# Circularity in Renewable Energy

## Embedding circularity in Victoria's renewable energy future

Authorised and published by
Sustainability Victoria
Level 12, 321 Exhibition Street
Melbourne Victoria 3000 Australia

**Circularity in Renewable Energy**

May 2026

This report should be attributed to Sustainability Victoria.

Sustainability Victoria acknowledges Aboriginal and Torres Strait Islander people as the Traditional Custodians of the land and acknowledges and pays respect to their Elders, past and present.

# Circularity in Renewable Energy

## Embedding circularity in Victoria’s renewable energy future

## Contents

# Executive summary

Victoria's renewable energy transition is accelerating to meet ambitious climate targets, with renewable electricity expected to reach 95% by 2035 alongside significant growth in energy storage, electrification of transport, and increased electricity demand. This transformation is materially-intensive and will generate substantial volumes of end-of-life renewable energy and electric vehicle assets over the coming decades, particularly from rooftop solar photovoltaic (PV) systems and Electric Vehicle (EV) batteries.

Advancements in technology, business, and recycling are delaying the challenges posed by waste generated from the energy transition in Victoria. However, without sufficient investment and resourcing, the industry will be unable to manage this waste at scale over the next decade. Recognising the benefits of transitioning both the energy and materials economy is vital for addressing future energy generation challenges and minimising emissions. Overlooking this opportunity risks generating significant waste from decommissioned renewable energy assets, leading to waste management issues and a decline in public support for renewable initiatives.

This research highlights that circularity in renewable energy infrastructure is not a secondary consideration, but a strategic response to these intersecting challenges. The integration of circular economy principles into the energy transition offers substantial opportunities to mitigate these risks. The implementation of circular economy methodologies – such as designing for reuse and disassembly, extending product lifespans, reusing, refurbishing, remanufacturing, and enhancing material data – presents an opportunity to minimise waste, reduce emissions, and strengthen the capacities of local industries. Targeted investments in onshore renewable energy manufacturing, along with the development of skills and infrastructure for reuse and remanufacturing, will help establish a resilient, low-emission, and circular energy future.

# 1. Introduction

This report summarises the findings of Sustainability Victoria's research on circular economy opportunities within the renewable energy sector. In 2024, Sustainability Victoria launched a 3-year strategy that identified the systems and materials integral to renewable energy generation as a target sector. As Victoria progresses toward its net-zero emissions targets for 2050, the demand for critical minerals is anticipated to increase sixfold. The International Energy Agency has indicated that current and planned extractive infrastructure is inadequate to satisfy this rising global demand. Furthermore, the consumption and utilisation of these resources and materials contribute to emissions in Victoria. This research aims to strengthen the case for a circular economy and identifies renewable energy generation systems and materials as a priority area.

At its core, the research's hypothesis is: *'How might a circular economy support Victoria's renewable energy transition?'.* It draws on decarbonisation scenario data, technical analysis of material requirements, historical renewable asset data, and input from industry stakeholders.

In 2024, Sustainability Victoria partnered with the Climateworks Centre to conduct scenario modelling, employing decarbonisation datasets from 2023. Dr Scott Bryant performed a technical analysis to quantify the materials required for Victoria's transition to renewable energy. In 2025, Sustainability Victoria analysed historical installations across solar PV, wind energy, battery systems, and electric vehicles, back to 2000.

To gain further insight into the private sector, Sustainability Victoria engaged with the Clean Energy Council and a range of industry stakeholders, to provide an industry perspective on the solutions highlighted in this paper.

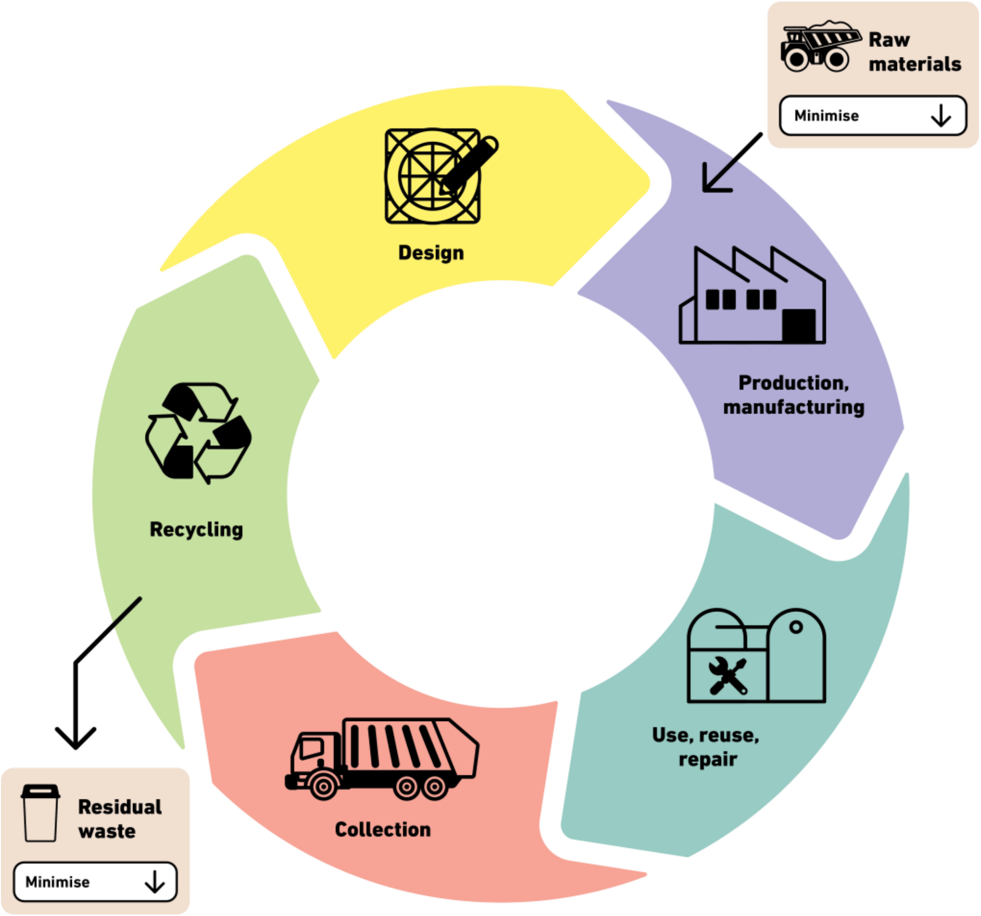
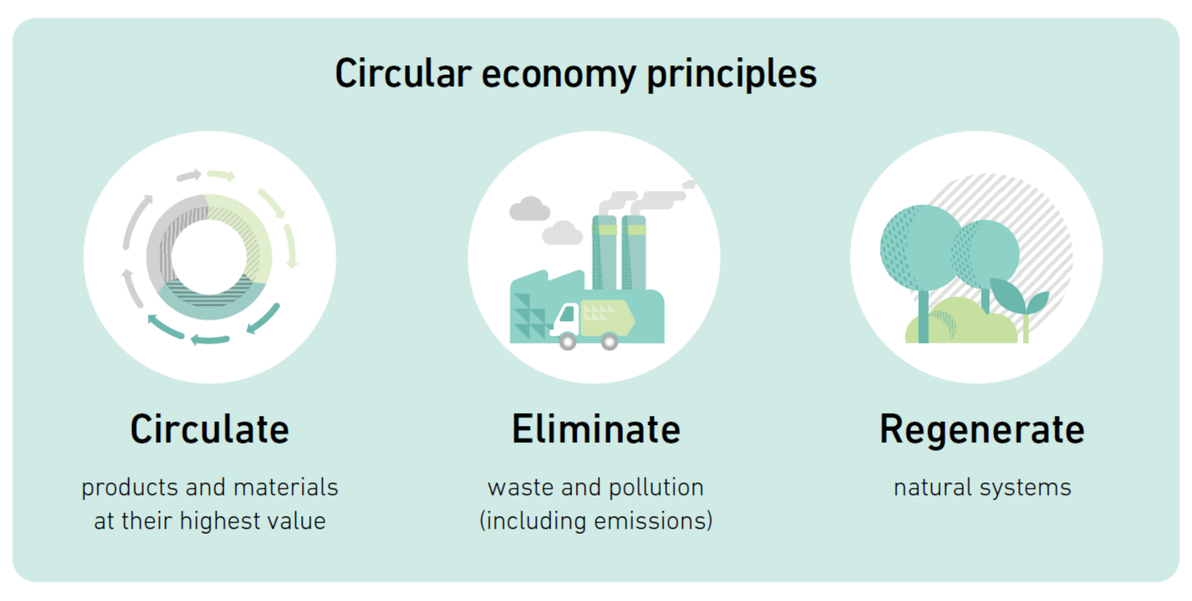


*Figure 1 The circular economy.*

**What is a circular economy?**
A circular economy uses resources such as materials, energy, and water more efficiently by applying 3 core principles. In contrast to the growing economic, social, and environmental impacts of a linear ‘take–make–waste’ model, transitioning to a circular economy is essential as part of our energy transition.



*A circular economy follows 3 principles (Ellen MacArthur Foundation, 2024).*

The circular economy involves designing out waste and keeping products and materials circulating at their highest value for as long as possible. By adopting a systems-based approach that highlights the importance of design, the circular economy offers an opportunity to reimagine the traditional linear economic model. This transition aims to reduce waste generation and enhance resource circulation, including water and energy, while promoting nature-positive, low-carbon, and resource-efficient systems and practices.

# 2. Strategic context

The Victorian Government has committed to reducing emissions by 75–80% below 2005 levels by 2035, and to achieving net zero emissions by 2045. These commitments have initiated a comprehensive action plan for climate action, underpinned by targets for renewable energy, energy storage, and the advancement of a clean economy. Victoria was one of the first jurisdictions globally to enact legislation for a net zero target, including interim targets every five years to ensure progress towards its long-term goals.

A key pillar in achieving these targets is Victoria's renewable energy and energy storage goals, as outlined in *Cheaper, Cleaner, Renewables: Our Plan for Victoria's Electricity Future*. This plan sets renewable electricity generation targets of 65% by 2030 and 95% by 2035, underpinned by legislated offshore wind energy targets, which are:

- at least 2 gigawatts (GW) of offshore generation capacity by 2032 – enough to power 1.5 million homes
- 4 GW by 2035
- 9 GW by 2040.

