthermore, providing financial incentives to customers purchasing properly tested, repaired, or refurbished PV systems can promote better price competitiveness of second-hand PV systems.

# Abbreviations

| Abbreviation | Description |
|---|---|
| AC | Alternating Current |
| CEC | Clean Energy Council |
| CER | Clean Energy Regulator |
| CIRCUSOL | Circular Business Models for the Solar Power Industry |
| DC | Direct Current |
| EEE | Electrical and Electronic Equipment |
| EIS | Electrochemical Impedance Spectroscopy |
| EL | Electroluminescence |
| EOL | End-of-Life |
| EPR | Extended Producer Responsibility |
| ESS | Energy Storage System |
| EV | Electric Vehicle |
| EVA | Ethylene Vinyl Acetate |
| FIT | Feed-in-Tariff |
| IEC | International Electrochemical Commission |
| LGC | Large-scale Generation Certificate |
| LAB | Lead Acid Battery |
| LIB | Lithium-ion Battery |
| NREL | National Renewable Energy Agency |
| NTCRS | National Televisions and Computers Recycling Scheme |
| PPA | Power Purchase Agreement |
| PV | Photovoltaic |
| STC | Small-scale Technology Certificate |
| UL | Underwriters Laboratories |
| UV | Ultraviolet |
| VPP | Virtual Power Plant |

# Table of Contents

# 1. Introduction

## 1.1. Background

End-of-life (EOL) photovoltaic (PV) systems are an emerging electronic waste problem globally and will present environmental problems and a lost opportunity for resource recovery if not properly managed at EOL.[1] A typical PV system comprises PV panels, inverters, racking/mounting system and may include a battery, also known as an energy storage system (ESS). Besides the embedded hazardous materials, PV panels are manufactured using diverse rare and critical metals[2] – making it necessary to prolong the lifetime of this product and recover these metals at EOL. In Australia, waste PV systems will reach a critical level by 2030 and this is mainly driven by small-scale PV systems reaching EOL (Figure 1).

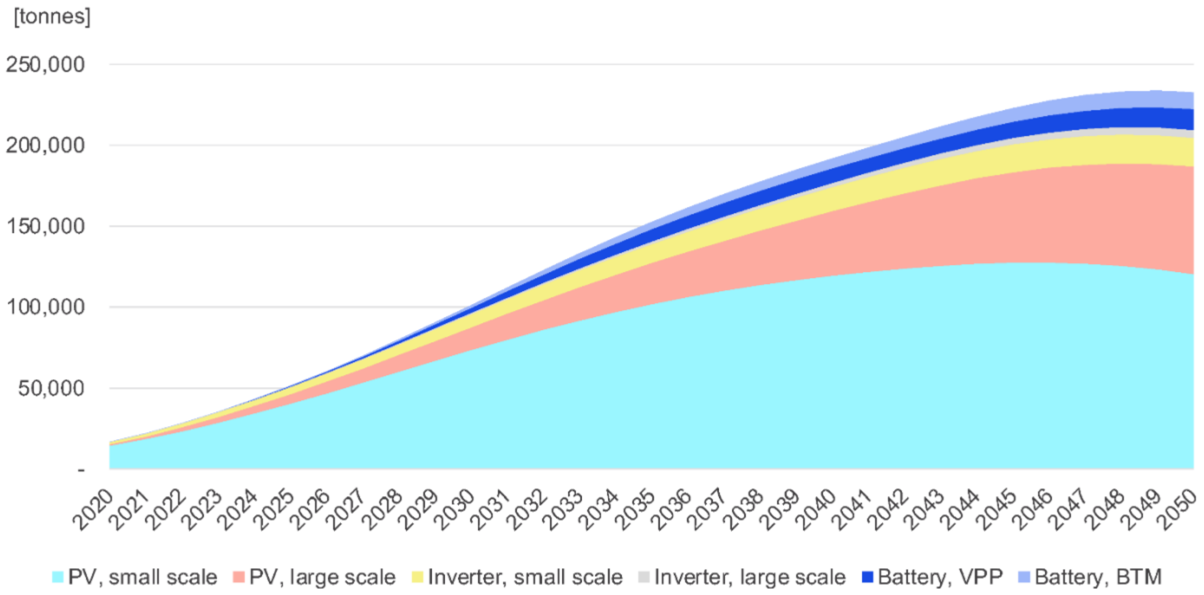



*Figure 1. Australian EOL PV systems arising over time by system type[3]*

Research around EOL PV systems has largely focused on the recycling of PV panels and ESS, including recycling technology development and policy change supporting the establishment of new collection and recycling industries.[4] However, reuse could represent an integral part of a circular economy solution for PV systems. Evidence suggests that many PV systems are being decommissioned early (i.e., before 10–12 years)[5,6] and it is likely that some of these systems still retain significant efficiency levels allowing for lifetime extension. Prioritising reuse helps to avoid resource and energy wastage and reduces environmental impacts from the recycling process.[7] Reuse can also lead to a greater revenue generation with less processing steps and lower energy inputs compared to recycling.[8]

---

[1] Gentilini, E. and Salt, M., 2020. *Circular Photovoltaics: Circular Business Models for Australia's Solar Photovoltaics Industry*. Arup. Available at: https://www.arup.com/-/media/arup/files/publications/c/circular-photovoltaics.pdf
[2] Grandell, L., Lehtilä, A., Kivinen, M., Koljonen, T., Kihlman, S. and Lauri, L.S., 2016. Role of critical metals in the future markets of clean energy technologies. *Renewable Energy*, 95, pp. 53-62
[3] Based on the ongoing analysis of PV waste projections undertaken by UTS Institute for Sustainable Futures.
[4] Franco, M.A. and Groesser, S.N., 2021. A systematic literature review of the solar photovoltaic value chain for a circular economy. *Sustainability*, 13(17), p. 9615
[5] Mathur, D., Gregory, R. and Hogan, E., 2021. Do solar energy systems have a mid-life crisis? Valorising renewables and ignoring waste in regional towns in Australia's Northern Territory. *Energy Research & Social Science*, 76, p. 101934
[6] Weckend, S., Wade, A. and Heath, G., 2016. *End-of-Life Management: Solar Photovoltaic Panels*. IRENA and IEA-PVPS. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf?rev=49a75178e38c46288a18753346fb0b09
[7] Walzberg, J., Carpenter, A. and Heath, G., 2021. Role of the social factors in success of solar photovoltaic reuse and recycle programmes. *Nature Energy*, 6, pp. 913-924
[8] Tao, M., Fthenakis, V., Ebin, B., Steenari, B., Butler, E., Sinha, P., Corkish, R., Wambach, K. and Simon, E.S., 2020. Major challenges and opportunities in silicon solar module recycling. *Progress in Photovoltaics: Research and Applications*, 28(10), pp. 1077-1088

The potential market and pathways for reusing PV systems are not fully understood. There are existing marketplaces that test, repair, and refurbish PV panels and inverters as well as pilot projects for reusing EV batteries as ESSs. These markets are primarily located in Europe and North America and still largely fragmented.[9] The lack of second-hand market development in Australia is caused by diverse challenges, including the regulatory, economic, market, and technological environment.

Previous studies undertaken by UTS[10] and Circular PV Alliance[11] provided an overview of the opportunities and challenges for reuse and refurbishment of PV panels and batteries. A better understanding of the opportunities, challenges, and enablers is a necessary first step for planning and creating a responsible second-hand market for PV systems.

> **"A responsible second-hand market means that organisations handling decommissioned PV systems properly test, repair, and/or refurbish components ensuring compliance with relevant guidelines or standards."**

## 1.2. Aim and objectives

This study is part of the broader project through the New South Wales (NSW) Environmental Protection Authority Circular Solar Grants Program led by PV Industries to investigate circular economy opportunities for PV systems in NSW. The broader project seeks to develop safe handling procedures, establish collection and logistic networks for urban and regional NSW, optimise high-value recycling approaches, activate new end-markets for recovered glass, and investigate future market opportunities for reuse. UTS ISF has been commissioned to evaluate market opportunities for reusing PV systems in Australia.

The objectives of this specific study are to understand:

- The **opportunities for reusing PV systems** by reviewing decommissioning behaviour for PV systems considering age, types of faults and damages, and performance testing requirements;
- The **existing second-hand market** for PV systems in Australia, Europe, and North America; and,
- The **challenges and enablers** for a responsible second-hand market for PV systems in Australia.

## 1.3. Project scope and approach

This study considers the reuse of PV system components for a similar application, either through direct reuse or reuse following repair and/or refurbishment. Downcycling activities, such as converting PV panels for use as greenhouses, workshop tables, etc. are excluded from this study. Despite being defined as giving second life to decommissioned PV systems, these pathways represent a loss in economic and material value.[12]

The study employed a combination of research methods:

---

[9] PV CYCLE, 2021. *RE-USE of PV modules, challenges and opportunities of the circular economy*. Available at: https://pvcycle.be/wp-content/uploads/Press-Release-Reuse-08032021.pdf
[10] Florin, N., Wakefield-Rann, R., Dominish, E., Dwyer, S., Gertsakis, J. and Hartford, N., 2020. *Scoping Study for Solar Panels and Battery System Reuse and Recycling in NSW*. University of Technology Sydney and Eqilibrium. Available at: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/grants/infrastructure-fund/isf-solar-pv-and-battery-recycling-report.pdf
[11] Circular PV Alliance, 2023. *Reclaimed PV Panels Market Assessment Industry Report*. The University of Queensland. Available at: https://www.circularpv.com.au/_files/ugd/10e921_d7a4fbb30adb4fd585b5d4784ccdc24b.pdf
[12] Florin, N., Wakefield-Rann, R., Dominish, E., Dwyer, S., Gertsakis, J. and Hartford, N., 2020. Scoping Study for Solar Panels and Battery System Reuse and Recycling in NSW. University of Technology Sydney and Eqilibrium. Available at: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/grants/infrastructure-fund/isf-solar-pv-and-battery-recycling-report.pdf

1. **Literature review**: This involved a synthesis of information from academic journals and grey literature.
2. **Expert interviews (n=10)**: Key experts were interviewed, including industry stakeholders (e.g., recyclers, installers) and academics with technical and/or policy expertise in the PV system reuse domain. A semi-structured interview approach was used, interviews were conducted online, and interviewees were asked questions about the challenges and enablers for a responsible reuse market for PV systems, including their existing reuse practices if applicable.
3. **PV system installer survey (n=44)**: an online survey was distributed to solar installers and distributors in Australia to gain insights about decommissioning activities and existing disposal, reuse, and recycling practices for PV systems. This provided data to help understand the limitations of existing practices, early decommissioning activities, and strategies to promote the development of a responsible second-hand market for PV systems in Australia.

## Key definitions

**Extended producer responsibility**

Extended producer responsibility (EPR) looks to extend a producer's financial responsibilities to the collection, recycling, and safe disposal of products at the post-consumption stage of the lifecycle.[13]

**Product stewardship**

Product stewardship aims to manage and reduce the environmental and human health impacts of products and materials throughout their lifecycle. This aligns with the three principles of a circular economy – eliminate waste and pollution, keep products and materials in use and regenerate natural systems. Everyone who designs, makes, sells, and uses a product has a role to play, however, the primary responsibility for managing impacts across the product's lifecycle rests with those placing products onto the market—including brands, importers, distributors, and retailers.

**Circular economy**

Circular economy tackles climate change and other challenges such as biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources. It based on three principles including eliminating waste and pollution, circulate products and materials at their highest value, and regenerate natural environment.

