VICTORIA UNIVERSITY OF WELLINGTON TE HERENGA WAKA NEW ZEALAND
Archives of Sustainable Energy Systems
https://www.wgtn.ac.nz/sustainable-energy-systems

Towards a viable roadmap for solar and wind waste recycling in Aotearoa New Zealand

Judy Okebe, Alan Colin Brent

Abstract

Aotearoa New Zealand's ambition for 100 percent renewable electricity by 2030 and full decarbonisation by 2050 has driven a rapid expansion of solar photovoltaic and wind power generation infrastructure. However, this growth presents a parallel sustainability challenge in the effective management of end-of-life waste management. This study therefore estimates future volumes of renewable energy waste through to 2080 and evaluates the economic potential of material recovery alongside an assessment of relevant policy and infrastructure conditions. Using a mixed-methods approach, quantitative projections based on installation lifespans and material intensity were developed for solar and wind waste streams, and a qualitative analysis of European Union and Australian best practices were undertaken to inform policy recommendations. The results indicate that cumulative waste from utility-scale systems will reach approximately 1.68 million tonnes by 2080, with high-value materials such as aluminium, copper, and steel offering a recoverable economic value of up to NZ$ 11.8 billion. Moreover, the analysis reveals that technical complexity, regulatory gaps, and limited economies of scale currently hinder the development of a local recycling industry. Additionally, our findings suggest that a viable recycling roadmap is achievable through extended producer responsibility schemes, targeted regional infrastructure investment, and integration of circular economy policies. Finally, proactive planning will enable Aotearoa New Zealand to align environmental sustainability with renewable energy deployment and position itself as a leader in the responsible management of clean energy transitions.

Keywords: Solar energy waste; Wind energy waste; Renewable energy; Waste projections; End-of-life management.

1. Introduction

The global transition to low-carbon energy systems has accelerated rapidly in response to climate change with solar photovoltaic (PV) systems and wind turbines playing a pivotal role in decarbonisation strategies. The International Energy Agency's Renewables 2024 report projects an increase of 5 500 GW of global renewable capacity by 2030, with solar and wind accounting for 95 % of that growth (IEA, 2024a). Solar PV alone is expected to represent 80 % of new installations due to continued cost declines and supportive policies, while wind capacity additions are forecasted to double between 2024 and 2030 compared with 2017–2023 levels (IEA, 2024b). These trends demonstrate the necessity of full lifecycle considerations as renewable deployment scales.

Aotearoa New Zealand already sources most of its electricity from renewables. In 2023, renewable generation supplied 87 % of national electricity, with wind at 6.5 % and solar at 0.36 % (MBIE, 2023). Projections indicate that wind and solar could jointly meet over 50 % of demand by 2050, underscoring ambitious decarbonisation targets (NIWA, n.d.). Moreover, over 19 GW of new renewable projects are under development, highlighting sustained infrastructure growth in the country (Transpower, 2022). This underscores the necessity of embedding lifecycle management within Aotearoa New Zealand's energy planning.

End-of-life (EoL) management of solar photovoltaic (PV) modules and wind turbine components presents a significant emerging challenge. According to IRENA and the IEA-PVPS (2016), global PV waste could accumulate to 78 million tonnes by 2050 in the absence of effective recycling strategies. Without dedicated EoL frameworks, valuable materials risk landfilling or mismanagement undermining the environmental benefits achieved during operation.

Despite a growing waste stream, Aotearoa New Zealand lacks both domestic recycling infrastructure and a regulatory framework for renewable energy waste. End-of-life PV panels and wind turbine components are predominantly exported raising logistical and environmental concerns (Blake et al., 2019). Unlike the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive or Australia's imminent Extended Producer Responsibility scheme for solar modules, Aotearoa New Zealand currently has no tailored policy to ensure producer accountability or facilitate material recovery. This policy gap underscores the rationale for context-specific research.

The paper bridges this knowledge and policy void by evaluating the feasibility of a domestic recycling industry for end-of-life solar PV and wind turbine components in Aotearoa New Zealand. It synthesises projections of future waste volumes, explores the economic potential of recovering valuable materials, and evaluates international best practices for their applicability in Aotearoa New Zealand.

1.1. Objective of the paper

The overarching objective is to propose a viable roadmap that integrates policy mechanisms, technological solutions and economic incentives to enable the end-of-life (EoL) management of waste from solar and wind farms in Aotearoa New Zealand. To achieve this, the paper:

- Projects future waste volumes from utility-scale solar and wind technologies through to 2080;
- Evaluates the economic potential of recovering valuable materials;
- Identifies barriers and enablers affecting recycling adoption in the Aotearoa New Zealand context; and
- Recommends policy and infrastructure strategies adapted from international best practices.