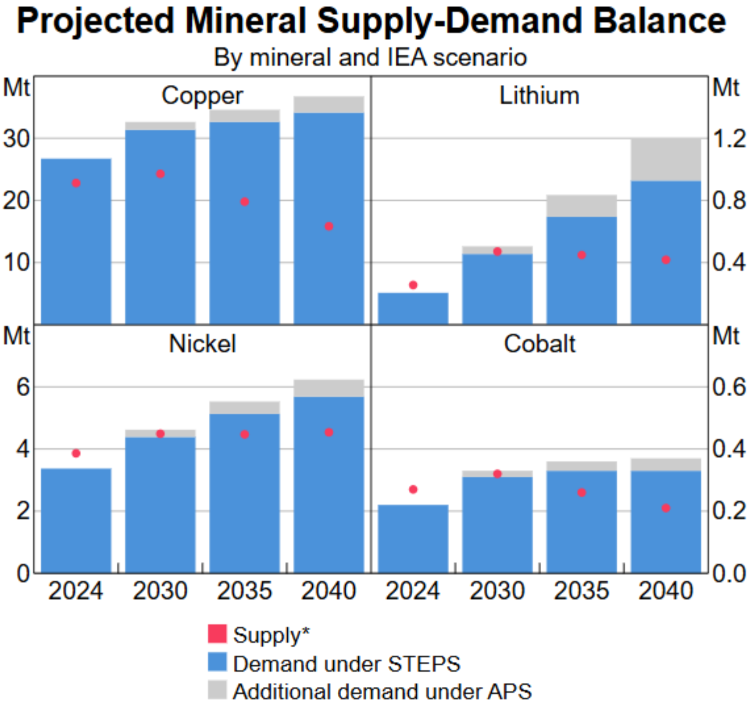
Victoria's legislated energy storage targets are:

- at least 2.6 GW of energy storage capacity by 2030
- at least 6.3 GW by 2035.

Since the introduction of climate legislation, the Victorian Government has made significant strides in reducing its energy emissions, largely due to the decarbonisation of the electricity grid, which has played a key role in achieving interim targets. This transition is resource-intensive, affecting both household and utility-scale operations.

As government and industry implement new energy infrastructure, it is essential to consider the simultaneous decommissioning of older assets, including solar panels, wind turbines, EVs, and batteries. This analysis highlights the potential for significant waste generation, particularly in steel, glass, aluminium, copper, and various high-value critical minerals such as silver, graphite, nickel, lithium, and manganese. By adopting the principles of a circular economy, the Victorian Government, industry and businesses can retain the highest possible value of these materials, promote economic development, reduce waste sent to landfills, and abate emissions.

The Reserve Bank of Australia report, *The Global Energy Transition and Critical Minerals, 2025* (Harry & Irene, 2026), identifies a growing mismatch between supply and demand for critical minerals under current policy settings. By 2035, this gap is expected to widen, with Figure 2 showing significant shortages in key materials such as lithium and copper – critical to renewable energy and electrification. While new and unannounced projects may come online before 2040, uncertainty around their delivery means they are unlikely to fully close the gap. This tightening supply outlook underscores the need to reduce reliance on virgin materials through efficiency and circular economy approaches.



* Projected supply is based on mined output expected from existing and announced projects. Does not account for recycled volumes that may contribute as secondary supply.

*Figure 2 Projected minerals supply-demand balance.*

Research by the Ellen MacArthur Foundation shows emissions from the production of goods and land use cannot be fully addressed through even the most ambitious improvements in energy efficiency or a shift to net zero energy sources. Yet the materials associated with the production of goods play a vital role in fulfilling people's needs – for housing, nutrition, mobility, manufacturing, healthcare, education, and communication. Making circularity the goal is the next logical step in reducing emissions. **Without a circular economy – we will not hit our net zero emissions target.**

At the federal level, the Commonwealth's Circular Economy Ministerial Advisory Group has identified the challenge and potential opportunity for the circular economy in the coming decade (Department of Climate Change, Energy, the Environment and Water, 2024) The advisory group's interim report adds:

*'More than 90% of the materials from renewable energy infrastructure can be used again when designed for reuse and recycling, according to the European Environment Agency.'* (European Environment Agency, 2021) The Victorian Government has introduced a circular economy policy to cut waste and boost the recycling and reuse of materials, including critical minerals. The Australian Government is implementing initiatives to cut waste and pollution, with mandatory reporting of Scope 3 emissions for large energy consumers as part of upcoming climate regulations. The Australian Government has also introduced the 'Future Made in Australia' approach to integrate circular economy principles into the renewable energy sector. The plan targets priority industries to reduce waste, enhance economic and material resilience, and establish Australia as a global leader in renewable energy. The plan prioritises the development of domestic supply chains for renewable energy technologies. This initiative aims to strengthen economic security and resilience by decreasing reliance on imported components. By integrating circular approaches in energy transition, Victoria ensure our industry and government agencies are prepared to achieve our sustainability and economic goals.

# 3. Research methodology and assumptions

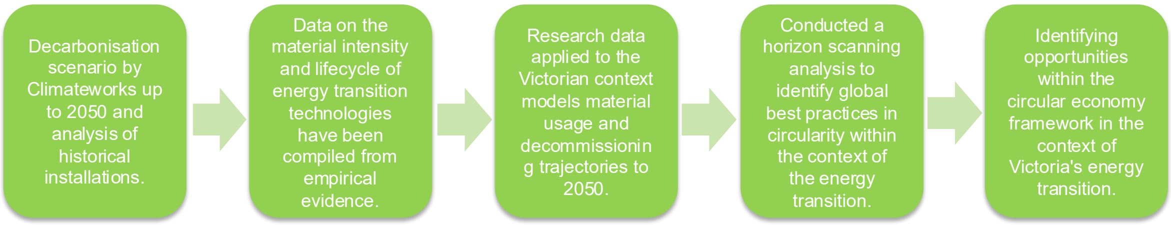
The modelling underpinning this report was conducted by the Climateworks Centre and data from various sources including the Australian Energy Market Operator (AEMO), the Australian PV Institute, Clean Energy Regulator, Australian Automobile Association and Victoria's Department of Transport and Planning.

## 3.1 Climateworks Centre modelling

The Climateworks Centre modelling (Climatework, 2023) outlines 2 scenarios aimed at achieving climate targets to limit global warming. The research introduces a model that forecasts energy demand across Australian sectors – buildings, transport, industry, agriculture, and land. It also estimates the electricity generation, and capacity required to meet the emissions reduction pathways of these climate scenarios. This modelling is detailed at the state level, with the report's circular economy and materials modelling based on Victorian data from the Climateworks Centre's 2scenarios. The 2scenarios are:

1. Limiting global warming to 1.5 degrees Celsius
2. Limiting global warming to Well Below 2 degrees Celsius

A technical report outlining the modelling assumptions and methodology has been provided by the Climateworks Centre. The research, analysis and conclusions from this project were based on best practice modelling and research. The process undertaken to complete the project is as follows:



Decarbonisation scenario by Climateworks up to 2050 and analysis of historical installations.

Data on the material intensity and lifecycle of energy transition technologies have been compiled from empirical evidence.

Research data applied to the Victorian context models material usage and decommissioning trajectories to 2050.

Conducted a horizon scanning analysis to identify global best practices in circularity within the context of the energy transition.

Identifying opportunities within the circular economy framework in the context of Victoria's energy transition.

*Graphic 1 Research methodology.*

## 3.2 Energy transition material intensity and lifecycle data

The modelling underpinning the results and circular economy opportunities presented in this report draws together the following sets of information:

- Climateworks decarbonisation scenarios for Victoria to 2050.
- AEMO's 2024 and 2026 plans for generation, storage, and electric vehicles.
- Data for material intensity and lifecycle of energy transition technology compiled from peer-reviewed journal articles and global best practice research.

This section summarises the results from the modelling activities, which included the following processes:

- The amalgamation of annual electricity capacity prerequisites (categorised by technology) with the material requirements for energy infrastructure (per unit capacity) to approximate the annual material demand necessary for Victoria's energy transition through to 2050.

- The integration of annual installation rates with statistical lifespan models (Weibull) aims to predict the annual volume of infrastructure and the corresponding materials for decommissioning through to 2050.

This comprehensive analysis of Victorian energy transition infrastructure and its associated materials requirements up to2050 draws upon diverse research and datasets. These resources are sourced from peer-reviewed scientific journals and reputable international agencies, ensuring a robust and credible foundation for the modelling undertaken in this research. The data in this analysis has been validated by cross-referencing academic and industry publications to ensure consistency with established sectoral knowledge.

Due to the complexities associated with the systems, the analysis excludes the following areas of the Victorian renewable energy transition:

- The products and materials related to future energy efficiency and in-home electrification in Victoria, including insulation, heat pumps, and induction cooktops.
- The commercial transportation sector faces significant challenges in achieving decarbonisation and adhering to the emissions reduction pathways of the Climateworks Centre's scenarios. This sector is more complex than passenger vehicles, with ongoing uncertainties about the technologies and material requirements needed for an effective transition.

The findings focus on the ‘1.5C’ emissions reduction pathway scenario rather than the ‘Well Below 2C’ scenario. While the results are quite similar, the ‘Well Below 2C’ scenario typically shows a slower and lower adoption of renewable energy, resulting in reduced overall renewable generation capacity and fewer EVs needed due to a slower shift away from fossil fuels.

Year-to-year fluctuations in the graphed data reflect the nature of the Climateworks Centre’s whole-of-economy modelling approach, rather than any inconsistency in the underlying analysis.

**Assumptions for materials and lifespan:**

This section outlines the anticipated lifespan of various technology types and the associated material factors. It aims to estimate the volume of materials that will be decommissioned in tonnes per year, projected through to 2050.

*Table 1 The assumed lifespan of renewable energy generation varies based on the technology type.*

| | *Small-scale renewable energy equipment* | | | *Utility renewable energy equipment* | | | |
|---|---|---|---|---|---|---|---|
| Weibull Shape Parameters | Rooftop PV | Small-scale battery | EV - Resi | Utility PV | Onshore wind turbine | Offshore wind turbine | Utility battery |
| B | 17 | 15 | 15 | 29 | 19.48 | 19.48 | 15 |
| a | 2.4928 | 3.5 | 3.5 | 2.4928 | 4.25 | 4.25 | 3.5 |
| **Average Life (Yrs)** | **15.6** | **14.0** | **14.0** | **25.1** | **18.2** | **18.2** | **14.0** |

**Solar:**

The findings presented by Tan et al. (2023) provide insights into the anticipated lifespan of solar panels. Rooftop solar panels are projected to have an average lifespan of approximately 15.6 years, while utility-scale panels are expected to last around 25.1 years. As detailed in Appendix A, the average wattage of these panels is estimated at 180 watts, reflecting a steady growth from 1 kW between 2001 and 2012. Key cell capacities (W/panel) have been derived from the Australian Energy Council (2016) and Solar Energy UK (2016) and are forecast to increase linearly, reaching a maximum capacity of 350 W/panel.

Recent advancements in Solar PV technology and battery systems have brought about notable changes in the materials used in their production. For example, there has been a significant reduction in the amount of silver used in solar panels since the early 2000s, alongside a moderate increase in the use of glass. These shifts in composition are informed by the findings of Tan et al. (2023), and they have been integrated into the model, subsequently influencing the results.

**Wind:**

The anticipated operational lifespan of both onshore and offshore wind turbines is estimated to be 18.2 years, with each turbine typically having an energy generation capacity of 3 megawatts. The material intensity factors used in this report are derived from research conducted by Crawford (2009).

**Batteries:**

The assumed lifespan for both small-scale and utility-scale batteries approximately 14 years. The intensity factors related to materials used in battery production have been derived from *Transport & Environment (2021), From dirty oil to clean batteries.*

## 3.3 Global best practice circular economy opportunities in the energy transition

The researchers reviewed global best practices from research papers, international and national organisations, NGOs, businesses, and industry, combined with their own professional experience to understand existing and yet-to-be-implemented opportunities for circular economy in the energy sector. Each source of information used in the ***Circular economy opportunities*** section of this report is referenced where it appears, with a broader list of research and case studies included in the project dataset spreadsheet.