**Reusability**

The ability of decommissioned PV panels to be reused for other purposes. There is no agreement in defining PV system reusability to date. For this study, a reusable PV system means it can either be directly reused (i.e., without any faults or damages) or reused with treatment (i.e., repair or refurbish).

**Reuse**

Using second-hand PV systems in a similar or new application. It covers the definition of direct reuse, repair, and refurbishment. Reuse of a PV systems directly for a similar or new application without any repair or refurbishment requires prior performance and safety testing to demonstrate that they can be safely and effectively reused.

**Refurbishment**

Inspected, repaired, tested, and restored to a like-new condition or a better condition than the state of the decommissioned components. For example, this may involve the replacement of battery cells to increase battery efficiency levels, or replacement of faulty capacitors in inverters.

---

[13] OECD, 2016. Extended Producer Responsibility: Updated Guidance for Efficient Waste Management. OECD. Available at: https://www.oecd.org/development/extended-producer-responsibility-9789264256385-en.htm

**Repair**

Inspected, repaired, and tested for any damage, defect, or faults and restoring them to a working condition.

**Responsible second-hand market**

Second-hand market that whereby all market players conduct proper tests, repair, and/or refurbishment of components ensuring compliance with relevant standards.

**Regulation**

Imposition of limitations or responsibilities on individuals, corporations, and other entities. It refers to both the use of legislation and regulations established by organisations.

**Standard**

A level of quality of PV systems expected by industry or customers. Typically, this is reflected through a certification that indicates the product has undergone quality assurance procedures and meets or exceeds the requirements.

# 2. Characterising decommissioning activities

**This section provides an overview of decommissioning activities for PV panels, ESSs, and inverters. The aim of this review is to understand the typical age of decommissioned systems, the technical characteristics (e.g., component failure and damages, performance) at decommissioning, and the common safety and performance testing approaches. Research findings are drawn from the literature review, expert interviews, and surveys with installers.**

## 2.1. PV panels

PV panels are technically designed for long operational lifetimes. It is generally accepted that good quality PV panels that are properly installed and maintained should still produce 90% of their original power output after 10 years and around 80% after 25 years.[14,15] However, there are several factors that contribute to performance degradation, including local weather conditions, heat, exposure to ultraviolet (UV) rays, build quality, as well as the installation and handling methods.[16]

Evidence suggests that many PV panels are being decommissioned early at around 10-12 years and not meeting their designed for lifetimes (i.e. 25 years).[17,18] Reasons for these early decommissioning activities can include failure or damage to one part of the system, upgrades to a higher capacity system, or winding back generous government feed-in-tariffs (FiTs).[19] Our survey of installers indicated that around 58% of the overall PV panel replacement cases in Australia are due to failure or damages to panels and inverters.

### System failures and PV panel damage occurring in the early stages of operation

There are a wide range of causes of early-stage failures in PV panels which can be categorised as infant or mid-life failures:[20,21]

1. **Infant failures**: Occur during the first four years of operation and primarily within the electrical systems, including junction boxes, string boxes, charge controllers, cabling, and grounding.
2. **Mid-life failures**: Occur in the first 12 years and includes more varied failures within the PV panel layers and the electrical system, including degradation of the anti-reflective coating of the glass layer, discoloration of the ethylene vinyl acetate (EVA), delamination, cracked solar cells, junction boxes, and cabling.

In addition, the handling and transport of the decommissioned PV panels from site to a treatment facility can also risk increasing the number of damaged panels. Rough handling and improper stacking of decommissioned PV panels are the primary cause of cracked glass layer(s) which is challenging to repair.[22] This will be discussed in more detail in Part 3.

---

[14] Olalla, C., Maksimovic, D., Deline, C. and Martinez-Salamero, L., 2017. Impact of distributed power electronics on the lifetime and reliability of PV systems. *Progress in Photovoltaics: Research and Applications*, 25(10), pp. 821-835
[15] Tekumalla, D.V., Pal, D. and Bajpai, P., 2019. Comprehensive performance evaluation of various solar PV system configurations. *IET Renewable Power Generation*, 13(8), pp. 1261-1270
[16] Sodhi, M., Banaszek, L., Magee, C. and Rivero-Hudec, M., 2022. Economic lifetimes of solar panels. *Procedia CIRP*, 105, pp. 782-787
[17] Weckend, S., Wade, A. and Heath, G., 2016. End-of-Life Management: Solar Photovoltaic Panels. IRENA and IEA-PVPS. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf?rev=49a75178e38c46288a18753346fb0b09
[18] Mathur, D., Gregory, R. and Hogan, E., 2021. Do solar energy systems have a mid-life crisis? Valorising renewables and ignoring waste in regional towns in Australia's Northern Territory. Energy Research & Social Science, 76, p. 101934
[19] Ibid.
[20] Weckend, S., Wade, A. and Heath, G., 2016. End-of-Life Management: Solar Photovoltaic Panels. IRENA and IEA-PVPS. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf?rev=49a75178e38c46288a18753346fb0b09
[21] Köntges, M., Kurtz, S., Packard, C., Jahn, U., Berger, K.A., Kato, K., Friesen, T., Liu, H. and Van Iseghem, M., 2014. *Review of Failures of Photovoltaic Modules*. IEA-PVPS. Available at: https://iea-pvps.org/wp-content/uploads/2020/01/IEA-PVPS_T13-01_2014_Review_of_Failures_of_Photovoltaic_Modules_Final.pdf
[22] Ibid.

In Australia, customers generally replace their entire PV system with a new one when there are a few damaged panels, especially PV systems using string inverters. A major reason is the ineligibility to receive small-scale technology certificate (STC) rebates when only the damaged panels are replaced, making this option uncompetitive with complete system replacement.[23] Manufacturers also typically replace the whole set of PV panels with new ones in the case of a warranty claim.[24] Thus, it is highly likely that PV panels in good condition are being decommissioned, and this presents a clear opportunity for reuse.

## Performance testing

It is challenging to accurately estimate a PV panel's reusability solely based on the number of years of operations when considering the range of factors leading to a system failure (described above). Thus, conducting performance testing is essential. Typical performance tests for reusability require ensuring 1) adequate efficiency levels, 2) safety testing (e.g., fire risk, electrical safety, etc.) and 3) identifying if there are any faults or damage that could be repaired.[25]

There are a wide variety of tests for PV panels, however, according to the literature there are five that are most used (see Table 1):[26,27]

1. **Visual inspection**: Inspect if there are any visible defects present around the panel area. Some major defects require panels to be directed to recycling, including:
    a) Deformation and bloating of the junction box,
    b) Burn spots on the panel,
    c) Fractures or cracks in the glass layer,
    d) Severe dents on the frame.
2. **Current-voltage (I-V) curve measurement**: Measure the remaining maximum power output of a PV panel by showing the current and voltage values using a hand-held meter. This test can be performed either in the field or at a treatment facility under controlled lighting and temperature conditions.[28]
3. **Electroluminescence (EL) imaging**: Typically carried out after I-V curve measurement, the test is to measure the general state of health of a PV panel and identify the failure mechanisms. It is capable of identifying internal defects in a PV panel such as:
    a) Solar cell cracks,
    b) Increased resistance values,
    c) High potential difference between solar cells and other parts of the panel.
4. **Thermal imaging**: Detect possible failures of a PV panel by revealing the temperature distribution at the individual solar cell and PV panel level. Relatively high temperatures can indicate possible internal damages. This is usually carried out using a hand-held infrared camera, although there is an emerging approach using drones fitted with infrared cameras that speeds up the testing process and is applicable for large-scale PV plants.[29]
5. **Insulation testing**: For safety purposes, it is important to measure whether a PV panel has adequate insulation between its internal components and the frame or between the internal components and the

---

[23] Mathur, D., Gregory, R. and Hogan, E., 2021. Do solar energy systems have a mid-life crisis? Valorising renewables and ignoring waste in regional towns in Australia's Northern Territory. Energy Research & Social Science, 76, p. 101934
[24] Ibid.
[25] van der Heide, A., 2022. *Labelling and Certification Protocols for Second Life PV Modules*. CIRCUSOL. Available at: https://www.circusol.eu/files/Deliverables/D3-2_Labelling_and_certification_protocols_for_second_life_PV_modules.pdf
[26] Ibid.
[27] Tsanakas, J.A., van der Heide, A., Radavičius, T., Denafas, J., Lemaire, E., Wang, K., Poortmans, J. and Voroshazi, E., 2020. Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. *Progress in Photovoltaics: Research and Applications*, 28(6), pp. 454-464
[28] van der Heide, A., 2022. Labelling and Certification Protocols for Second Life PV Modules. CIRCUSOL. Available at: https://www.circusol.eu/files/Deliverables/D3-2_Labelling_and_certification_protocols_for_second_life_PV_modules.pdf
[29] Ibid.

external environment. A common cause for insufficient insulation is wearing in the encapsulation or delamination.

Table 1 summarises five published studies highlighting testing results for decommissioned PV panels. The percentage of PV panels that were identified as reusable varies widely across these studies (between ~30-65%), therefore, it is hard to determine an industry average. The location in which the modules have operated prior to decommissioning may also contribute to this variation. Furthermore, there is no agreed definition or criteria for reusability. The development of standardised testing procedures and approaches is required to produce consistent results and establish a definition of reusability.

*Table 1. A summary of five studies that conducted performance testing of decommissioned PV panels*

| Author(s) | Sample | Age | Tests conducted | Can be done in-field? | Percent of reusability |
|---|---|---|---|---|---|
| Shah[30] | 25 | 6 to 12 years | Visual inspection<br>I-V curve<br>Thermal imaging | Yes | Not specified |
| Stromberg[31] | 221 | 2 to 20 years | Visual inspection<br>I-V curve<br>Thermal imaging | Yes | 64% |
| Skoczek et al.[32] | 204 | 19 to 23 years | Visual inspection<br>Insulation test<br>I-V curve<br>Thermal imaging | Yes | 65.7% |
| Peacock[33] | 1,450 | Not specified | Not specified | Not specified | 31% |
| Tsanakas et al.[34] | Not specified | Not specified | Not specified | Not specified | 45-65% |

## 2.2. Energy storage systems

There are two common types of batteries used in ESSs, lithium-ion batteries (LIBs) and lead-acid batteries (LABs). LIBs typically have longer lifetimes (around 15 to 20 years) compared to LABs (around 8.5 years).[35] We are not aware of any research conducted to evaluate the performance efficiency of ESSs decommissioned from PV systems to date. This is likely because there is still no significant number of ESSs integrated with PV systems that are being decommissioned.

Given the lack of information about the reuse of ESSs, we have instead focused on the reuse of EV batteries. Currently most efforts are focussed on reusing electric vehicle (EV) batteries for stationary energy applications. EV batteries are typically decommissioned when the capacity declines to about 80%, which can

---

30 Shah, R., 2021. *Second Life of Solar Panels*. Federation University. Available at: https://gccn.org.au/wp-content/uploads/2021/07/GCCN_Recycling-and-Reuse-of-Solar-Panels-Report_Version1.2.pdf
31 Stromberg, R., Year. Reuse of solar photovoltaic systems for social and economic benefit. *SOLAR 2021 Proceedings*
32 Skoczek, A., Sample, T. and Dunlop, E.D., 2009. The results of performance measurements of field-aged crystalline silicon photovoltaic modules. *Progress in Photovoltaics: Research and Applications*, 17, pp. 227-240
33 Peacock, B., 2022. *One third of disused solar panels found fit for reuse as recycling partnership strengths circular push*. Available at: https://www.pv-magazine-australia.com/2022/05/18/one-third-of-disused-solar-panels-found-fit-for-reuse-as-recycling-partnership-strengths-circular-push/
34 Tsanakas, J.A., van der Heide, A., Radavičius, T., Denafas, J., Lemaire, E., Wang, K., Poortmans, J. and Voroshazi, E., 2020. Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. Progress in Photovoltaics: Research and Applications, 28(6), pp. 454-464
35 Yudhistira, R., Khatiwada, D. and Sanchez, F., 2022. A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage. *Journal of Cleaner Production*, 358, p. 131999

be around 10 years.[36] Compared to EV applications, ESSs do not require the equivalent efficiency levels.[37] In some cases EV batteries can be reused directly if they meet performance and safety standards.[38] Otherwise, they need to be refurbished by replacing defective battery cells or components.