In doing so, this research aims to inform policymakers and industry stakeholders as Aotearoa New Zealand advances toward its 2030 renewable electricity and 2050 decarbonisation targets, ensuring both environmental integrity and economic resilience of its clean energy transition.

2. Literature review

This section reviews global and local developments in the end-of-life (EoL) management of solar photovoltaic (PV) and wind turbine infrastructure with the aim of identifying strategies applicable to Aotearoa New Zealand. The literature spans technological innovations, policy frameworks, and economic drivers that support or hinder the recycling of renewable energy components. Insights are drawn from comparative case studies in the European Union and Australia, alongside local assessments of Aotearoa New Zealand's e-waste management system.

2.1. Global waste trends and local gaps

As the global deployment of solar and wind energy technologies accelerates, so too does the volume of EoL infrastructure requiring safe disposal or recovery. Some studies estimate that global solar PV waste could reach somewhere between 60 and 78 million tonnes by 2050 (IRENA & IEA-PVPS, 2016; IEA-PVPS, 2022). Wind waste, particularly from turbine blades made of composite materials, is also projected to rise steeply, with global blade waste reaching around 43 million tonnes by mid-century (Liu & Barlow, 2017). These trends have prompted early policy responses in regions with mature renewable energy markets.

Understanding these global trends is essential for Aotearoa New Zealand, which is still in the early stages of formulating appropriate responses to renewable energy waste. Aotearoa New Zealand currently lacks dedicated legislation or recycling infrastructure for solar and wind waste. The country exports all decommissioned solar and wind components to destinations such as China while only a proportion of small electronic waste is handled through voluntary schemes (Blake et al., 2019). This reliance on export not only shifts environmental risks to other countries, but also prevents Aotearoa New Zealand from capturing the economic value of recovered materials. National data report around 99,000 tonnes of general e-waste per year without disaggregating renewable waste streams thereby making it impossible to forecast specific volumes or plan infrastructure (Blake et al., 2019). Without accurate projections and local capacity, Aotearoa New Zealand will struggle to cope with large wind and solar waste volumes as installations reach their end of life.

2.2. Environmental and infrastructure challenges

Solar PV modules contain materials such as lead, cadmium, and silver, while wind turbines include steel, copper, and rare earth elements. Without appropriate recovery systems, these components pose environmental risks like soil and water contamination (Nain & Kumar, 2020; Artaş et al., 2023). At the same time, these materials offer significant resource value if effectively recycled. For instance, glass and aluminium from PV modules and steel from wind turbines are highly recoverable and already part of global recycling supply chains (IEA-PVPS, 2022; Clean Energy Council, 2023).

Material recovery is not without its challenges. Aotearoa New Zealand's geographic isolation, small market size, and limited economies of scale make it difficult to establish cost-effective recycling operations. Logistics, labour, and capital investment constraints all contribute to the underdevelopment of solar and wind waste infrastructure (Trypolska et al., 2022). Therefore, coordinated policy or financial incentives are required for these systemic barriers to be effectively addressed.

2.3. Technological pathways and barriers

International recycling technologies prove that high-value recovery of solar and wind materials is achievable. Mechanical recycling of PV panels can recover up to 90% of aluminium frames and 80–95% of glass, while advanced processes aim to extract silicon and rare metals with greater efficiency (Mousavian et al., 2023). For wind turbines, pyrolysis and co-processing techniques show promise in recycling fibreglass blades, though widespread commercialisation remains limited (Xu et al., 2024).

Despite this progress, high processing costs, composite material complexity, and contamination risks reduce the economic viability of recycling in small markets like Aotearoa New Zealand. Recovery of silicon and rare earths remains technically feasible but commercially challenging without supportive policy frameworks (IEA-PVPS, 2022; Heath et al., 2020).

2.4. Policy and economic drivers

Mandatory producer responsibility and financial incentives are essential to catalyse a domestic recycling industry. Policy frameworks such as the EU's Waste Electrical and Electronic Equipment (WEEE) Directive and Japan's national solar recycling programme demonstrate the importance of mandatory product stewardship and extended producer responsibility (EPR) in building successful recycling systems (Chowdhury et al., 2020; Xu et al., 2018). These models require manufacturers to participate in EoL planning and finance recovery operations, creating accountability and promoting innovation. Chowdhury et al. (2020) report that clear regulatory obligations force producers to internalise end-of-life costs, which in turn drives investment in infrastructure and innovation.