## 3.4 Opportunity and scale of circular economy in the Victorian energy transition

The circular economy opportunities identified in this project are summarised in a subsequent section of this report: ***Circular economy opportunities***. These opportunities reflect both the application of established circular economy best practice to Victoria’s energy infrastructure, as well as identification of existing gaps, risks and opportunities for technologies and materials. The opportunities are assessed across the 10 rungs of the circularity 'R-Ladder' (Sustainability Victoria, 2024) and approaches outlined in the circularity deck (Konietzko et al., 2020).

# 4. Material use and availability in the energy transition

This section outlines Victoria's infrastructure and material needs for achieving its energy transition and climate targets. Figure 3 shows the annual renewable energy infrastructure capacity required from 2010 to 2050. Data from 2010 to 2024 reflects historical installations, while projections from 2025 onward are based on the Accelerated Transition scenario in the Australian Energy Market Operators' 2024 Integrated System Plan. The dark blue section represents capacity from rooftop solar, green indicates wind energy production, light blue shows energy storage capacity, and purple highlights large-scale solar project installations.

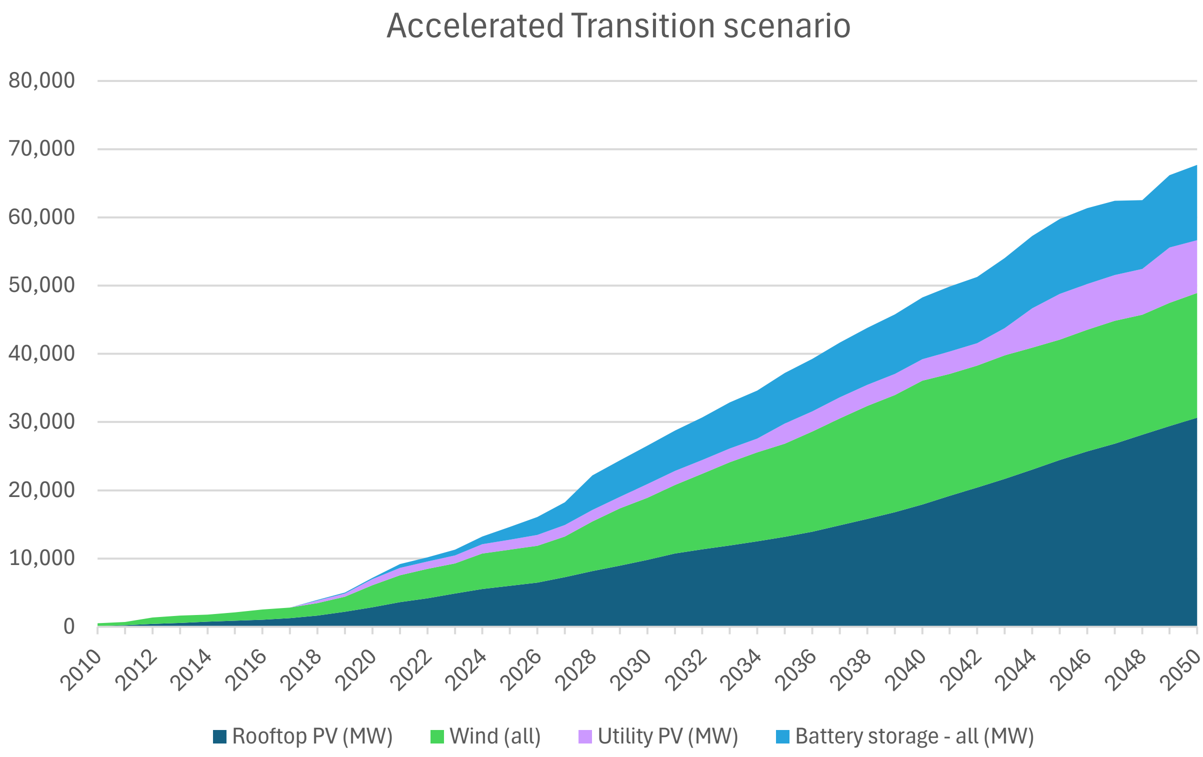


*Figure 3 Required annual Victorian electricity capacity installation by technology.*

In Victoria, wind energy and roof-top solar (shown in dark blue in Figure 3), are projected to dominate renewable energy infrastructure by 2050. Compared to other jurisdictions, large-scale solar farms will play a smaller role due to the comparative suitability of wind farms over solar farms for large-scale energy installations. This highlights the essential role of wind energy in facilitating Victoria's shift to a sustainable energy future.

The model considers anticipated fossil fuel generation closures, the need for renewable energy to replace it, and the projected increase in demand due to widespread electrification in Victoria.

## 4.1 Solar

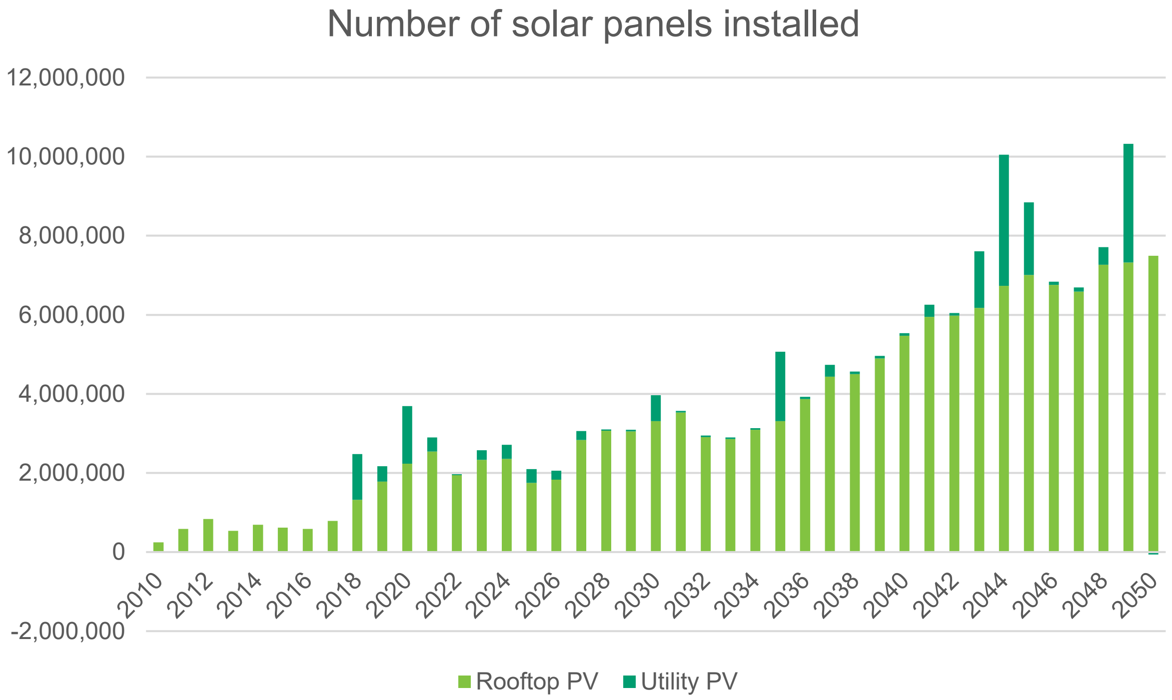


*Figure 4 Number of Solar PV panel installed in Victoria.*

Figure 4 presents the installation figures for solar panels in Victoria, with data sourced from the Australian PV Institute and the Clean Energy Regulator, covering the period before 2024. According to Figure 4, projections suggest that by 2030, more than 40 million solar panels are expected to be installed on residential rooftops and at utility-scale solar farms. This trend is anticipated to escalate, reaching nearly 160 million panels by the year 2050.

According to data in Figures 3 and 4, the solar PV installation sector has demonstrated significant early growth. Government incentives and prevailing market conditions largely drive this momentum. Consequently, it is projected that solar PV panels will become the largest contributor to waste in the near future as predicted in Figure 5. Based on average lifespans of 15.6 years for rooftop solar panels and 25 years for utility-scale solar panels, it is projected that by 2030, over 5.7 million rooftop solar panels and more than 430,000 utility-scale solar panels will reach the end of their operational life and be decommissioned. Appendices B and C illustrate the materials that can be obtained from the decommissioned panels.