## Uncertainties in battery characteristics upon decommissioning

EV batteries are typically being decommissioned during regular vehicle services (through an auto-dealership or service centre) if they do not meet the EV performance and safety requirements.[39] Two main battery characteristics upon decommissioning impact reusability for stationary applications: 1) performance (affected by degradation or damage) and 2) design.

EV batteries reaching EOL have varied performance characteristics influenced by a range of factors leading to degradation including EV milage, temperature, and rates of charge or discharge.[40] There could also be faults present in the EV batteries that require replacement. Car accidents can also contribute to damaged EV batteries which typically makes them non-reusable owing to safety concerns.[41]

Further variability in terms of battery design impacts reusability. There is a wide variety of chemistries, battery cells sizes and formats (e.g., cylindrical, prismatic, and pouch), control systems, and thermal management systems.[42,43] This means there are compatibility issues as well as technical limitations unique to individual products that prevents effective and automated refurbishment processes. A few manufacturers including Nissan and Renault have established EV battery reuse programs only focussed on their batteries.[44]

## Performance testing

Performance testing is a necessary step to determine reusability of EV batteries for ESSs. As noted above, EV batteries with a remaining capacity of about 80% can be tested to determine whether they can be directly reused, refurbished, or sent for recycling.[45] Tests may be carried out at the pack-level, module-level, or cell-level.[46] Each EV battery pack usually consists of several battery modules. Within a module, there are several battery cells grouped together (Figure 2).

---

[36] Colarullo, L. and Thakur, J., 2022. Second-life EV batteries for stationary storage applications in Local Energy Communities. *Renewable and Sustainable Energy Reviews*, 169, p. 112913

[37] Heath, G.A., Ravikumar, D., Hansen, B. and Kupets, E., 2022. A critical review of the circular economy for lithium-ion batteries and photovoltaic modules – status, challenges, and opportunities. *Journal of the Air & Waste Management Association*, 72(6), pp. 478-539

[38] Mulder, G., De Craemer, K. and Lemaire, E., 2021. *Development of Labelling and Certification Protocols for Second Life Batteries*. CIRCUSOL. Available at: https://zenodo.org/record/6674934/files/D3.4-Labeling_and_certif_protocols_2nd_life_batteries.pdf?download=1

[39] Engel, H., Hertzke, P. and Siccardo, G., 2019. *Second-life EV batteries: The newest value pool in energy storage*. Available at: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

[40] Montes, T., Etxandi-Santolaya, M., Eichman, J., Ferreira, V.J., Trilla, L. and Corchero, C., 2022. Procedure for assessing the suitability of battery second life applications after EV first life. *Batteries*, 8, p. 122

[41] Bisschop, R., Willstrand, O. and Rosengren, M., 2020. Handling lithium-ion batteries in electric vehicles: Preventing and recovering from hazardous events. *Fire Technology*, 56, pp. 2671-2694

[42] Montes, T., Etxandi-Santolaya, M., Eichman, J., Ferreira, V.J., Trilla, L. and Corchero, C., 2022. Procedure for assessing the suitability of battery second life applications after EV first life. Batteries, 8, p. 122

[43] Engel, H., Hertzke, P. and Siccardo, G., 2019. *Breathing new life into used electric vehicle batteries*. Available at: https://www.mckinsey.com/capabilities/sustainability/our-insights/sustainability-blog/breathing-new-life-into-used-electric-vehicle-batteries

[44] Ibid.

[45] Haram, M.H.S.M., Lee, J.W., Ramasamy, G., Ngu, E.E., Thiagarajah, S.P. and Lee, Y.H., 2021. Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges. *Alexandria Engineering Journal*, 60(5), pp. 4517-4536

[46] Mulder, G., De Craemer, K. and Lemaire, E., 2021. Development of Labelling and Certification Protocols for Second Life Batteries. CIRCUSOL. Available at: https://zenodo.org/record/6674934/files/D3.4-Labeling_and_certif_protocols_2nd_life_batteries.pdf?download=1

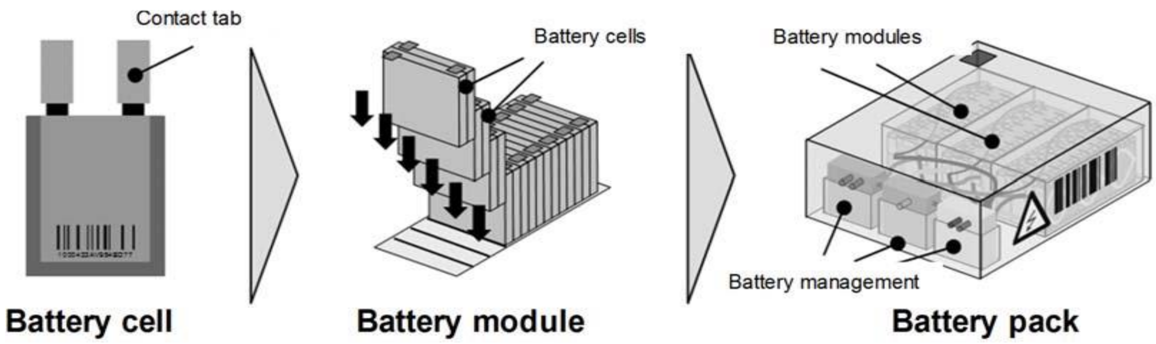



*Figure 2. Battery cell, module, and pack*[47]

There are several common tests based on a technical guideline developed from the CIRCUSOL project to determine the reusability of EV batteries for ESSs:[48]

1. **Initial observation**: Observe the external appearance of batteries if there is any bloating, weeping, and pocking. BMSs can also be accessed prior to conducting the tests to check if the batteries have good internal conditions, which typically provides the following information:
    a) The amount of energy or charge that has been delivered (energy throughput),
    b) Module and/or cell voltage (open-circuit voltage) and its spread,
    c) Temperature information (temperature fluctuations can indicate damage).
2. **Open circuit voltage test**: To measure the voltage applied to the terminals of a cell or battery when no load is connected. If voltage information from the BMS cannot be accessed, the battery pack, module and cell voltages must be tested manually.
3. **Insulation resistance test**: A simple test that shows if any internal damage is present that could lead to an electric shock. This is usually tested through a handheld insulation resistance meter.
4. **Capacity test**: To measure a battery's ability to store energy referred to as the state of health (SOH). This is done by charging and discharging batteries under certain conditions defined by the refurbishing company.
5. **Internal resistance test**: Another approach to express SOH is using the ratio of the original and current internal resistance value. Typically done by applying a discharge pulse to the battery when the state of charge is brought between 80% and 90%.
6. **Electrochemical impedance spectroscopy (EIS)**: Used to monitor and control the degradation of the performance of a battery during cycling by investigating their internal behaviour.
7. **Self-discharge test**: To investigate if there is any excessive continuous cell discharging independent of the connected load. A slow discharge of less than 2% of the capacity within a month indicates a normal battery operating condition.

## Likelihood of reusability

Table 2 summaries published studies that conducted performance testing to determine the reusability of EV batteries for ESSs. Like PV panels the percentage of tested batteries identified as reusable varies widely across the studies. This is likely because there are no standardised test procedures. However, all studies report > 70%.

---

[47] Kampker, A., Heimes, H.H., Ordung, M., Lienemann, C., Hollah, A. and Sarovic, N., 2016. Evaluation of a remanufacturing for lithium-ion batteries from electric cars. *International Journal of Mechanical and Mechatronics Engineering*, 10(12), pp. 1922-1928

[48] Mulder, G., De Craemer, K. and Lemaire, E., 2021. Development of Labelling and Certification Protocols for Second Life Batteries. CIRCUSOL. Available at: https://zenodo.org/record/6674934/files/D3.4-Labeling_and_certif_protocols_2nd_life_batteries.pdf?download=1

*Table 2. Six selected studies conducted performance testing of decommissioned EV batteries for ESSs*

| Author(s) | Sample | Test level | Tests conducted | Percent of reusability |
|---|---|---|---|---|
| Liao et al.[49] | 20 | Pack | Initial observation<br>Capacity test<br>EIS | 70% |
| Martinez-Laserna et al.[50] | 4 | Module | Capacity test<br>Internal resistance test | 75% |
| Ramirez-Meyers et al.[51] | 16 | Module | Internal resistance test<br>EIS | 75-94% |
| Ramirez-Meyers et al.[52] | 96 | Cell | Internal resistance test<br>EIS | 90-99% |
| Abdel-Monem et al.[53] | 62 | Cell | Initial observation<br>Open circuit voltage test<br>Capacity test<br>EIS | 73% |
| Kampker et al.[54] | 196 | Cell | Open circuit voltage test<br>Internal resistance test<br>Capacity test | 75% |

## 2.3. Inverters

Inverter failure is reported as one of the common reasons for customers to replace their PV systems early.[55, 56] It was noted that customers usually use this opportunity to upgrade to a higher capacity PV system.[57] Given the shorter lifetime of inverters (i.e.,10 years on average) and a relatively high chance of failure there may be limited options for direct reuse. Our stakeholder research indicated that most inverters are recycled through established scrap metal recycling.

[49] Liao, Q., Mu, M., Zhao, S., Zhang, L., Jiang, T. and Ye, J., 2017. Performance assessment and classification of retired lithium ion battery from electric vehicles for energy storage. *International Journal of Hydrogen Energy*, 42(30), pp. 18817-18823
[50] Jiang, T., Jiang, J., Zhang, C., Zhang, W., Gao, Y. and Na, L., 2018. State of health estimation of second-life LiFePO4 batteries for energy storage applications. *Journal of Cleaner Production*, 205, pp. 754-762
[51] Ramirez-Meyers, K., Rawn, B. and Whitacre, J.F., 2023. A statistical assessment of the state-of-health of LiFePO4 cells harvested from a hybrid-electric vehicle battery pack. *Journal of Energy Storage*, 59, p. 106472
[52] Ibid.
[53] Abdel-Monem, M., Hegazy, O., Omar, N., Trad, K., den Bossche, P.V. and Mierlo, J.V., Lithium-ion batteries: Comprehensive technical analysis of second-life batteries for smart grid applications. *2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)*
[54] Kampker, A., Wessel, S., Fiedler, F. and Maltoni, F., 2021. Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells. *Journal of Remanufacturing*, 11, pp. 1-23
[55] Formica, T.J., Khan, H.A. and Pecht, M.G., 2017. The effect of inverter failures on the return on investment of solar photovoltaic systems. *IEEE Access*, 5, pp. 21336-21343
[56] Mathur, D., Gregory, R. and Hogan, E., 2021. Do solar energy systems have a mid-life crisis? Valorising renewables and ignoring waste in regional towns in Australia's Northern Territory. Energy Research & Social Science, 76, p. 101934
[57] Ibid.