In Aotearoa New Zealand, the Waste Minimisation Act (Parliamentary Counsel Office, 2008) provides a foundation for stewardship schemes but does not yet mandate EPR for renewable technologies (Blake et al., 2019). Without policy levers, recycling PV modules, for instance, can cost up to six times more than landfilling making such initiatives financially unsustainable in the absence of regulatory incentives (Suyanto et al., 2023). Another significant challenge lies in the technical complexity and high processing costs of composite materials, particularly wind turbine blades made from thermoset fibreglass-reinforced polymers. These materials are resistant to degradation and are difficult to disassemble or recycle using conventional mechanical or thermal methods (Clean Energy Council, 2023). Financial models such as landfill levies, leasing agreements, and public-private partnerships could improve the economics of recycling by internalising environmental costs and incentivising circular design (Suyanto et al., 2023).

2.5. Implications for Aotearoa New Zealand

These studies demonstrate that international technological and policy solutions must be adapted to local conditions. A decentralized network of regional recycling hubs, supported by targeted incentives, may overcome the scale of challenges. Partnerships with Australia and neighbouring Pacific Island states could also help overcome scale and cost limitations.

Ultimately, the success of solar and wind ewaste recycling in Aotearoa New Zealand will depend on integrated policy development, investment in specialized infrastructure, and early engagement with industry stakeholders, while simultaneously realizing the environmental co-benefits of reduced demand for virgin resource extraction, lower lifecycle emissions, and improved sustainability of renewable energy deployment. These combined advantages are critical for supporting Aotearoa New Zealand's sustainability ambitions and reinforcing its position as a global leader in climate action.

3. Research methods

A mixed-methods strategy was adopted to capture both the quantitative scale of end-of-life solar and wind waste and the qualitative dimensions of policy and infrastructure development. Quantitative projections of solar photovoltaic (PV) and wind turbine waste were based on historical installation data from the Electricity Authority (2022–2029) and the New Zealand Wind Energy Association (1996–2023), applying lifespan assumptions of 30 years for PV modules and 20 years for existing wind turbines and 30 years for new installations (Electricity Authority, 2022; NZWEA, 2023). To forecast post-2029 capacity growth, the disruptive growth scenario of Pimentel Pincelli et al. (2025) was implemented via a logistic growth model:

$$dP/dt = a\mathrm{P}(1 - \frac{P}{K})$$

where P represents cumulative installed capacity, a is the intrinsic growth rate, and K is the saturation level. Saturation values were set at 10.5 GW for utility-scale solar PV, 6.7 GW for distributed solar, and 5.8 GW for onshore wind. Each decommissioned capacity cohort was paired with material intensity factors (kg/MW) to estimate the waste volumes of components such as module frames, panels, towers, and nacelles.

Qualitative insights were obtained through comparative policy analysis of the EU Waste Electrical and Electronic Equipment Directive and Australia's extended producer responsibility and landfill ban schemes (Chowdhury et al., 2020). National policy targets and growth trends were supplemented by government reports from the Ministry of Business, Innovation and Employment (MBIE) and the Electricity Authority. Furthermore, international benchmarks on circular-economy practices and recycling technologies were sourced from International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA), as well as from the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL).

3.1. Analytical framework and synthesis

End-of-life waste projections were calculated by shifting each installation cohort forward by its assumed lifespan and applying material intensity factors to derive annual waste outputs. Descriptive statistics identified peak waste flows and material recovery thresholds. Comparative policy analysis employed thematic coding to extract transferable mechanisms such as mandatory stewardship requirements, collection infrastructure models and cost-recovery frameworks from international case studies.

The economic potential of recyclables was assessed by evaluating aluminium, copper, glass, silicon and rare earth element recovery values against current market prices (Deng et al., 2024; Heath et al., 2020). Steel and copper recovery from wind turbine nacelles was similarly evaluated, with rare earth element recycling considered as an emerging opportunity (European Commission Joint Research Centre, 2022).

Through iterative integration of quantitative projections and qualitative themes, an evidence-based roadmap was developed. Forecasted waste trajectories highlighted priority intervention years while policy insights informed governance and financing mechanisms. This combined approach ensures that the proposed recycling strategy is technically sound, economically viable, and aligned with Aotearoa New Zealand's low-carbon transition goals.