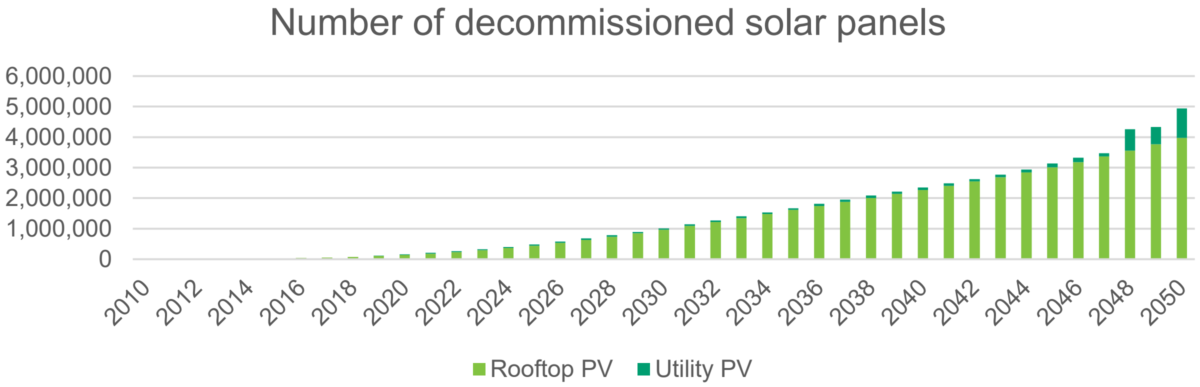


*Figure 5 Number of decommissioned solar panels in Victoria.*

## 4.2 Wind

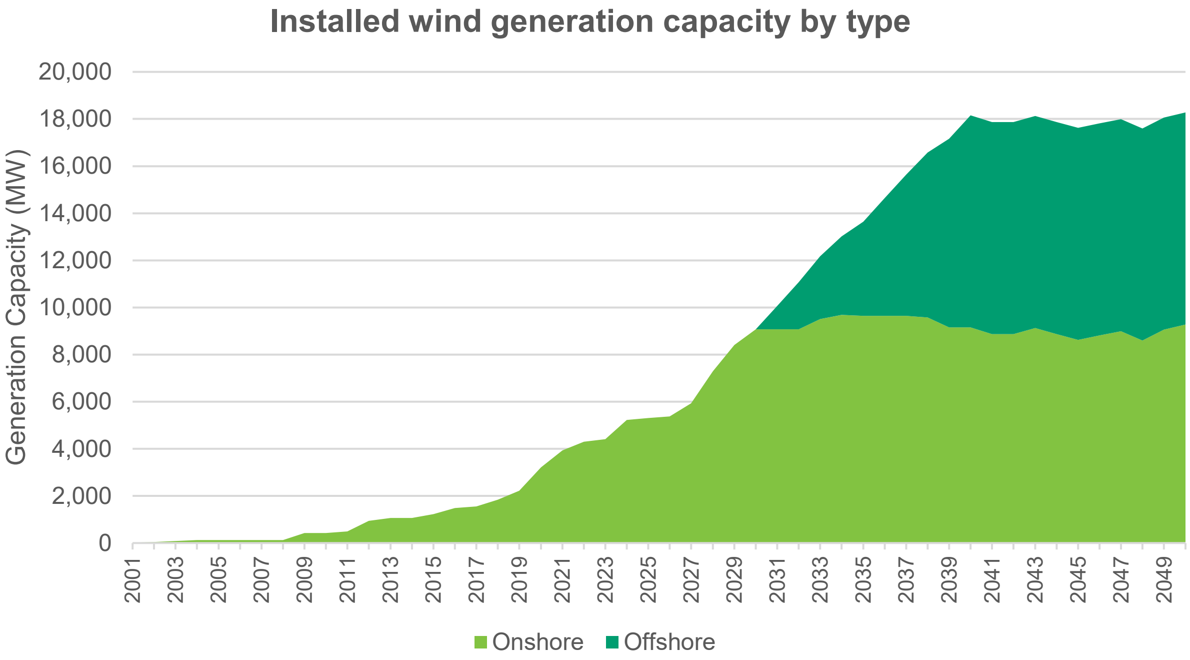


*Figure 6 Megawatt capacity of wind turbines installed in Victoria.*

Based on the projections illustrated in Figure 6, it is projected that in 2030, Victoria will have around 3,365 wind turbines installed. These will require approximately 10,095 blades, (assuming each turbine has three blades). This growth could lead to the installation of roughly 10,033 wind turbines and 30,099 blades by 2050 in Victoria.

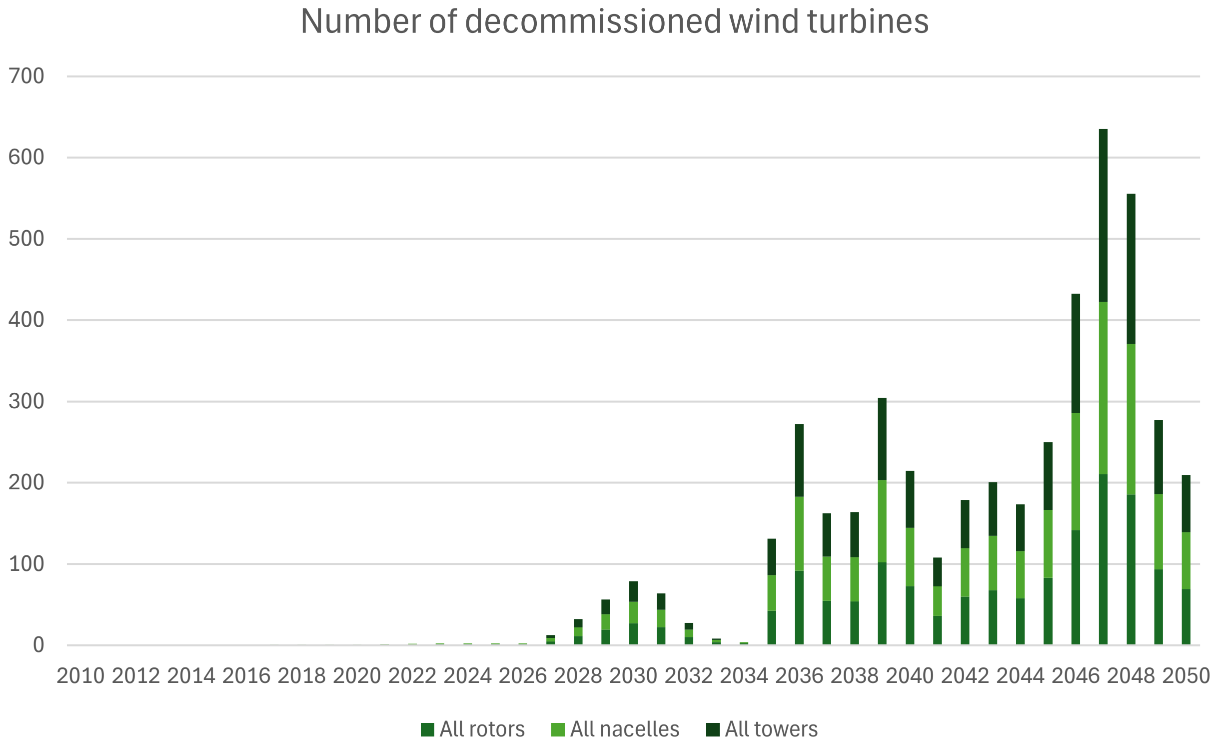


*Figure 7 Projected number of wind turbines to be decommissioned annually in Victoria.*

As shown in Figure 7, it is projected that by 2030, 57 wind turbines and over 170 blades will be decommissioned. By 2050, this number is expected to exceed 1,509 wind turbines and 4,527 blades, underscoring the need for effective management of wind energy infrastructure.

As illustrated in Appendix D, cement and steel comprise a sizeable portion of the materials derived from decommissioned wind turbines. The majority of wind farms are in regional Victoria, leading to concerns about the disposal of large turbine blades. Their considerable size presents challenges for handling and recycling, particularly in remote areas. At present, the epoxy composite materials used in turbine blades lack effective recycling solutions. By 2040, waste from decommissioned wind turbines and their blades is expected to pose a significant challenge. Although metals offer promising avenues for resource recovery, there is substantial potential to develop a circular economy for composite materials and other rare earth elements

## 4.3 Batteries

The projections provided by the Australian Energy Market Operator (AEMO) and Climateworks indicate a notable increase in electricity consumption within the transportation sector, alongside a rise in the adoption of battery technologies at both small- and utility-scale levels. Figure 8, illustrates the projected decommissioning trends for Battery Energy Storage Systems (BESS) across these scales. As demonstrated in Figure 8, the decommissioning of BESS is anticipated to rise exponentially beginning in the 2030s.