## Existing reliability issues

Studies examining the causes of inverter failure and typical lifetimes are limited. Inverter failure is typically linked to two main components inside the inverter:[58]

1. **Capacitors**: Two most common capacitors in inverters are electrolytic and film. Film capacitors are considered more reliable than electrolytic ones, albeit more expensive. Technically, electrolytic capacitors can be replaced with film ones, although the economic feasibility is unclear.
2. **Semiconductor devices**: Typically degrade or fail owing to high-voltage, high-current, or extreme temperature conditions.

Microinverter technology, a relatively new technology is thought to have longer lifetimes up to 25 years however because their use is relatively recent there is limited data on reliability and failures.[59,60]

## Performance testing

In terms of reusability, decommissioned inverters need to be tested in terms of their performance, to identify damage and/or cause of failure and to determine the need for refurbishment processes. We are not aware of any studies discussing performance testing or diagnostics of decommissioned inverters from PV systems. Furthermore, there are no standardised procedures to test inverter performance.

There is also an issue in reusing older generation inverters as they may not meet current safety standards. In Australia, the inverter standard was updated in 2020 after identifying several power system security risks that were not addressed by the previous standard.[61] Old inverters may be able to be refurbished and retested to meet this new standard however the economic feasibility remains unknown.

---

[58] Formica, T.J., Khan, H.A. and Pecht, M.G., 2017. The effect of inverter failures on the return on investment of solar photovoltaic systems. IEEE Access, 5, pp. 21336-21343

[59] Kennedy, R., 2021. *How long do residential solar inverters last?* Available at: https://www.pv-magazine.com/2021/09/16/how-long-do-residential-solar-inverters-last/

[60] Formica, T.J., Khan, H.A. and Pecht, M.G., 2017. The effect of inverter failures on the return on investment of solar photovoltaic systems. IEEE Access, 5, pp. 21336-21343

[61] AEMO, 2022. *AS/NZS 4777.2 – Inverter Requirements standard*. Available at: https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/as-nzs-4777-2-inverter-requirements-standard

# 3. Review of existing second-hand markets

**This section reviews the status of second-hand markets for PV systems in Australia and the more established markets in Europe and North America. Findings from this section are drawn from literature review and supported by expert interviews. European and North American second-hand markets are the most established and thus there is more available information. We also sought interviews from experts from these regions.**

Overall, there are limited examples of domestic reuse in all regions assessed, however there are several examples of unregulated exports to low- and middle-income countries. These international exports are typically happening without sufficient testing, repair, and/or refurbishment.

## 3.1. Domestic markets

Domestic applications of second-hand PV systems in Australia, Europe, and North America are relatively immature. The market characteristics, by system component, are summarised in Table 3.

*Table 3. Summary of existing domestic second-hand PV system markets in Australia, Europe, and North America*[62]

| Component | Australia | Europe | North America |
|---|---|---|---|
| **PV panel** | • Dominated by **informal reuse activities**.<br>• PV panels in good conditions are being sold at a very low price without proper performance and safety testing on online marketplaces (e.g., buy/sell sites).[63]<br>• A common example of reuse is for small-scale applications such as caravans, RVs, and mobile homes.[64]<br>• Entities exporting PV panels are also sourcing used panels from online marketplaces. | • **Responsible online marketplaces** exist mainly in Germany with companies such as SecondSol[65], pvXchange[66], and Rinovasol[67] selling properly tested, repaired, and/or refurbished panels.<br>• Commonly reused in off-grid applications such as EV or mobile phone charging stations.[68]<br>• Another reuse case is driven by FiT schemes in some Western European countries that allow customers to replace damaged panels with similar or identical ones to retain their FiT.[69] | • **Responsible online marketplaces** exist with companies such as EnergyBin[70] and KinectSolar[71] selling and conducting testing, repair, and refurbishment of PV panels.<br>• Commonly reused for off-grid solar applications and grid-connected solar in certain states where regulations do not impede grid-connection for second-hand PV panels.[72]<br>• A company, Good Sun[73] is enabling the donation of PV panels to low- and middle-income homes in the US. |

[62] Summarised based on literature review and key interviews.
[63] Carroll, D., 2021. *Sunday read: Out of landfill, back in the stream*. Available at: https://www.pv-magazine-australia.com/2021/10/10/saturday-read-out-of-landfill-back-in-the-stream/
[64] Mathur, D. and Muhammad, I., 2021. *Stop removing your solar panels early, please. It's creating a huge waste problem for Australia*. Available at: https://theconversation.com/stop-removing-your-solar-panels-early-please-its-creating-a-huge-waste-problem-for-australia-160546
[65] https://www.secondsol.com/en/index.htm
[66] https://www.pvxchange.com
[67] https://www.rinovasol.de
[68] Pareek, M., 2021. *Supply Chain of Second Life PV Modules for Reuse in Europe*. Ghent University. Available at: https://zenodo.org/record/6344387#.ZBPOPS8RpYg
[69] Ibid.
[70] https://energybin.com
[71] https://kinectsolar.com
[72] Curtis, T.L., Buchanan, H., Smith, L. and Heath, G., 2021. *A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations*. NREL. Available at: https://www.nrel.gov/docs/fy21osti/74550.pdf
[73] https://www.goodsun.life/

| Component | Australia | Europe | North America |
|---|---|---|---|
| **ESSs from EV batteries** | • Market is **not yet established**.<br>• There are only a few ongoing projects to reuse EV batteries for commercial and industrial-scale solar energy applications and for research purposes in Australia.[74]<br>• As an example, Infinitev[75] and Relectrify[76] are conducting a pilot project to refurbish and reuse EV batteries for rooftop solar applications, farms, microgrids, and rural energy generation.<br>• Nissan Australia is also set to launch a program to reuse their decommissioned EV batteries to power their own production facility.[77] | • Market for refurbished ESSs from EVs is **fragmented** and largely driven by trial projects run through joint ventures consisting of EV manufacturers, utility companies, and technology developers.[78,79]<br>• Refurbished ESSs are usually in the form of custom-built solutions which is based on clients' needs while off-the shelf second hand ESSs marketed online remain limited.[80]<br>• Custom-built solutions are generally part of trial projects for electricity demand management and power backup support.[81]<br>• An example of off-the-shelf refurbished ESSs made from EV batteries is the PowerVault ECO which will be targeted for residential homes.[82]<br>• Markets for refurbished ESSs from decommissioned ESSs are still not available. | • Market for refurbished ESSs from EVs is **fragmented** and driven by manufacturers such as Spiers News Technology[83], Moment Energy[84], Smartville[85], RePurpose Energy[86], and B2U[87] and EV manufacturers.<br>• Refurbished ESSs are mainly being marketed as custom-built solutions as part of trial projects, with limited off-the-shelf ESSs marketed online.[88]<br>• Custom-built solutions are primarily for trials and reused in large-scale energy applications (i.e., commercial, and industrial buildings) for electricity demand management and power backup support.[89]<br>• An example of an off-the shelf ESSs is from Smartville MOAB which provides utility-scale ESSs from refurbished EV batteries.[90]<br>• Markets for refurbished ESSs from decommissioned ESSs are still not available. |

---

[74] Faessler, B., 2021. Stationary, second use battery energy storage systems and their applications: A research review. *Energies*, 14(8), p. 2335
[75] https://infinitev.au
[76] https://www.relectrify.com
[77] Nissan, 2022. *Leaf comes full circle*. Available at: https://www.nissan.com.au/about-nissan/news-and-events/news/2022/september/nissan-node-new-2nd-life-battery-project.html
[78] Faessler, B., 2021. Stationary, second use battery energy storage systems and their applications: A research review. Energies, 14(8), p. 2335
[79] Ibid.
[80] Ibid.
[81] Ambrose, H., 2020. *The second-life of used EV batteries*. Available at: https://blog.ucsusa.org/hanjiro-ambrose/the-second-life-of-used-ev-batteries/
[82] https://www.powervault.co.uk
[83] https://www.spiersnewtechnologies.com
[84] https://www.momentenergy.com
[85] https://smartville.io
[86] https://www.repurpose.energy
[87] https://www.b2uco.com
[88] Ambrose, H., 2020. The second-life of used EV batteries. Available at: https://blog.ucsusa.org/hanjiro-ambrose/the-second-life-of-used-ev-batteries/
[89] Ibid.
[90] Murray, C., 2022. *Second life energy storage firm Smartville Inc on modules vs packs, ramp-up plans and Tesla's approach*. Available at: https://www.energy-storage.news/second-life-energy-storage-firm-smartville-inc-on-modules-vs-packs-ramp-up-plans-and-teslas-approach/

| Component | Australia | Europe | North America |
|---|---|---|---|
| **Inverter**  | • Market is **not yet established**. | • **Responsible online marketplaces** exist with some companies offering refurbished PV panels (e.g., SecondSol and pvXchange) and selling properly repaired or refurbished inverters. | • **Responsible online marketplaces** exist with companies such as EnergyBin and KinectSolar are also selling properly repaired or refurbished inverters. |

## Opportunities

Australian domestic second-hand PV system markets are less well established compared to Europe and North America. We are not aware of any market offerings in Australia where there is sufficient prior performance and safety testing. Besides the challenges outlined in Section 3, there is a relatively low volume of decommissioned EV batteries[91] and inverters[92] to justify formal market development. This study identified several opportunities for domestic reuse in Australia, although there needs to be more coordinated efforts from private industries and government to ensure quality assurance of second-hand PV systems, this includes:[93,94]

1. Provide renewable energy generation to outer regional or rural homes,
2. Reuse on farms and the agriculture sector more broadly,
3. Reuse as a solar farm as second-hand PV panels can claim large-scale generation certificate (LGC),
4. Reuse to power city or public infrastructure (e.g., swimming pools, street lightings, community solar gardens, public parking spaces, EV charging stations, and mobile charging stations).

As the Australian market develops there is an opportunity to learn from more established markets in Europe and North America. Globally, there are at least 15 companies active in the reuse sector and the volume being traded in Europe alone is around 300 MW per year.[95] No trading data is available for North America to date. Furthermore, there are more widespread pilot projects reusing EV batteries for solar energy generation in Europe and North America. These pilot projects could be useful to reveal important data on actual field lifetimes for these systems, as well as insight into best practices for their management.

---

[91] Dominish, E., Florin, N. and Wakefield-Rann, R., 2021. *Reducing New Mining for Electric Vehicle Battery Metals: Responsible Sourcing through Demand Reduction Strategies and Recycling*. University of Technology Sydney. Available at: https://www.uts.edu.au/sites/default/files/2021-04/20210423_EW%20report%20final.pdf

[92] Florin, N., Wakefield-Rann, R., Dominish, E., Dwyer, S., Gertsakis, J. and Hartford, N., 2020. Scoping Study for Solar Panels and Battery System Reuse and Recycling in NSW. University of Technology Sydney and Eqilibrium. Available at: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/grants/infrastructure-fund/isf-solar-pv-and-battery-recycling-report.pdf

[93] Barfoot, C. and McCubbin, D., 2021. *Recycling and Reuse of Used Solar Panels: An Investigation into Current Opportunities for Gippsland*. Gippsland Climate Change Network. Available at: https://gccn.org.au/wp-content/uploads/2021/07/GCCN_Recycling-and-Reuse-of-Solar-Panels-Report_Version1.2.pdf

[94] Dubbo Regional Council, 2022. *Waste not, want not - Dubbo leads circular economy for solar panels*. Available at: https://www.dubbo.nsw.gov.au/news-and-media/news-and-resources/media-releases/2022/waste-not-want-not-dubbo-leads-circular-economy-for-solar-panels

[95] PV CYCLE, 2021. RE-USE of PV modules, challenges and opportunities of the circular economy. Available at: https://pvcycle.be/wp-content/uploads/Press-Release-Reuse-08032021.pdf

## 3.2. International exports

According to the literature and expert interviews the export of decommissioned PV panels to low- and middle-income countries is considerable. These operations are largely unchecked and conducted without prior testing, repair, and/or refurbishment. These export activities are driven by demands from these regions for accessible and affordable renewable energy generation.[96]

An interviewee was aware of the shipping of decommissioned PV panels from Australia to low- and middle-income regions such as Timor-Leste and Africa. An interview with an industry representative from PV Magazine indicated that export to Africa has been going on for at least a decade at a large volume (2,000 panels per month).[97] Based on our research, the number of solar panels shipped overseas from Australia could be significantly higher. PV CYCLE also noted similar export activities from Europe to developing regions such as Middle East, Southeast Asia, and Africa.[98]

There is a significant risk that countries receiving second hand PV panels do not have established electronic waste management and recycling industries. This may contribute to a significant waste and pollution problem as these components reach EOL. With no requirements for testing prior to export there are also potentially defective systems being exported that further exacerbates the problem.