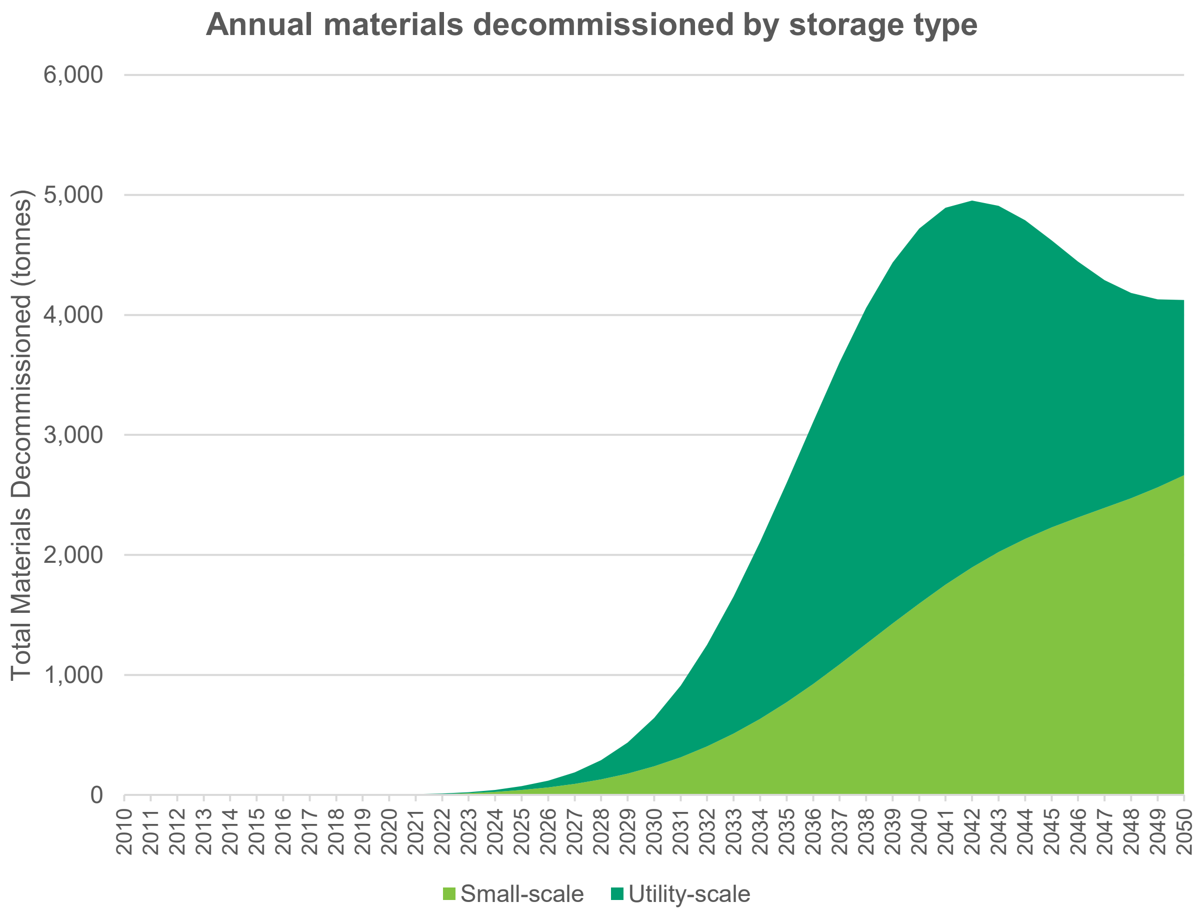


*Figure 8 Total battery storage capacity decommissioning in Victoria.*

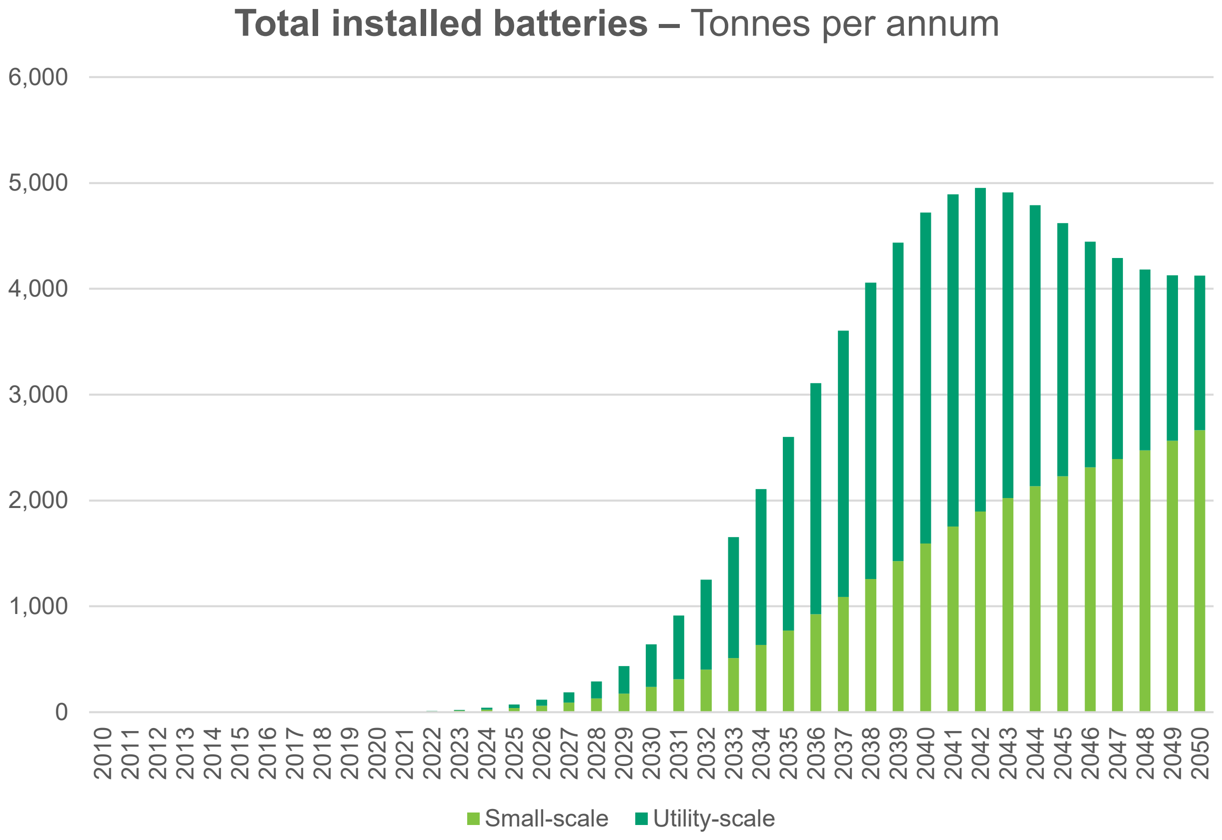


*Figure 9 Estimated capacity of batteries by type of EV in Victoria.*

Figure 9 presents the annual decommissioning projections for BESS. It is predicted that by the year 2030, more than 1,800 tonnes of BESS from both small-scale and utility-scale installations will have been taken out of service. This figure is expected to increase significantly, surpassing 10,300 tonnes by 2035. Furthermore, projections indicate that by 2050, the overall amount of decommissioned BESS will exceed 75,600 tonnes.

Appendices E and F provide an overview of the materials designated for decommissioning in the context of small-scale Battery Energy Storage Systems (BESS) and utility-scale BESS, respectively. EV batteries are typically decommissioned when they reach approximately 70% to 80% of their original capacity (Sustainability Victoria, 2023). Once EV batteries come the end of their useful life, they can be repurposed for stationary energy storage in industrial applications, small businesses, or as backup solutions. This results in a significant amount of functional battery storage capacity from these end-of-first-life EVs.

## 4.4 Material available from decommissioning

The expansion of renewable energy technologies is expected to significantly increase demand for various materials, thereby increasing waste generation. Figure 10 highlights potential materials that can be recovered from decommissioned renewable energy systems, including solar and wind, electric vehicles, and batteries. The list of recoverable materials includes concrete, steel, glass, aluminium, and copper, as well as valuable minerals such as silver, graphite, nickel, lithium, and manganese.

In Victoria, proactive management of end-of-life materials from renewable energy infrastructure will become increasingly critical from the late 2030s. Without early planning, existing local capabilities risk being overwhelmed by the rising volume of decommissioned solar PV panels and batteries, which pose safety hazards and the potential for long-term entrapment within foundational structures. As waste generation in the 2030s is expected to outpace current industry capacity, there is an urgent need for strategic foresight, investment in recycling infrastructure, and coordinated end-of-life planning for solar panels and electric vehicle batteries.

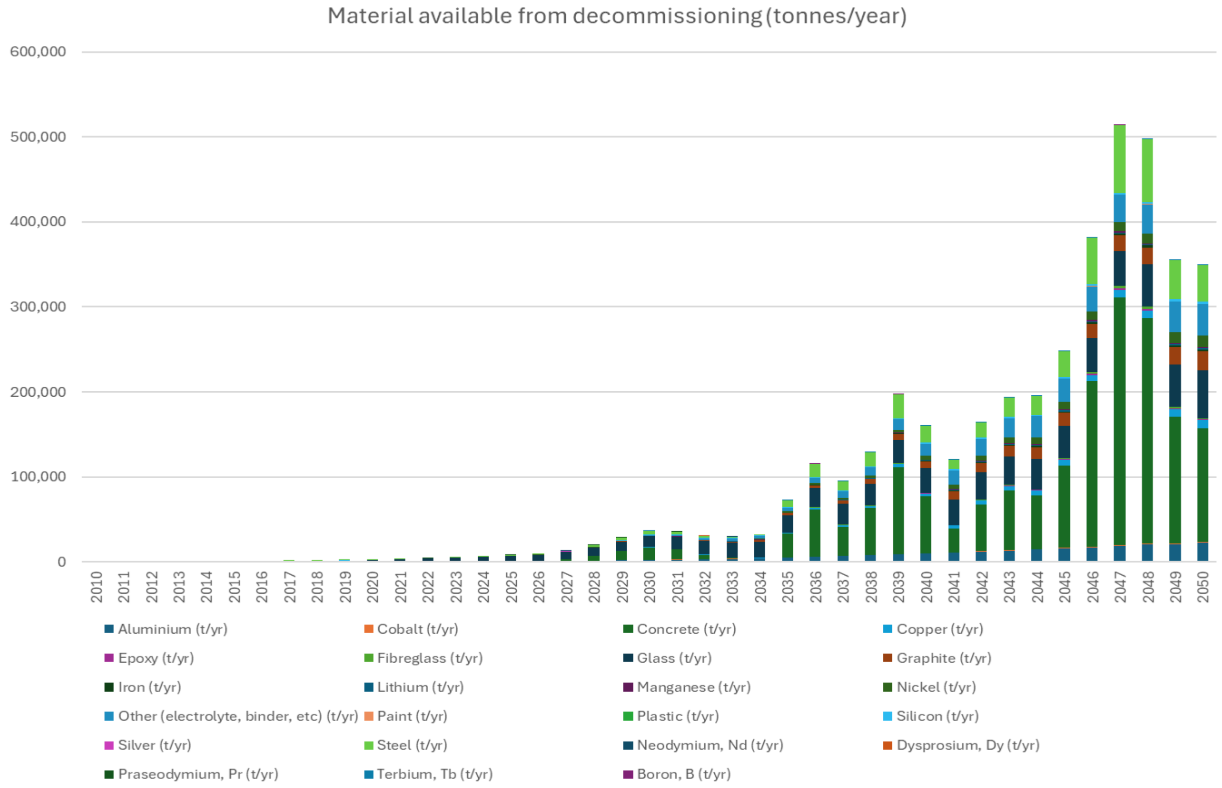


*Figure 10 Projected annual availability of materials from the decommissioning of energy infrastructure in Victoria.*

While some materials may be indicated in smaller quantities in Figure 5, they could hold substantial value or face risks of scarcity, particularly in Australia. The reliance on imported technology poses challenges regarding material availability and supply chain stability as the transition to new energy products continues. These complexities highlight the barriers to achieving sustainable energy solutions.

# 5. Engagement with industry

To gain a comprehensive understanding of the renewable energy sector's interest in adopting a circular economy, Sustainability Victoria collaborated with 6 leading renewable energy companies in Victoria. Additionally, Sustainability Victoria conducted a workshop in partnership with the Clean Energy Council. This workshop included participants from energy generation firms, renewable infrastructure suppliers, energy infrastructure installers, and waste processors within the energy domain.

During the workshop, Sustainability Victoria presented preliminary findings and approaches to circularity. While participants generally supported the principles of circularity, the workshop revealed a consistent set of structural, technical, and economic barriers that currently hinder the industry's ability to implement circular practices at scale.

In addition to this, stakeholder interviews were conducted with a small number of renewable energy developers to ground the analysis in industry experience. These discussions provided practical insights into emerging challenges, particularly around material supply, project delivery, and end-of-life management.

### Technology and skills constraints

Participants highlighted that most renewable energy infrastructure deployed in Australia is imported, with limited local influence over product design. As a result, Australian businesses have minimal control over design features that would enable circular outcomes, such as modularity, ease of repair, or disassembly at the end of life. In addition, some technologies –particularly wind turbine blades and certain composite materials – are inherently difficult to reuse or recycle due to their complex materials and upstream design choices. Skills gaps also persist locally, with limited technical capability to repair, remanufacture, or repurpose complex renewable energy components.

### Split incentives across the value chain

A major barrier identified was the misalignment of incentives between manufacturers, developers, asset owners, and end users. Producers typically do not face costs beyond the warranty period for performance degradation, repair, or end-of-life management. This weakens incentives to design products for longevity, reuse, or recyclability. Workshop participants noted a significant gap in extended manufacturer responsibility for solar panels, batteries, and wind turbines, resulting in end-of-life risks being externalised to asset owners, communities, or governments rather than embedded within business models.

### Information asymmetry and data gaps

The workshop identified widespread information gaps across the sector. Consumers and businesses often lack clear, accessible information on the environmental impacts, expected durability, repairability, and material composition of renewable energy products. While individual businesses may understand their own waste streams, they are often unaware of complementary waste or by-product streams generated by others. This information asymmetry limits collaboration, aggregation of materials, and the development of shared circular economy solutions across industry.

### Externalities and Cost Signals

Economic signals were identified as a critical constraint. Producing new renewable energy infrastructure is perceived as more cost-effective than designing modular, repairable, or recyclable products. Lifecycle costs – including pollution, resource depletion, and landfill impacts – are often overlooked in investment and procurement decisions. The absence of appropriate pricing signals for environmental externalities reinforces reliance on virgin materials and discourages investment in circular design, reuse pathways, and advanced recycling solutions. As a result, linear 'take-make-waste' models continue to dominate despite stated sustainability objectives.

In discussions with industry stakeholders,  there is a willingness to implement circularity within the energy sector, despite challenges identified by these stakeholders. They recognise waste generated from renewable resources poses significant concerns that could affect their social license to operate. In response to these issues, they are advocating for clearer definitions of circularity from a policy perspective, as well support and guidance to implement circularity effectively.

# 6. Global scan on best practices

The renewable energy sector is making significant progress in circular practices, particularly in solar PV technology, wind turbine blades (WTBs), and battery energy storage systems (BESS). These practices involve policies and standards that align with circular economy principles, highlighting the importance of data transparency, extended producer responsibility (EPR), material reuse, and innovative recycling methods for recovering high-value materials. New regulatory frameworks, along with digital product passports and service-oriented business models, are transforming the design and end-of-life management of clean energy assets. Sustainability Victoria conducted a global analysis to evaluate relevant initiatives, identifying examples of government programs, policies, and industry practices. These findings offer valuable insights for Victoria, informing the development of effective interventions and helping to avoid unintended consequences.

**International and industry approaches to advancing solar PV circularity**

The CIRCUSOL project, funded by the European Commission from 2018 to 2022, advanced Product-as-a-Service models in the solar sector by shifting from asset ownership to service-oriented delivery (Circusol, 2018). This initiative involved 15 organisations across seven countries, establishing standardised protocols for the second-life use of photovoltaic (PV) modules. It focused on the reuse of solar panels, the repurposing of electric vehicle (EV) batteries, eco-design principles for disassembly and repair, and improved recycling methods to reduce downcycling.

In Japan, a standards-led approach was implemented with national guidelines introduced in 2021 that created a framework for decommissioned PV modules, supporting domestic reuse and exports to developing economies (Basnet et al., 2025). The Japan Photovoltaic Energy Association (JPEA) also introduced voluntary guidelines in 2017 for manufacturers to disclose hazardous-substance information and maintain safety data sheets, promoting industry-led material transparency for safe end-of-life management.

Germany established a comprehensive regulatory framework through the Stiftung EAR (Elektro-Altgeräte Register) and the ElektroG, enforcing extended producer responsibility for PV modules (Madrigal et al., 2023). Manufacturers must register products, provide financial guarantees for end-of-life management, and meet recovery targets of 85% recovery and 80% mass recycling, enhancing traceability and secondary markets (Madrigal et al., 2023).

Neoen's Degrussa solar and battery hub in Western Australia demonstrated renewable energy's potential for off-grid mining decarbonisation, reducing approximately 12,000 tonnes of $CO_2$ emissions annually (PV Magazine, 2024). However, despite Neoen's preference for reusing decommissioned panels, a lack of public information on end-of-life outcomes indicates planning gaps.

Jinko Solar exemplifies integrated lifecycle governance by promoting circularity throughout the product lifecycle receiving global recognition (Jinko, 2023).

These case studies suggest that solar PV circularity is gaining traction through practical reuse economics (as seen with Neoen), industry-led transparency (as seen with JPEA), and comprehensive value-chain responsibility (as seen in Germany and with Jinko Solar).

For Victoria, transitioning to circular systems requires coordinated ecosystems that link project-level innovation, industry standards, and traceability with a focus on reuse before recycling.

### Regulatory and industry approaches to wind turbine blade (WTB) circularity

Germany leads with a regulatory approach to the circularity of wind turbine blades (WTBs), having imposed a landfill ban in 2009 on materials with Total Organic Carbon levels exceeding 5% (Reglobal, 2020). This policy has eliminated landfilling for WTB waste, prompting the industry to invest in circular design and alternative disposal strategies. In December 2025, Germany launched its National Circular Economy Strategy, mandating the application of circular design principles across the renewable energy sector. Coupled with the ElektroG law's extended producer responsibility (EPR), WTBs are classified as electrical equipment, enforcing registration, reporting, labelling, and take-back obligations (Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety, 2024).

The ZEBRA (Zero Waste Blade Research) Project marks a significant step in blade recyclability, demonstrating that traditional thermoset resins can be replaced with fully recyclable thermoplastic liquid resins. Coordinated by the French research institute IRT, this project was validated at an industrial scale without the need for new manufacturing equipment (Spini & Bettini, 2024).

Launched in 2024, the EU-funded EOLIAN project advances material innovation through vitrimer composites, which are recyclable and can be reshaped by heat. Embedded sensors in these blades assist with rapid damage detection, promoting proactive maintenance (Beauson et al., 2021).

Denmark offers a model of voluntary leadership through the DecomBlades project, which facilitates sustainable WTB recycling, creates standardised blade material passports, and establishes value chains for decommissioning (Abrahamsen et al., 2023). This initiative achieved the first successful recovery of glass fibre from decommissioned blades for new production.

In 2023, China proposed national standards for WTB recycling, requiring manufacturers to design for disassembly and take responsibility for eco-friendly decommissioning, while emphasising advanced recycling techniques (Wang et al., 2025).

These strategies highlight the path to circularity in wind turbine blades through regulation, material innovation, collaborative policies, and national standards, which are essential for transitioning to circular wind energy infrastructure.

### Emerging Asian approaches to end-of-life lithium-ion battery management

Recent international developments indicate a shift toward regulatory and standards-based approaches for managing end-of-life disposal of lithium-ion batteries from electric vehicles. A comparative analysis of global policy frameworks demonstrates that effective battery circularity depends on key factors, including extended producer responsibility (EPR), safety controls, traceability, and clear recycling obligations. The European Union has set a global benchmark, while countries like China and South Korea are rapidly advancing their regulatory systems (Paul et al., 2024).

China has intensified its efforts through the State Administration for Market Regulation (SAMR) Action Plan (2025), expanding national standards for waste battery management to cover 22 guidelines, including dismantling and lithium recovery (China Energy Storage Alliance, 2025). Technical guidance on automated battery disassembly has improved recovery efficiencies, aligning with circular economy principles. However, challenges remain, such as low recycling capacity utilisation due to longer battery lifespans and ongoing non-compliance from informal operators, underscoring the need for stronger enforcement.

Similarly, South Korea has adopted a lifecycle-based regulatory model through the Resource Circulation of Electrical and Electronic Equipment and Vehicles Act, embedding EPR principles throughout the battery lifecycle (International Energy Agency, 2025). This framework mandates detailed data reporting and requires recycled content in new batteries. Planned pre-disposal performance evaluations set for 2027 aim to enhance battery reuse and recycling, reinforcing circular value.

These approaches exemplify a broader global trend: effective battery circularity is achieved through regulations that integrate producer accountability, performance standards, and data transparency. For regions like Victoria, these models highlight the importance of early regulatory clarity and alignment with safety and circular economy objectives.

# 7. Circular economy opportunities

The transition to renewable energy systems presents a significant opportunity to embed circular economy principles across solar PV, wind energy, and battery storage technologies. Circular strategies focus on extending asset lifetimes, reducing material intensity, enabling reuse and repurposing, and recovering high-value materials at the end of life. Together, these approaches reduce reliance on virgin resources, lower lifecycle emissions, and strengthen the resilience of renewable energy supply chains.

### Cross-cutting circular strategies

Several core circular approaches are shaping the design and operation of renewable energy systems. Technologies are being designed for durability, modularity, and ease of maintenance, enabling individual components to be repaired or replaced without full system replacement. This reduces material demand and embedded emissions over the lifecycle.

**Lifetime extension** and repowering are also central strategies. By extending the operating life of solar and wind farms through improved operations and maintenance, selective component replacement, and partial repowering, material throughput per unit of energy generated is significantly reduced.

**Product-as-a-service** and leasing models are emerging as important enablers of circularity. Under these arrangements suppliers retain ownership of assets and responsibility for performance, upgrades, and end-of-life management. This aligns commercial incentives with long lifetimes, high performance, and material recovery.

**Extended producers responsibility** and take-back schemes further support closed-loop systems by ensuring manufacturers and developers remain accountable for collection, reuse, and recycling at the end of life. In parallel, advances in mechanical, chemical, and metallurgical recovery processes are improving the recovery of high-purity metals, glass, and composites from renewable energy equipment.

## 7.1 Solar photovoltaics

### Design and manufacturing

Upstream circularity in solar PV focuses on design for disassembly and material transparency. Panels are increasingly designed to minimise hazardous or hard-to-recover materials and use reversible bonds and standardised components, improving dismantling and recycling outcomes. Material transparency tools, such as material passports and ecolabel-type schemes, support recyclers and encourage manufacturers to select recyclable, traceable inputs. At the same time, reductions in material intensity through thinner wafers, lower precious metal content, and higher-efficiency cells reduce raw material demand per unit of capacity.

### Use phase and business models

During operation, circularity is enabled through lifetime extension and alternative ownership models. Performance-based service contracts place responsibility for monitoring, maintenance, and upgrades with suppliers, incentivising robust design and repairability. Secondary markets for refurbished modules are emerging, allowing panels that no longer meet high-performance thresholds to be redeployed in off-grid, community, or lower-demand applications.

### End-of-life management

At end of life, dedicated PV recycling schemes can recover the majority of module mass, including glass, aluminium frames, and selected metals. Advanced thermal and chemical processes further enable recovery and purification of silicon and precious metals, supporting their reuse in new manufacturing. As these processes mature, recycled materials can be reintegrated into new panel production, reducing embodied carbon and resource risks.

## 7.2 Wind energy: turbines, blades, and systems

### Design and operation

Circularity in wind energy is driven by lifetime extension and repowering strategies. Proactive maintenance, digital monitoring, and partial replacement of nacelles or rotors allow continued use of towers and foundations, significantly reducing the need for new steel and concrete. New turbine designs increasingly incorporate materials selected for recyclability, including resins that enable chemical recycling of blades.

### Reuse and repurposing

Major turbine components such as gearboxes, generators, and towers can be refurbished and reused in repowering projects or smaller installations. Blade repurposing offers additional value pathways, with retired composite blades being converted into civil infrastructure applications such as bridges, noise barriers, and structural elements, delaying disposal and substituting for virgin materials.

### Recycling and decommissioning

Where reuse is not feasible, blades can be processed through mechanical, thermal, or chemical recycling routes to recover fibres, fillers, and energy. Integrating circular decommissioning strategies at the project planning stage – through contractual obligations and defined recycling pathways – reduces landfill dependency and supports stable secondary material markets.

## 7.3 Batteries and energy storage

### Design for circularity

Battery systems are increasingly designed with modular architectures that allow cell replacement, repair, and easier disassembly. Alongside this, advances in battery chemistry are reducing reliance on high-impact materials, although maintaining recyclability and economic recovery remains critical.

### Lifetime extension and second life

Improved battery management systems, thermal control, and predictive analytics slow degradation and extend first-life performance. Once batteries fall below automotive performance thresholds, they can be repurposed for less demanding stationary applications such as grid support, backup power, and microgrids, delaying recycling and reducing demand for new batteries.

### Recycling and closed-loop supply chains

Industrial recycling processes enable the recovery of lithium, nickel, cobalt, and other critical materials from end-of-life batteries. A fully circular vision integrates design, collection, and recycling so that recovered materials systematically re-enter new battery production. Policy mechanisms such as extended producer responsibility and recycling targets are central to achieving high recovery rates and economic viability.

# 8. Conclusion

This research highlights that circularity in renewable energy infrastructure is not a secondary consideration, but a strategic response to these intersecting challenges. Embedding circular economy principles across the renewable energy lifecycle can strengthen supply chain resilience, reduce exposure to international material risks, and retain value from critical materials within the economy. Circularity is vital for achieving emissions reduction and enhancing energy security. It aligns with the goals of Future Made in Australia’s Net Zero Transformation Stream, which seeks to strengthen Australia’s competitive position in the global net zero economy. Additionally, it encourages economic resilience by advancing domestic capabilities.

Quantifying material flows, future infrastructure volumes and end-of-life pathways is essential to identifying where investment opportunities exist and where policy and market interventions can have the greatest impact. While further work is required to fully understand and operationalise circular solutions across solar, wind and battery technologies, this research provides an evidence base to begin planning. This data is timely, providing early signals to industry, investors and government on the scale of the opportunity and the importance of acting ahead of anticipated waves of asset retirement and replacement.

The global transition to renewable energy is unfolding within a broader context of a ‘polycrisis’, where compounding risks from geopolitical instability, economic volatility and accelerating climate impacts reinforce one another. Recent geopolitical events have exposed vulnerabilities in global energy and material supply chains, contributing to price volatility and a renewed focus on short-term energy security. In this environment, there is a risk that climate action and longer-term system transformation are deprioritised in favour of immediate economic and energy concerns.