According to the Technical Guidelines on **Transboundary Movements of Electrical and Electronic Waste and Used Electrical and Electronic Equipment**, export of used PV panels, EV batteries, and inverters are prohibited unless they meet certain criteria for reuse, repair, or refurbishment. However, ensuring compliance to this guideline is a challenge as they are often not reflected in the regulation of exporting or importing countries.

**Technical Guidelines on Transboundary Movements of Electrical and Electronic Waste and Used Electrical and Electronic Equipment (EEE)[99]**

A technical guideline has been drafted that relates to overseas export of EEE waste and used EEE. It is available to use for countries that are signatories to the **Basel Convention that prohibits the import or export of hazardous waste.** Waste PV panels, ESSs, EV batteries are considered as hazardous waste as they contain hazardous materials as outlined in the Annex I of the guideline.

The guideline provides definitions to differentiate used electronics, electronic waste, hazardous waste, and non-hazardous waste. Specifically, it provides guidance and requirements for performance testing or evaluation to satisfy the definition of used equipment. The guideline is intended for government agencies that wish to implement, enforce, and control the import and export of EEE waste and minimise the potential impacts of dumping defective systems in regions where recycling infrastructure is limited or does not exist under the guise of reuse.

According to the guidelines, it is likely that used equipment may be categorised as waste if they do not meet the minimum performance requirement or if any damage and/or failures are present in the products. This performance requirement will differ across different EEE products and should be determined according to the respective acceptable testing procedures which in some cases are lacking, especially for PV panels.[100] Specifically, used equipment is not considered a waste and allowed for import or export if they are destined for:

[96] Ibid.
[97] Carroll, D., 2021. Sunday read: Out of landfill, back in the stream. Available at: https://www.pv-magazine-australia.com/2021/10/10/saturday-read-out-of-landfill-back-in-the-stream/
[98] van der Heide, A., Tous, L., Wambach, K., Poortmans, J., Clyncke, J. and Voroshazi, E., 2021. Towards a successful re-use of decommissioned photovoltaic modules. *Progress in Photovoltaics: Research and Applications*, 30(8), pp. 910-920
[99] Basel Convention, 2019. *Technical Guidelines on Transboundary Movements of Electrical and Electronic Waste and Used Electrical and Electronic Equipment, In Particular Regarding the Distinction between Waste and Non-Waste under the Basel Convention*. UNEP. Available at: http://www.basel.int/Portals/4/download.aspx?d=UNEP-CHW.14-7-Add.6-Rev.1.English.pdf
[100] Tsanakas, J.A., van der Heide, A., Radavičius, T., Denafas, J., Lemaire, E., Wang, K., Poortmans, J. and Voroshazi, E., 2020. Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment

1. **Direct reuse** in the destination country. The products need to be accompanied by evidence of appropriate testing or evaluation, copy of sales invoices, and a declaration that they are not considered waste in the destination countries and transiting countries during transport. They should also be properly packed and protected during transport.
2. **Failure analysis, repair, or refurbishment** in the destination country. This requires a valid contract to exist between the person organising the export, the facility where the equipment is going to be treated, and a legal representative.

According to an Australian industry representative, freight costs have gone up around three-fold since the beginning of COVID-19, leading them to stockpile PV panels that were destined for export.[101] This provides an opportunity for reform and the development of domestic reuse solutions in Australia.

---

and re-certification. Progress in Photovoltaics: Research and Applications, 28(6), pp. 454-464

[101] Carroll, D., 2021. Sunday read: Out of landfill, back in the stream. Available at: https://www.pv-magazine-australia.com/2021/10/10/saturday-read-out-of-landfill-back-in-the-stream/

# 4. Review of challenges and enablers for responsible second-hand markets

**This section discusses the main challenges currently inhibiting the establishment of responsible second-hand markets for PV systems in Australia and across international supply chains. It also identifies potential enablers supporting market development. A summary of these challenge areas and enablers are presented in Table 4.**

*Table 4. Overview of challenge areas and enablers*

| Challenge area | Challenges | Enablers |
|---|---|---|
| **Definition and criteria for reusability** | • There is currently no agreed definition or criteria for reusable PV systems in Australia or globally. Without technical guidelines, there are no protocols or criteria to determine and sort decommissioned PV systems as “waste” vs “reusable” vs “recyclable”. | • The Australian government has announced its intention to regulate PV systems at the Environment Ministers Meeting (21 October 2022). There is an opportunity to introduce technical requirements to support reuse in the context of this regulatory approach.<br>• Technical guidelines are needed to provide industries with detailed procedures for evaluating PV system reusability. Export and import restrictions of decommissioned PV systems can be adapted from the Technical Guidelines on Transboundary Movements of Electrical and Electronic Waste and Used EEE. |
| **Standards and regulatory requirements** | • There are several installation and product standard requirements for PV systems in Australia (e.g., AS/NZS 5033 which requires PV panel’s compliance to IEC 61215 and IEC 61730 standards, IEC 61270:2017 for ESSs, and AS/NZS 4777.2 for inverters).<br>• These requirements inhibit the use of second-hand PV systems in domestic applications as second-hand systems do not comply with these standards nor is there a pathway for them to comply with these standards. | • A potential enabler is to update existing standards to include second-hand PV systems; decommissioned PV systems could then be tested to meet certain performance and safety requirements for reuse.<br>• Other voluntary standards that demonstrate quality and safety of second-hand PV systems could also be developed and used in the absence of commonly approved standards in Australia (e.g., IEC). Currently this voluntary standard is only available for reusing EV batteries for ESSs (UL 1974). |
| **Customer quality assurance** | • Consumers have limited or no access to information regarding performance, ownership and repair histories, warranty status and/or performance guarantees to help make an informed purchasing decision regarding second-hand PV system reliability, safety, and quality. | • Second-hand PV system sellers should disclose information that demonstrate quality, reliability, and safety of the systems and components. Compliance can be ensured if via a new organisation administering and monitoring the second-hand market.<br>• Providing product warranties and performance guarantees could boost customer confidence in buying second-hand PV systems. |
| **Circular design consideration** | • Existing PV panels, ESSs, and EV battery design does not allow effective and easy repair and refurbishment as some design elements prevent easy access to or removal of parts that may need to be repaired or replaced. | • Further R&D is required to investigate circular design opportunities such as standardising design, design for repairability (e.g., easily removable components, modular design), first life |

| Challenge area | Challenges | Enablers |
|---|---|---|
| | | data provisions, and automated disassembly processes.<br>• The development of a repairability index could also inform consumers and help to differentiate PV systems that can be more easily repaired. |
| **Collection and transport** | • Risk of breakage of potentially reusable PV panels during transport due to improper stacking and rough handling. Cracking of glass and cells is commonly reported during transport and handling that undermines the opportunity for repair. | • Guidelines or protocols ensuring safe handling, stacking, and transporting are required to minimise breakage of PV panels and other components.<br>• The provision of training for decommissioning and transport workers is also required. |
| **Economic feasibility for reuse** | • Challenges in making second-hand PV systems more price competitive with new systems owing to continuously declining prices for new systems, access to incentives available for new systems (e.g., second hand systems are ineligible for STC rebates) and the added costs to test, repair and/or refurbish and certify second-hand PV systems. | • Lower testing, repair, and refurbishment costs are anticipated via improved circular design, improved field-testing capabilities, and the promotion of more repairable systems in the market.<br>• Providing financial incentives to customers purchasing properly tested, repaired, or refurbished PV systems could help to address cost competitiveness, |

## 4.1. Definition and criteria for reusability

There is no agreed definition and criteria for reusable PV systems in Australia or globally, making it challenging to identify the characteristics that would make decommissioned PV systems reusable.[102] For many electronic and electrical products, their reusability can be determined if they are “working” or “not working”.[103] This is not the case for PV panels and batteries as their performance degrades overtime and they are technically still working even if they have lower efficiency.[104] Without technical guidelines, there are no standard definitions, criteria, and/or processes to determine and sort decommissioned PV systems as “waste” vs “reusable” vs “recyclable”.

The Australian government has announced its intention to regulate PV systems (and household electronics) at the Environment Ministers Meeting (21 October 2022).[105] In the context of this regulatory development process, there is an opportunity to introduce technical requirements to support reuse. Technical guidelines are necessary to provide industries with detailed procedures for evaluating PV system reusability beyond technical performance requirements.[106] Technical guidelines need to cover the following aspects to establish a definition and criteria for reusability:[107]

1. Procedures and requirements for reuse preparation prior to testing (e.g., inspections, disassembly),
2. Performance and safety testing procedures and requirements,
3. Sorting for direct reuse, reuse with repair, and recycling,
4. Options and procedures for repair or refurbish,

---

[102] van der Heide, A., Tous, L., Wambach, K., Poortmans, J., Clyncke, J. and Voroshazi, E., 2021. Towards a successful re-use of decommissioned photovoltaic modules. Progress in Photovoltaics: Research and Applications, 30(8), pp. 910-920
[103] Ibid.
[104] Ibid.
[105] DCCEEW, 2022. *Environment Ministers Meeting - 21 October 2022 Agreed Communiqué*. Available at: https://www.dcceew.gov.au/sites/default/files/documents/emm-communique-21-oct-2022.pdf
[106] Strupeit, L. and Tojo, N., 2023. *Circular Business Models for the Solar Power Industry - Guide for Policy Makers*. CIRCUSOL. Available at: https://www.circusol.eu/files/Deliverables/D5.7_CIRCUSOL_Policy_guide.pdf
[107] Ibid.

5. Guidelines for safe handling and transport,
6. Mechanisms to ensure compliance with newly developed standards for repair and/or refurbishment process,
7. Overseas import and export guidelines.

Australia has an AS5377:2022 standard that specifies requirements for recycling facilities to conduct inspections and testing prior to reuse including the requirements for international imports and exports of all used electronics.[108] However, it currently only applies in the context of the National Television and Computer Recycling Scheme (NTCRS) where co-regulatory arrangements are required to recycle in certified facilities. A future PV product stewardship scheme could accommodate similar requirements to enable responsible reuse and prevent illegal exportation.

The AS50377:2022 standard is not product-specific which means that inspections, testing, and performance requirements specifically for PV systems need to be established as a technical guideline. Technical guidelines for testing decommissioned PV panels and batteries have been developed in the Circular Business Models for the Solar Power Industry (CIRCUSOL) project[109] and this approach could be adapted for Australian context. Further to this, overseas import and export regulations for decommissioned PV systems could be adapted from the Technical Guidelines on Transboundary Movements of Electrical and Electronic Waste and Used EEE. This guideline already provides a general set of rules to define when a product is sorted as "waste" or when it is fit for preparation for reuse as well as its export requirements.[110]

**Technical Guidelines for Evaluating Reusability of PV Panels and Batteries**

Industry partners in a **CIRCUSOL** project in Europe[111] are currently working with the International Electrotechnical Commission (IEC) to develop standards for second-hand PV systems. As a first step, they have published two technical guidelines for reuse preparation, testing procedures and requirements, repair, and/or refurbishment of decommissioned PV panels and batteries.