Ultimately, taking a proactive approach to circularity in renewables enables Victoria to move beyond a linear ‘take-make-waste’ model and toward a more resilient, productive and secure energy system. By starting with robust data and a clear investment lens, this research lays the groundwork for coordinated action that aligns climate ambition with economic resilience in an increasingly uncertain global context.

# 9. References

Abrahamsen, A. B., Beauson, J., Lund, K. W., Madsen, E. S., Rudolph, D. P., & Jensen, J. P. (2023). Method for estimating the future annual mass of decommissioned wind turbine blade material in Denmark. *Wind Energy*, *27*(2), 165–178. https://doi.org/10.1002/we.2882

Australian Energy Council. (2016). SOLAR REPORT. In *Australian Energy Council*. https://www.energycouncil.com.au/media/xmwfsk2n/australian-energy-council-solar-report-q3-2023.pdf

Australian Energy Market Operator. (2024). *2024 Integrated System Plan (ISP).* https://www.aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2024-integrated-system-plan-isp

Australian Energy Market Operator. (2026). *2026 Integrated System Plan (ISP).* https://www.aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2026-integrated-system-plan-isp

Basnet, R., Jones, L., Azmie, M. A., Jones, M., McCann, M., & Ernst, M. (2025). Advancing circular economy of silicon Photovoltaics: Current status and challenges of PV module reuse. *Solar Energy Materials and Solar Cells*, *292*, 113816. https://doi.org/10.1016/j.solmat.2025.113816

Beauson, J., Laurent, A., Rudolph, D., & Jensen, J. P. (2021). The complex end-of-life of wind turbine blades: A review of the European context. *Renewable and Sustainable Energy Reviews*, *155*, 111847. https://doi.org/10.1016/j.rser.2021.111847

China Energy Storage Alliance. (2025). *A 100-Billion-Yuan Market for Power Battery Recycling Is on the Horizon!* https://en.cnesa.org/latest-news/2025/10/21/a-100-billion-yuan-market-for-power-battery-recycling-is-on-the-horizon

Circusol. (2018). *D5.9 Project website 776680.* https://www.circusol.eu/files/publications/D5.9.CIRCUSOL_Website_Report.pdf

Climateworks Centre. (2023). *Climateworks Centre decarbonisation scenarios 2023: About the modelling - Climateworks Centre*. https://climateworkscentre.org/resource/climateworks-centre-scenarios-2023-about-the-modelling/

Crawford, R. (2009). Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews*, *13*(9), 2653–2660. https://doi.org/10.1016/j.rser.2009.07.008

Department of Climate Change, Energy, the Environment and Water. (2024). *The Circular Advantage. https://www.dcceew.gov.au/sites/default/files/documents/circular-advantage-final-report-cemag.pdf*

Department of Energy, Environment and Climate Action. (2023). Victoria's*, 2035 Emissions REDUCTION TARGET Driving Real Climate Action*. https://www.climatechange.vic.gov.au/__data/assets/pdf_file/0028/635590/Victorias-2035-Climate-Target_Driving-Real-Climate-Action.pdf

Ellen MacArthur Foundation. (2024). *Circular Economy Principles*. Ellenmacarthurfoundation.org. https://www.ellenmacarthurfoundation.org/circular-economy-principles

European Environment Agency. (2021) *Emerging waste streams: Opportunities and challenges of the clean-energy transition from a circular economy perspective.* https://www.eea.europa.eu/en/analysis/publications/emerging-waste-streams-opportunities-and-challenges-of-the-clean-energy-transition-from-a-circular-economy-perspective

Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety. (2024). *The National Circular Economy Strategy (NCES).* https://www.bundesumweltministerium.de/en/download/the-national-circular-economy-strategy-summary

*From dirty oil to clean batteries*. (2021). https://www.transportenvironment.org/wp-content/uploads/2021/07/2021_02_Battery_raw_materials_report_final.pdf

International Energy Agency. (2025). *Act on resource circulation of electrical and electronic equipment and vehicles (EEEV Act).* https://www.iea.org/policies/16960-act-on-resource-circulation-of-electrical-and-electronic-equipment-and-vehicles-eeev-act

Jinko Solar. (2023). *Climate Action White Paper.* https://jinkosolar.eu/wp-content/uploads/2024/10/2023-JinkoSolar-Climate-Action-White-Paper.pdf

Konietzko, J., Bocken, N., & Hultink, E. J. (2020). A tool to analyze, ideate and develop circular innovation ecosystems. *Sustainability*, *12*(1), 417. https://doi.org/10.3390/su12010417

Madrigal, A. N., Iyer-Raniga, U., & Yang, R. J. (2023). Exploring PV waste management solutions using circular strategies. *Journal of Sustainability Research*, *5*(2). https://doi.org/10.20900/jsr20230008

Paul, D., Pechancová, V., Saha, N., Pavelková, D., Saha, N., Motiei, M., Jamatia, T., Chaudhuri, M., Ivanichenko, A., Venher, M., Hrbáčková, L., & Sáha, P. (2024). Life cycle assessment of lithium-based batteries: Review of sustainability dimensions. *Renewable and Sustainable Energy Reviews*, *206*, 114860. https://doi.org/10.1016/j.rser.2024.114860

PV Magazine. (2024). *Neoen shut down Australian solar-plus-storage plant after 7 years.* https://www.pv-magazine.com/2024/01/18/neoen-shut-down-australian-solar-plus-storage-plant-after-7-years/

Reglobal. (2020). *Decommissioning of Onshore Wind Turbines*. https://reglobal.org/decommissioning-of-onshore-wind-turbines/#:~:text=blades%20in%20particular:-,%E2%80%A2,fibres%2C%20they%20cannot%20be%20landfilled.

Solar Energy UK. (2021). *Why are Solar PV Panels Getting Bigger?* Solar Energy UK. https://solarenergyuk.org/why-are-solar-pv-panels-getting-bigger/

Spini, F., & Bettini, P. (2024). End-of-Life wind turbine blades: Review on recycling strategies. *Composites Part B Engineering*, *275*, 111290. https://doi.org/10.1016/j.compositesb.2024.111290

Sustainability Victoria. (2023). *Watts next for old EV batteries.* https://www.sustainability.vic.gov.au/news/news-articles/watts-next-for-old-ev-batteries

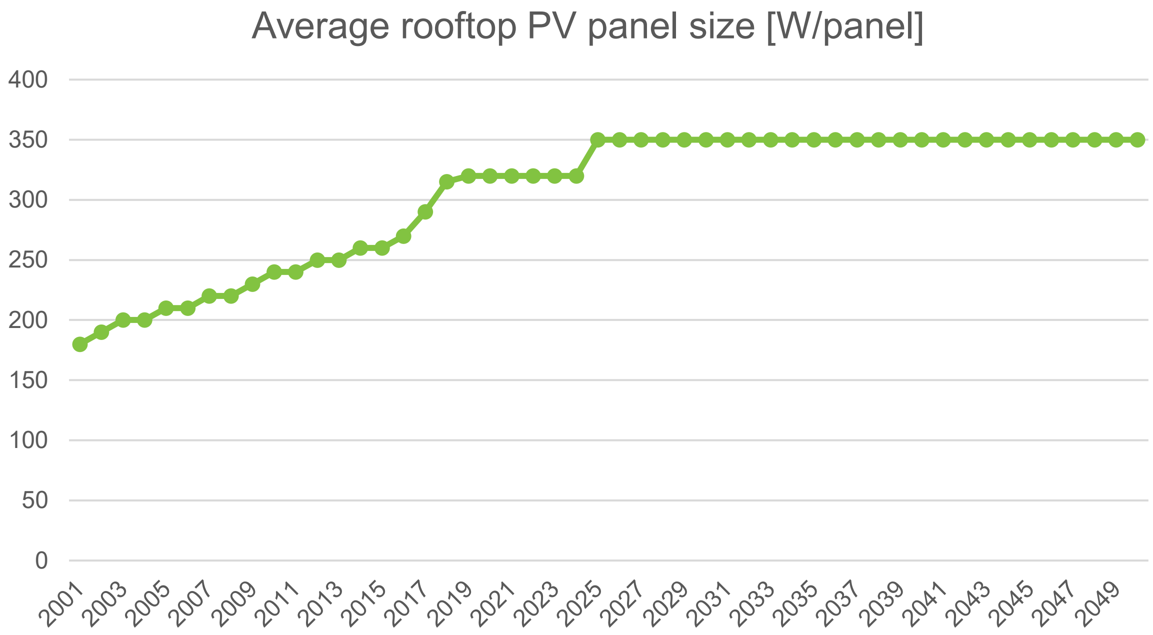
Sustainability Victoria. (2024). Strategic Plan. In *Sustainability Victoria Strategic Plan 2024-2027*. https://assets.sustainability.vic.gov.au/susvic/Document-Our-strategy-SV-3-year-strategic-plan-2024-2027.pdf

Tan, V., Deng, R., & Egan, R. (2023). Solar photovoltaic waste and resource potential projections in Australia, 2022–2050. *Resources Conservation and Recycling*, *202*, 107316. https://doi.org/10.1016/j.resconrec.2023.107316

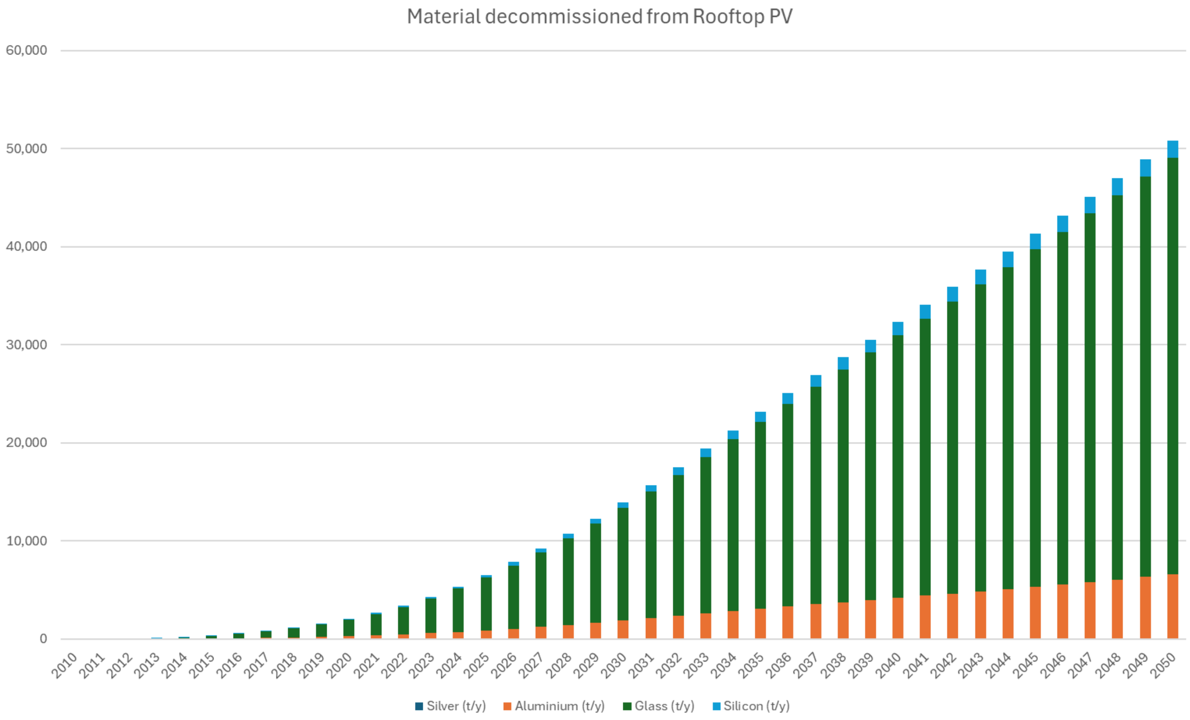
Wang, Y., Wang, Y., Dong, B., Dai, J., Lu, G., Peng, K., Wang, Y., & Wang, Y. (2025). Value-added recycling strategies for decommissioned wind turbine blades: A review. *Renewable and Sustainable Energy Reviews*, *222*, 115950. https://doi.org/10.1016/j.rser.2025.115950