**Guideline for PV panels**

For PV panels, the guideline specifies in detail the sorting process and testing options, procedures, conditions, and performance requirements (Figure 3).[112] Upon conducting testing, PV panels can be categorised into three classes:

1. **Class 1**: Healthy panels suitable for direct reuse,
2. **Class 2**: Panels with repairable damages or faults and suitable for repair or refurbishment or if extra tests are required,
3. **Class 3**: Panels are not suitable for reuse and need to be recycled.

The general state of PV panels can be firstly evaluated via a quick visual inspection in-field or at a treatment facility to check any damage on individual PV panels. Subsequent tests for performance and safety are defined as **electrical testing** which can be conducted either in-field during decommissioning processes or at treatment facilities or a combination of both.[113] **Field-testing processes should be prioritised** as they offer greater efficiency and ensure appropriate sorting and handling. PV panels in good condition under Class 1 can be directly packed and labelled for reuse, whereas Class 3 should be

[108] Standards Australia, 2022. *AS 5377:2022 - Management of electrical and electronic equipment for re-use or recycling*. Available at: https://store.standards.org.au/product/as-5377-2022
[109] Strupeit, L. and Tojo, N., 2023. Circular Business Models for the Solar Power Industry - Guide for Policy Makers. CIRCUSOL. Available at: https://www.circusol.eu/files/Deliverables/D5.7_CIRCUSOL_Policy_guide.pdf
[110] van der Heide, A., Tous, L., Wambach, K., Poortmans, J., Clyncke, J. and Voroshazi, E., 2021. Towards a successful re-use of decommissioned photovoltaic modules. Progress in Photovoltaics: Research and Applications, 30(8), pp. 910-920
[111] Ibid.
[112] van der Heide, A., 2022. Labelling and Certification Protocols for Second Life PV Modules. CIRCUSOL. Available at: https://www.circusol.eu/files/Deliverables/D3-2_Labelling_and_certification_protocols_for_second_life_PV_modules.pdf
[113] Ibid.

directed to recycling. As specified earlier, some Class 2 decommissioned PV panels require further visual inspections, and electrical testing as existing **in-field equipment is limited and is not capable to identify and repair complex damages.**[114]

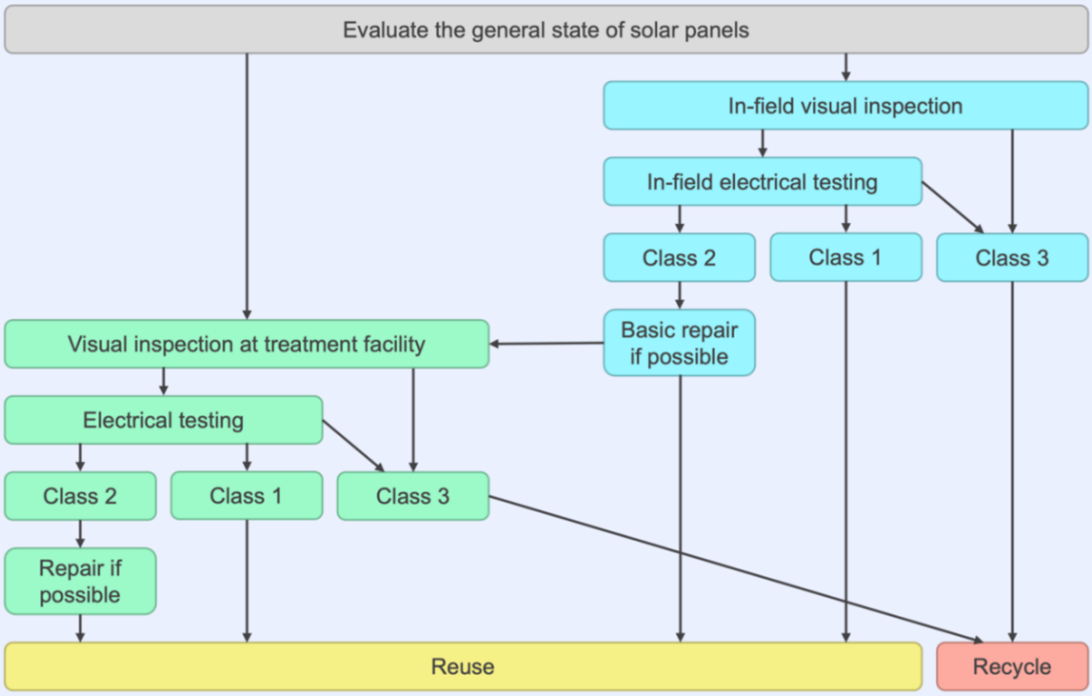



*Figure 3. High-level procedure for testing decommissioned PV panels from the CIRCUSOL project*[115]

**Guideline for batteries**

The technical guideline for batteries specifies the procedures and requirements for different types of performance and safety tests as well as validation tests for direct reuse or refurbishment.[116] The guideline was developed based on the UL 1974 standard which outlines the requirements for the evaluation of reusable batteries which can be differentiated into **direct reuse** and **reuse with refurbishment** (Figure 4). This guideline applies to EV batteries to be reused for stationary applications.

Firstly, visual inspection needs to be conducted and information in the BMS needs to be assessed. Batteries that can be directly reused need to undergo open circuit voltage and insulation resistance tests. If they meet the requirements, they can immediately go through the validation tests to be reused in a new application. Several testing procedures are required for batteries that need refurbishment as they need to be dismantled and tested for AC resistance, EIS, capacity, DC resistance, and self-discharge as described in Section 1. Replacement of degraded cells may then be required. Each battery module assembled needs to be tested again and reassembled into a battery pack. They will also need to go through validation tests for reuse in new applications.

[114] Ibid.
[115] Ibid.
[116] Mulder, G., De Craemer, K. and Lemaire, E., 2021. Development of Labelling and Certification Protocols for Second Life Batteries. CIRCUSOL. Available at: https://zenodo.org/record/6674934/files/D3.4-Labeling_and_certif_protocols_2nd_life_batteries.pdf?download=1

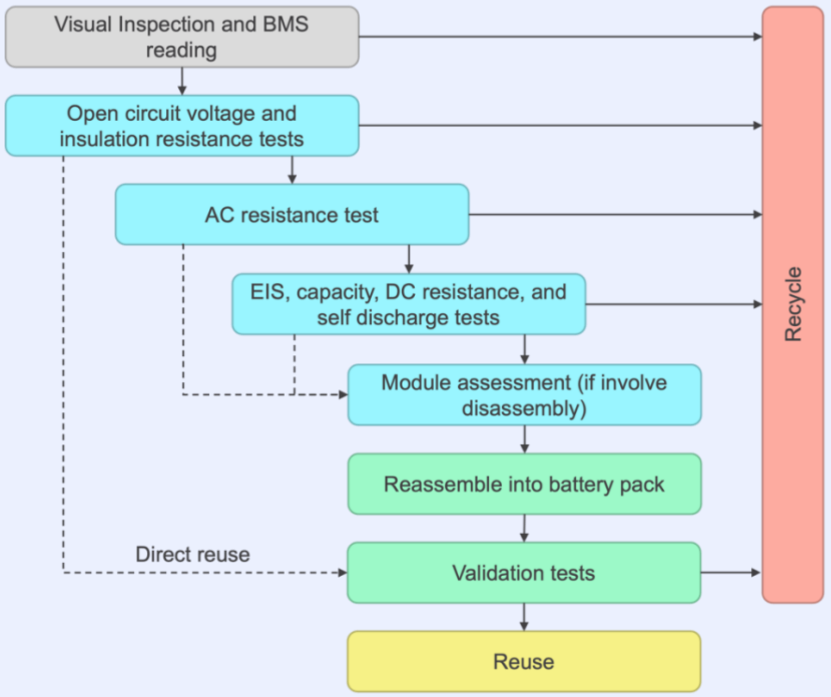



*Figure 4. High-level testing procedure for reusing batteries*

## 4.2. Standard and regulatory requirements

There are several standard requirements in Australia incorporated within the current regulatory system that inhibit the uptake of second-hand PV systems domestically (Table 5). In the first instance, second-hand PV systems are ineligible to be reused in a grid-connected environment and there are no economic drivers to encourage the proper testing and recertification against standards.

*Table 5. Summary of PV system reuse challenges related to standard requirements in Australia*

| **PV panel** | **ESS and EV batteries** | **Inverters** |
|---|---|---|
| According to the AS/NZS 5033:2021 installation and safety requirements standard, PV panels sold in Australia must meet the base standards set out by IEC 61215 for design and qualification testing and IEC 61730 for safety.[117]<br>There is also an “Enhanced Listing” developed by Clean Energy Council (CEC) to provide list of products that | CEC has a list of approved ESSs that meet the IEC 62619:2017 standard for LIB battery safety in which ESSs being sold on the Australian market needs to comply with.[119] This standard currently only applies to first-life batteries, not refurbished batteries. | There is a new standard requirement based on AS/NZS 4777.2 to improve grid stability and power quality concerns that may prevent reuse of old inverters that do not comply with this new requirement in a grid-connected environment.[120] The standard brings two additional requirements for inverters including the ability to switch to multiple setpoints depending on the region[121] |

[117] Clean Energy Council, 2018. *PV module terms and conditions*. Available at: https://www.cleanenergycouncil.org.au/industry/products/terms-and-conditions/module-terms-and-conditions
[119] Clean Energy Council, 2018. *Batteries*. Available at: https://www.cleanenergycouncil.org.au/industry/products/batteries
[120] AEMO, 2022. AS/NZS 4777.2 – Inverter Requirements standard. Available at: https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/as-nzs-4777-2-inverter-requirements-standard
[121] Inverter setpoints are defined based on the region: 1) Australia A: for large interconnected power systems, 2)

| | | |
|---|---|---|
| goes beyond these two standards which indicate better quality. To be considered for the list they need to be tested against additional standards assessing degradation and corrosion resistance.[118] | | and undervoltage ride-through performance to allow PV systems to stay connected in short periods of low voltages.[122] It remains unclear if older inverters can be refurbished to meet these new requirements. |

**The US Context**

Federal, state, and local regulations and standards exist to ensure safe PV system installation. However, there are three existing regulations in the United States that prohibit reuse activities in certain jurisdictions (noting that the implementation and enforcement of these three regulations varies across different states and localities): [123]

1. **Interconnection regulations**: Some jurisdictions adopt the IEEE 1547 or UL 1741 standard that set out safety requirements for inverters, converters, controllers, and interconnection system equipment. In California and Hawaii, PV system installations are also required to adopt smart inverters that allow independent regulation of voltage in the PV system.[124] This regulation may effectively prohibit reuse of old PV panels for grid-connected rooftop applications, building-mounted, or ground-mounted applications if they are not compatible with these smart inverters or are not complying with applicable standards.
2. **Fire and building regulations**: The purpose of this regulation is to reduce the risk of fire and mitigate fire damage to the building. Many jurisdictions have increased their fire classification rating requirements for roof covers to Class A (the most fire resistant) for high-risk fire areas in response to the recent wildfire incidents. Thus, many older PV panels and other components that only have Class B (less fire resistant) or C (least fire resistant) fire rating may be prohibited for reuse in either grid-connected or off-grid environment in areas where Class A roof covering are required. The UL 1703 standard provides the basis for classifying rooftop PV panels as Class A, B, or C depending on the evaluation of their flammability characteristics.
3. **Electrical regulations**: There are 46 states that have adopted the National Fire Protection Association's (NFPA) and National Electrical Code (NEC) which provides electrical installation standards to minimize risks associated with the use of electricity. Some jurisdictions require PV system circuits installed on buildings to have a rapid shutdown device to reduce the risk of electrical shock for first responders in emergency situations. Many older PV panels do not comply with this requirement, which may prevent reuse within these jurisdictions.