# 10. Appendices

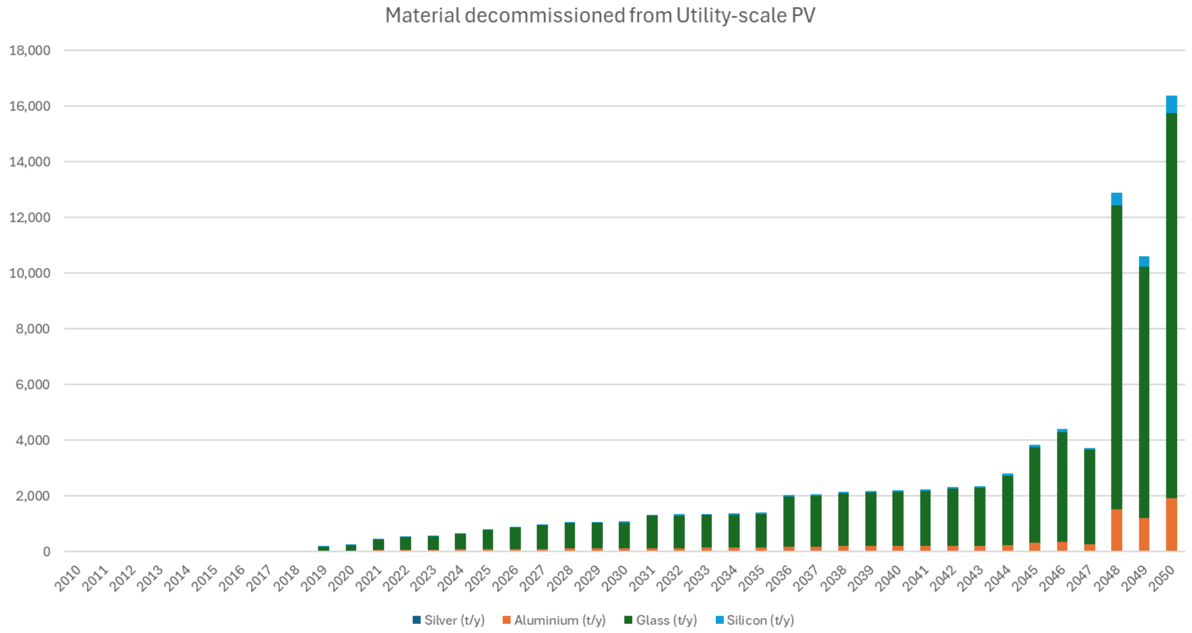
**Appendix A:** Average watt per Rooftop PV panel.



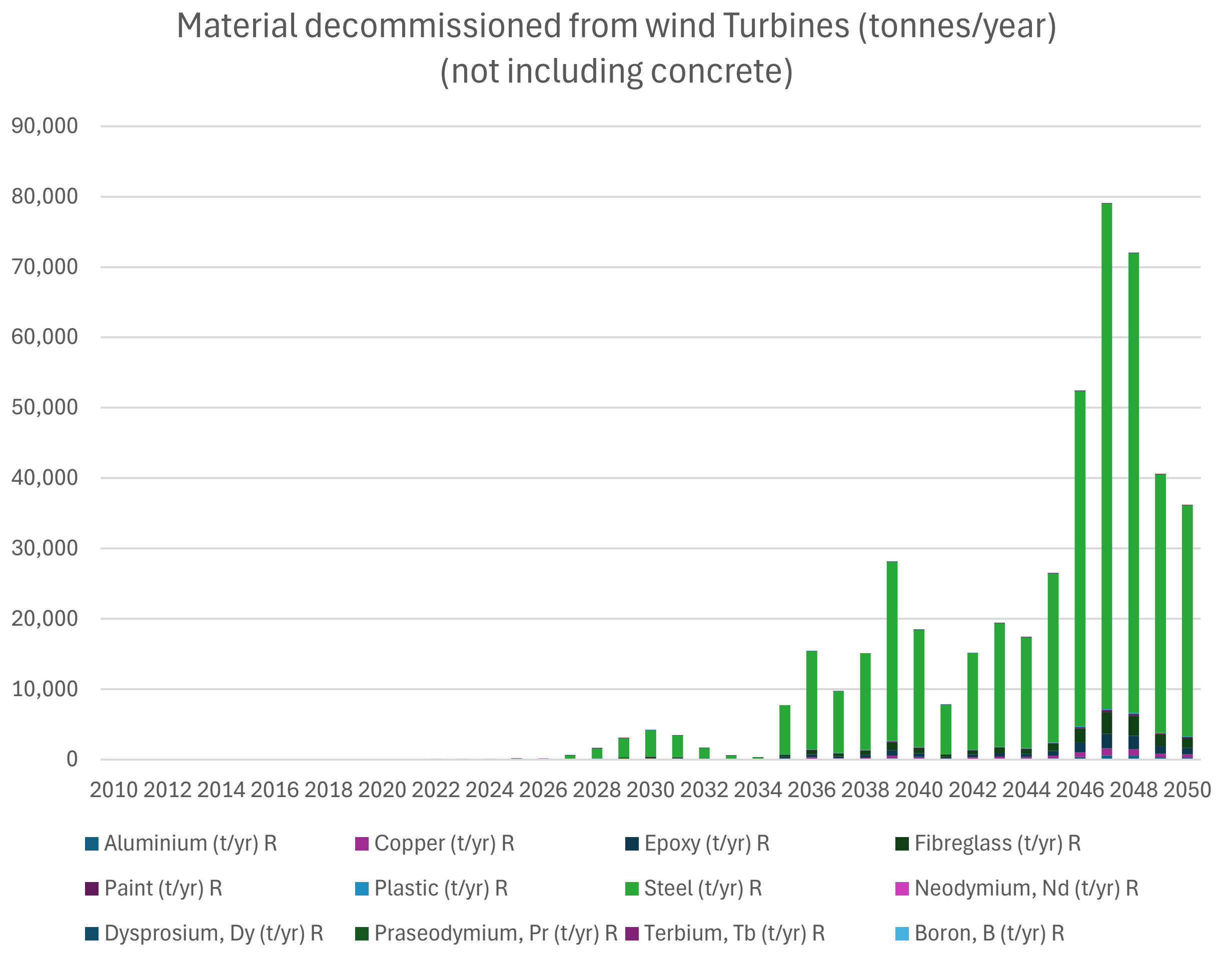
**Appendix B:** Material available from decommissioned rooftop solar panels in Victoria.



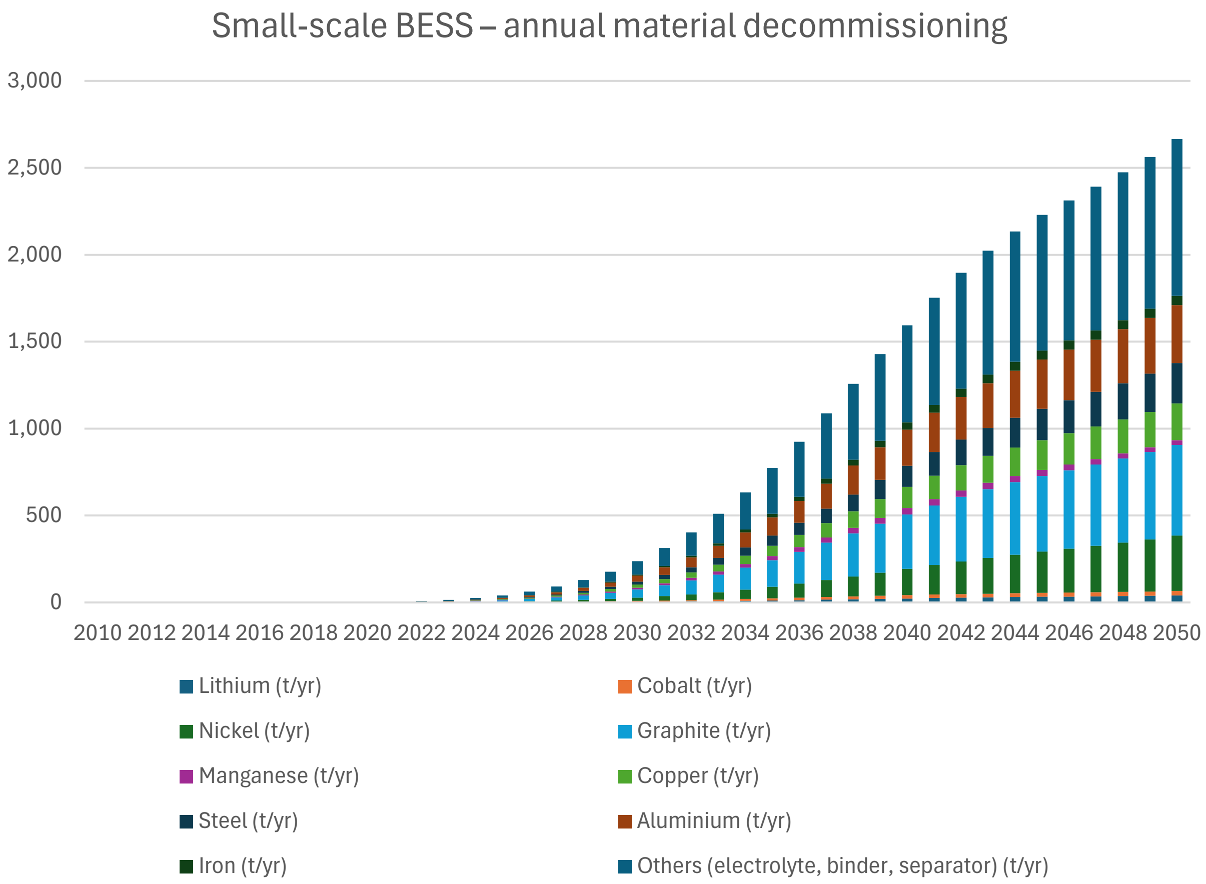
**Appendix C:** Material available from decommissioned utility-scale solar panels in Victoria.



**Appendix D:** Material available from decommissioned wind turbines in Victoria



## **Appendix E:** Small-scale BESS – annual material decommissioning



## **Appendix F:** Utility-scale BESS – annual material decommissioning