An important enabler is to update existing standards to include performance testing and safety requirements for second-hand PV systems. If applicable, certain conditions or limitations regarding reuse in certain cases could be outlined. Second-hand product standards are on the way for batteries that will be reused in residential and commercial stationary applications currently being developed by the IEC TC21 (secondary

Australia B: for small interconnected power systems, 3) Australia C: for isolated and remote power systems, and 4) New Zealand: all systems in New Zealand.

[118] Clean Energy Council, 2018. *Enhanced Listings*. Available at: https://www.cleanenergycouncil.org.au/industry/products/modules/enhanced-listings

[122] Clean Energy Council, 2021. *New inverter standard to improve grid stability*. Available at: https://www.cleanenergycouncil.org.au/news/new-inverter-standard-to-improve-grid-stability

[123] Curtis, T.L., Buchanan, H., Smith, L. and Heath, G., 2021. A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations. NREL. Available at: https://www.nrel.gov/docs/fy21osti/74550.pdf

[124] Driscoll, W., 2021. *In California and Hawaii, the benefits of smart inverters are just beginning*. Available at: https://pv-magazine-usa.com/2021/10/11/in-california-and-hawaii-the-benefits-of-smart-inverters-are-just-beginning/

cells and batteries).[125] These standards include IEC 63330 that outlines requirements for reuse of secondary batteries, and IEC 63338 for general guidance for reuse of secondary cells and batteries.[126]

In the absence of commonly approved standards in Australia such as IEC, other voluntary industry standards that demonstrate quality and safety of second-hand components could be used to increase the market value of second-hand PV systems.[127] An example is the UL 1974 standard for second-hand ESSs from EV batteries. However, similar voluntary standards do not exist for second-hand PV panels and inverters.

## 4.3. Customer quality assurance

There is limited or no information to help consumers make informed purchasing decisions regarding the reliability, safety, and quality of second-hand PV system components. The main information gaps for customers are:[128]

1. While information is available related to the original capacity or efficiency level and/or the years in operation, this information does not reflect the actual remaining lifetime or residual performance levels of PV systems.
2. Data on ownership history (although recorded by Clean Energy Regulator (CER) tied with the STCs), as well as information on repair history, is not available,
3. Product warranties are not available that would help to assure customers that second-hand systems are reliable.

An enabler is to require companies selling second-hand PV systems to disclose any information to demonstrate quality, reliability, and safety of components. Moreover, companies offering second-hand products could be required to follow testing requirements and procedures as per standards described in Part 1. However, it is difficult to implement as there are currently no regulations requiring these companies to conduct performance testing and established international or voluntary standards for second-hand PV systems do not exist to date.[129]

Furthermore, providing shorter-term or limited warranties to customers could potentially boost customer confidence in buying second-hand PV systems.[130] Since second-hand PV systems have reduced efficiency, product warranties and performance guarantees would be expected to be for shorter durations than new ones. In some existing marketplaces, a 2-year warranty is issued for repaired PV panels.[131]

## 4.4. Circular design considerations

Circular design involves creating products or services that support lifetime extension, reuse, and recovery at the EOL. Existing PV panels, ESSs, and EV battery designs do not currently reflect circular design considerations and a summary of challenges inhibiting circular material flows is presented in Table 6.

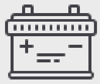
Further investigation into PV panel design opportunities to make them more durable and repairable (especially the internal components) without compromising the ability to withstand exposure to harsh environments is necessary. Battery manufacturing that considers second life would also facilitate easier,

---

[125] Mulder, G., De Craemer, K. and Lemaire, E., 2021. Development of Labelling and Certification Protocols for Second Life Batteries. CIRCUSOL. Available at: https://zenodo.org/record/6674934/files/D3.4-Labeling_and_certif_protocols_2nd_life_batteries.pdf?download=1
[126] Ibid.
[127] Curtis, T.L., Buchanan, H., Smith, L. and Heath, G., 2021. A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations. NREL. Available at: https://www.nrel.gov/docs/fy21osti/74550.pdf
[128] Walzberg, J., Carpenter, A. and Heath, G., 2021. Role of the social factors in success of solar photovoltaic reuse and recycle programmes. Nature Energy, 6, pp. 913-924
[129] Curtis, T.L., Buchanan, H., Smith, L. and Heath, G., 2021. A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations. NREL. Available at: https://www.nrel.gov/docs/fy21osti/74550.pdf
[130] Walzberg, J., Carpenter, A. and Heath, G., 2021. Role of the social factors in success of solar photovoltaic reuse and recycle programmes. Nature Energy, 6, pp. 913-924
[131] Tsanakas, J.A., van der Heide, A., Radavičius, T., Denafas, J., Lemaire, E., Wang, K., Poortmans, J. and Voroshazi, E., 2020. Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. Progress in Photovoltaics: Research and Applications, 28(6), pp. 454-464

automated disassembly and enable the replacement of damaged cells. Examples of strategies for better battery sorting and disassembly is providing reuse or refurbishment companies with disassembly instructions embedded in the battery pack, clear labelling battery chemistries, as well as using removable or less strong adhesives.[132]

*Table 6. Summary of PV system reuse challenges related to design*

| **PV panel**  | **ESS and EV batteries**  |
|---|---|
| • In a typical PV panel design, only the junction boxes, frames, cables, and backsheets are easily accessible to repairers.[133]<br>• Existing design also does not provide easy access to the internal parts such as the solar cells.[134] | • There is a lack of standardised design of ESSs and EV batteries. They typically have different chemistries, cell formats, adhesives, and welding methods between cells and other components.[135]<br>• Three types of cell formats commonly used in batteries include cylindrical, pouch, and prismatic, with the former reportedly being the most difficult to disassemble.[136] |

Enabling innovative business models that promote reuse and longer lifetimes is another relevant strategy. One example is a leasing model where an independent power generator retains ownership a PV plant and supplies power to residential or commercial customers. This model helps to promote better quality and more durable systems, including maintenance and repair to support good performance, that is closely aligned with the profitability of the business model.[137]

The concept of a repairability index is another strategy that can better inform consumers about the repairability of products when making purchasing decisions. There has been some progress in France to include a reparability index on five categories of electronic products including smartphones, laptops, televisions, washing machines, and lawnmowers.[138] This strategy is expected to promote better design for repairability and refurbishment and could be adapted for PV systems.[139]

## 4.5. Collection and transport

Solar installations in Australia are geographically dispersed ranging from metro areas to regional and rural areas. Extensive transportation is required when moving decommissioned PV panels from regional and rural areas to metro areas where treatment facilities are typically located. One challenge around collection and

---

[132] Kampker, A., Wessel, S., Fiedler, F. and Maltoni, F., 2021. Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells. Journal of Remanufacturing, 11, pp. 1-23
[133] Tsanakas, J.A., van der Heide, A., Radavičius, T., Denafas, J., Lemaire, E., Wang, K., Poortmans, J. and Voroshazi, E., 2020. Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. Progress in Photovoltaics: Research and Applications, 28(6), pp. 454-464
[134] Radavičius, T., van der Heide, A., Palitzsch, W., Rommens, T., Denafas, J. and Tvaronavičienė, M., 2021. Circular solar industry supply chain through product technological design changes. *Insights into Regional Development*, 3(3), pp. 10-30
[135] Kampker, A., Wessel, S., Fiedler, F. and Maltoni, F., 2021. Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells. Journal of Remanufacturing, 11, pp. 1-23
[136] Haram, M.H.S.M., Lee, J.W., Ramasamy, G., Ngu, E.E., Thiagarajah, S.P. and Lee, Y.H., 2021. Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges. Alexandria Engineering Journal, 60(5), pp. 4517-4536
[137] Gentilini, E. and Salt, M., 2020. Circular Photovoltaics: Circular Business Models for Australia’s Solar Photovoltaics Industry. Arup. Available at: https://www.arup.com/-/media/arup/files/publications/c/circular-photovoltaics.pdf
[138] Pérez-Belis, V., Braulio-Gonzalo, M., Juan, P. and Bovea, M.D., 2017. Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment. A Spanish case study. *Journal of Cleaner Production*, 158, pp. 261-275
[139] Gentilini, E. and Salt, M., 2020. Circular Photovoltaics: Circular Business Models for Australia’s Solar Photovoltaics Industry. Arup. Available at: https://www.arup.com/-/media/arup/files/publications/c/circular-photovoltaics.pdf

transport of decommissioned PV systems is around the rough handling including stacking during transport. This often results in cracks in the glass and cells that may not be repairable.[140]

New transport and handling guidelines or protocols are required to ensure safe handling, stacking, and transporting methods along the supply chain to minimise breakage of PV panels and other components destined for reuse.[141] A recent desktop study highlighted how proper packaging could be used to minimise breakage of decommissioned PV panels. The authors also recommended limiting transportation in trucks owing to the high intensity of vibrations and shocks that cause breakages.[142] Further research to optimise handling, stacking, and transport methods is necessary.

In addition, it is also noted that there is a need to train workers involved in the transport and handling to encourage more gentle handling for reuse.[143] In Australia, decommissioning of rooftop PV systems is typically carried out by an accredited installer when customers are replacing their system, whereas for larger-scale solar installations it is carried out by appointed contractors.[144] The provision of training to workers could be integrated into existing processes that certify workers for installation and be extended to include guidance on decommissioning, handling, and transport of PV systems for reuse.[145]

The CEC have education and training courses which are used to retain accreditation of solar installers.[146] Such guidance and training modules (for decommissioning different sizes of solar installations) can also be developed and included as part of retaining solar installer accreditation. Large-scale solar plant owners looking to decommission their systems should also adhere to this guideline and outline training completion requirements for contractors during the tendering process.[147]

## 4.6. Economic feasibility for reuse

There are challenges around the economic feasibility for reusing PV systems as there are high costs associated with manual labour to repair, recertification to comply with the relevant standards, and warranty support (Table 7). This is owing to the current immaturity of testing processes and the lack of in-field testing options.[148] In addition, given that the price of new PV panels and ESSs are continuously declining[149] coupled with access to incentives for new systems including STC rebates[150], second-hand PV systems are not price competitive with new systems.

---

[140] Köntges, M., Kurtz, S., Packard, C., Jahn, U., Berger, K.A., Kato, K., Friesen, T., Liu, H. and Van Iseghem, M., 2014. Review of Failures of Photovoltaic Modules. IEA-PVPS. Available at: https://iea-pvps.org/wp-content/uploads/2020/01/IEA-PVPS_T13-01_2014_Review_of_Failures_of_Photovoltaic_Modules_Final.pdf
[141] Strupeit, L. and Tojo, N., 2023. Circular Business Models for the Solar Power Industry - Guide for Policy Makers. CIRCUSOL. Available at: https://www.circusol.eu/files/Deliverables/D5.7_CIRCUSOL_Policy_guide.pdf
[142] Köntges, M., Kurtz, S., Packard, C., Jahn, U., Berger, K.A., Kato, K., Friesen, T., Liu, H. and Van Iseghem, M., 2014. Review of Failures of Photovoltaic Modules. IEA-PVPS. Available at: https://iea-pvps.org/wp-content/uploads/2020/01/IEA-PVPS_T13-01_2014_Review_of_Failures_of_Photovoltaic_Modules_Final.pdf
[143] Strupeit, L. and Tojo, N., 2023. Circular Business Models for the Solar Power Industry - Guide for Policy Makers. CIRCUSOL. Available at: https://www.circusol.eu/files/Deliverables/D5.7_CIRCUSOL_Policy_guide.pdf
[144] Mathur, D., Gregory, R. and Tristan, S., 2020. *End-of-Life Management of Solar PV Panels*. Charles Darwin University. Available at: https://www.cdu.edu.au/sites/default/files/the-northern-institute/eolmanagemnetsolarpv_final_e-version.pdf
[145] Strupeit, L. and Tojo, N., 2023. Circular Business Models for the Solar Power Industry - Guide for Policy Makers. CIRCUSOL. Available at: https://www.circusol.eu/files/Deliverables/D5.7_CIRCUSOL_Policy_guide.pdf
[146] As of March 2023, CEC announced that it will no longer oversee solar accreditation and product listing though it will continue its role until a new organisation is appointed.
[147] Strupeit, L. and Tojo, N., 2023. Circular Business Models for the Solar Power Industry - Guide for Policy Makers. CIRCUSOL. Available at: https://www.circusol.eu/files/Deliverables/D5.7_CIRCUSOL_Policy_guide.pdf
[148] Curtis, T.L., Buchanan, H., Smith, L. and Heath, G., 2021. A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations. NREL. Available at: https://www.nrel.gov/docs/fy21osti/74550.pdf
[149] Graham, P., Hayward, J., Foster, J. and Havas, L., 2022. *GenCost 2021-22*. CSIRO. Available at: https://publications.csiro.au/publications/publication/PIcsiro:EP2022-2576
[150] Barfoot, C. and McCubbin, D., 2021. Recycling and Reuse of Used Solar Panels: An Investigation into Current Opportunities for Gippsland. Gippsland Climate Change Network. Available at: https://gccn.org.au/wp-content/uploads/2021/07/GCCN_Recycling-and-Reuse-of-Solar-Panels-Report_Version1.2.pdf

*Table 7. A summary of reuse challenges related to economic feasibility*

| **PV panel** | **ESS and EV batteries** |
|---|---|
| • The current cost to repair PV panels can be high depending on its complexity, and experienced field operators argued that it ranges from approximately AU$30 –$90 per module (Table 8). Furthermore, this cost estimate does not include the cost for recertification to comply with standards that would add further costs.<br>• Simple repairs such as cables and diodes replacement can be straightforward[151] but estimating the economic feasibility of repairing junction boxes and backsheets remains unclear and largely depends on manual labour costs and is expected to be significantly impacted by economies of scale based on the volume being processed. | • The main challenge for refurbishing EV batteries for ESSs is owing to non-standardised designs that does not allow easy and effective disassembly and refurbishment with anticipated high costs for manual labour. There are inconsistencies around the estimate to refurbish and test batteries which ranges from about AU$30/kWh –$120/kWh.[152,153] The National Renewable Energy Laboratory (NREL) has developed a tool to estimate the cost of second-hand ESSs considering labour costs, warranty, initial battery size, and characteristics of the refurbishment process which will be useful in providing industries with an overview of business cases on the feasibility to reuse and refurbish EV batteries.[154]<br>• Another challenge is related to the existing immature testing methods. Specifically, methods for identifying battery SOH and remaining useful life (RUL) are considered inaccurate with current predictive methods not always able to reveal the actual battery ageing trajectory.[155] This is primarily owing to a lack of first life data stored in the batteries as well as the absence of a standardised testing processes.[156] |

The costs of testing, repair, and refurbishment can be reduced by implementing circular design principles, with R&D into more efficient testing approaches including in-field, and improved battery SOH and RUL estimations. For example, two studies suggested a statistical sampling to lower the cost of testing of PV panels.[157,158] However, this may risk unidentified failures in PV panels as each panel has unique degradation characteristics. Another strategy is to use advanced technology to make field-testing more efficient. Current developments include drone-based thermography[159] and automated failure identification.[160]

---

[151] Rajagopalan, N., Smeets, A., Peeters, K., De Regel, S., Rommens, T., Wang, K., Stolz, P., Frischknecht, R., Heath, G. and Ravikumar, D., 2021. *Preliminary Environmental and Financial Viability Analysis of Circular Economy Scenarios for Satisfying PV System Service Lifetime*. International Energy Agency. Available at:
[152] Ambrose, H., 2020. The second-life of used EV batteries. Available at: https://blog.ucsusa.org/hanjiro-ambrose/the-second-life-of-used-ev-batteries/
[153] Colarullo, L. and Thakur, J., 2022. Second-life EV batteries for stationary storage applications in Local Energy Communities. Renewable and Sustainable Energy Reviews, 169, p. 112913
[154] NREL, 2020. *Battery second-use repurposing cost calculator*. Available at: https://www.nrel.gov/transportation/battery-second-use.html
[155] Haram, M.H.S.M., Lee, J.W., Ramasamy, G., Ngu, E.E., Thiagarajah, S.P. and Lee, Y.H., 2021. Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges. Alexandria Engineering Journal, 60(5), pp. 4517-4536
[156] Ibid.
[157] Gentilini, E. and Salt, M., 2020. Circular Photovoltaics: Circular Business Models for Australia's Solar Photovoltaics Industry. Arup. Available at: https://www.arup.com/-/media/arup/files/publications/c/circular-photovoltaics.pdf
[158] Pandey, S., Pillai, P., Jadhav, S., Kumar, S., Mishra, S. and Dhuriya, R.K., 2019. Sampling guideline for inspection and testing of PV modules in the field. *PV Tech*, pp. 77-79
[159] Zhang, P., Zhang, L., Wu, T., Zhang, H. and Sun, X., 2017. Detection and location of fouling on photovoltaic panels using a drone-mounted infrared thermography system. *Journal of Applied Remote Sensing*, 11(1), p. 016026
[160] Wright, B. and Hameiri, Z., 2022. Maching learning-powered module end-of-life decisions from luminescence images. *3rd Asia-Pacific Solar Research Conference*

*Table 8. Estimated cost to repair defects in PV panels[161]*

| Part | Defect | Solution | Est. cost per panel (A$) |
|---|---|---|---|
| **Junction box** | Failed bypass diode(s) in junction box, typically leading to short-circuit | Replace bypass diode(s) with comparable ones. In the future, this solution may not be possible owing to the increasing trend to fill junction boxes with potting material | 30 |
| | Failed bypass diode(s) with potting in junction box | Replace the junction box with a new one (including diodes) that does not require potting | 90 |
| | Junction box with internal or external damage | Replace the junction box with a comparable new one | 90 |
| **Cable** | Damaged cables | Replace cables (including connectors) | 30 |
| | Damaged or missing cable connectors | Mount new connectors on cables | 7.5-15 |
| **Backsheet** | Cracked backsheet over entire surface | Clean backsheet and apply a coating on top of the original backsheet | Under development |

Providing financial incentives to customers purchasing properly tested, repaired, or refurbished PV panels can promote greater price competitiveness for second-hand PV systems. In the case of STCs, we note that this rebate scheme is expected to end by 2030.[162] Once the rebate is no longer available, second-hand PV panels will be more competitive. New incentives could align with the net zero agenda, including incentives linked to $CO_2$ footprints.[163] Given the footprint for a reused systems is likely to be substantially lower than a new system[164], this could be an effective way to adjust the relative price and stimulate second-hand market growth.

[161] van der Heide, A., Tous, L., Wambach, K., Poortmans, J., Clyncke, J. and Voroshazi, E., 2021. Towards a successful re-use of decommissioned photovoltaic modules. Progress in Photovoltaics: Research and Applications, 30(8), pp. 910-920

[162] Clean Energy Regulator, 2023. *Small-scale Renewable Energy Scheme*. Available at: https://www.cleanenergyregulator.gov.au/RET/About-the-Renewable-Energy-Target/How-the-scheme-works/Small-scale-Renewable-Energy-Scheme

[163] PV CYCLE, 2021. RE-USE of PV modules, challenges and opportunities of the circular economy. Available at: https://pvcycle.be/wp-content/uploads/Press-Release-Reuse-08032021.pdf

[164] Haram, M.H.S.M., Lee, J.W., Ramasamy, G., Ngu, E.E., Thiagarajah, S.P. and Lee, Y.H., 2021. Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges. Alexandria Engineering Journal, 60(5), pp. 4517-4536

# 5. Conclusions and Recommendations

**Second-hand PV system markets in Australia remain immature compared to those in Europe and North America. This report highlights the opportunity for promoting a responsible second-hand market for PV systems given that many PV panels are being decommissioned prematurely. These potentially reusable PV panels are being exported overseas, recycled, landfilled, and sold domestically without prior testing.**

This study highlighted the range of challenges in establishing a responsible second-hand PV system market in Australia. Overcoming these challenges requires action by government, manufacturers, emerging reuse and recycling industries, industry bodies, and research organisations (Table 9).

*Table 9. Key recommendations for stakeholders*

| Stakeholder | Potential areas of actions |
|---|---|
| **Federal government** | Federal government should work together with the industry to:<br>• Create a clear definition and criteria for reusability in the context of the emerging product stewardship solution. This is needed to help industries differentiate between “waste” and “reusable” or “recyclable” PV systems.<br>• Support the development and adoption of technical guidelines for performance and safety testing requirements, handling and transport, repair and/or refurbishment protocols, and standards for second-hand PV systems in the context of the emerging product stewardship solution.<br>• Support the development, piloting, and implementation of a PV system repairability and durability labelling approach and a national repairability index as recommended by the Productivity Commission. |
| **Independent statutory authority (e.g., CER)** | • Provide financial incentives to customers looking to purchase properly tested, repaired, and refurbished PV systems.<br>• Make existing ownership history data more accessible to customers and the reuse industry.<br>• Integrate repair or refurbishment history into the database in the case of an established responsible second-hand market for PV systems. |
| **Industry bodies (e.g., CEC)** | • Assist industry with the development of technical guidelines for reuse of PV systems.<br>• Develop guidelines and training modules for safe handling and transport of decommissioned PV systems and ensuring its compliance.<br>• Support the adoption of international standards or voluntary industry standards for second-hand PV systems and include these as standard requirements to remove market entry barriers for second-hand systems.<br>• Advocate for the disclose any information that demonstrates performance, quality, and safety of these components to provide greater quality assurance to customers. |
| **Reuse industries** | • Work together with governments and/or research organisations to trial different reuse options for PV systems to understand economic profitability and feasibility.<br>• Develop technical guidelines and conduct performance and safety tests for decommissioned PV systems.<br>• Provide shorter-term and limited product warranties to build customer trust in purchasing second-hand PV systems. |
| **Research organisations** | • Undertake R&D with industry to develop:<br>– Greater technological capability and efficiency in field-testing methods for PV panels.<br>– Predictive technologies that provide better accuracy in estimating battery SOH and RUL.<br>– Automated processing capability for repair and refurbishment of PV systems to provide greater economic feasibility |

| Stakeholder | Potential areas of actions |
| --- | --- |
| | – R&D in partnership with manufacturers to embed circular design principles in future product development |
| **Manufacturers** | • Research and implement circular design opportunities such as standardising design and promoting greater product repairability.<br>• Integrating first life data into batteries to assist industries to accurately estimate SOH and RUL.<br>• Implement proper battery labelling of chemistries and instructions for disassembly to support repair and/or refurbishment services. |