3.2. Limitations and assumptions

This study relies exclusively on secondary installation and policy data from national authorities and international reports, which may not fully capture emerging local recycling infrastructures or future regulatory shifts. Moreover, the lifespan assumptions and static material-intensity factors do not account for potential technological advances or degradation rate variability, and thus may under- or overestimate actual waste volumes. Finally, economic valuations omit the time value of money and assume constant recovery rates, without reflecting future market volatility or policy interventions that could alter material yields and processing costs.

4. Results and discussion

This section presents the projected end-of-life (EoL) waste volumes from solar and wind energy infrastructure in Aotearoa New Zealand, the material composition of these waste streams, the potential for economic recovery, and the implications for national policy and infrastructure planning. The findings are based on long-term forecasts, material recovery modelling, and international policy comparisons, providing a detailed evidence base for the development of a local recycling roadmap.

4.1. Projected growth in solar and wind e-waste

Aotearoa New Zealand is poised to experience an increase in renewable energy waste, with a substantial increase beginning to show in the 2050s.

Using historical installation data and forecast capacity growth, lifetime-based decay functions, namely 30 years for solar PV and 20 to 30 years for wind turbines, were applied to estimate end-of-life waste profiles. In the case of solar PV, waste volumes remain negligible until the early 2050s, reflecting the design lifespans of panels installed in the 2020s and early 2030s. After 2052, however, decommissioning accelerates sharply, producing approximately 2.2 million tonnes of PV waste in the 2076–2080 period. Cumulatively, from 2052 through to 2080, PV waste is projected to reach on the order of 9 million tonnes, assuming current capacity expansion trajectories are realised (see Figure 1).

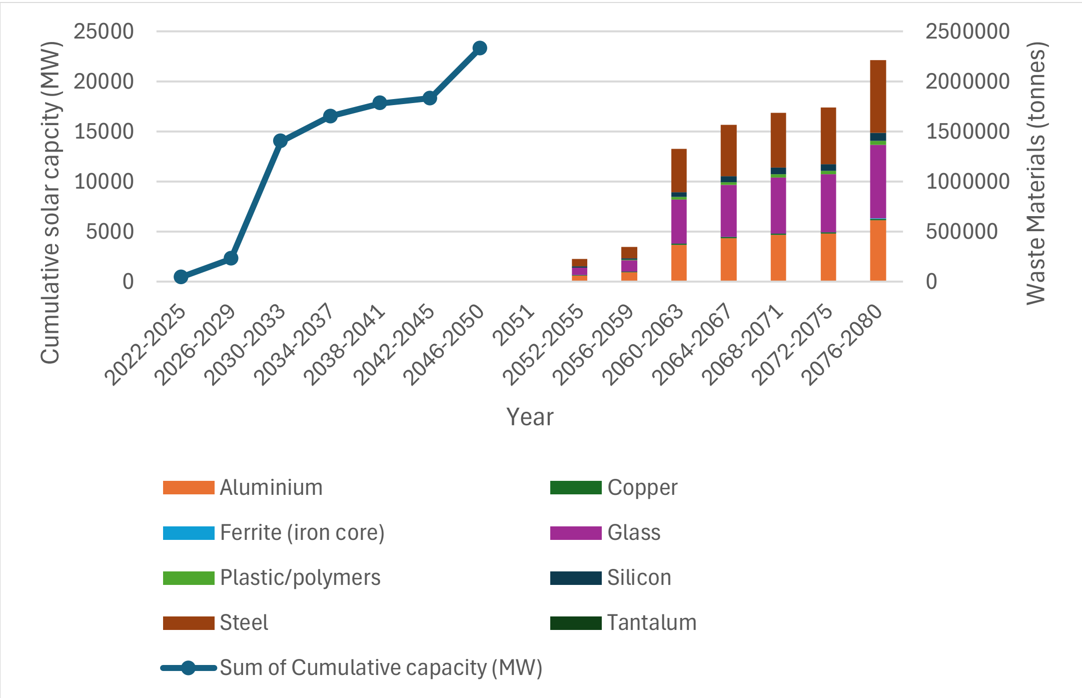

Figure 1. Cumulative installed and projected utility-scale solar capacity and EoL waste material in Aotearoa New Zealand (2022–2080)

Wind turbine waste follows a complex temporal pattern, with the first wave arising from early-generation turbines installed between 1999 and 2007 as they reach the end of their 20-year operational life. This initial surge is most pronounced in 2066–2070, when roughly 3 million tonnes of components, roughly 600,000 tonnes per year, will be decommissioned. A much larger second wave then unfolds in 2076–2080, driven by turbines commissioned after 2025 and assuming 30-year lifespans. During this interval, waste volumes could peak at around 3.17 million tonnes, which is approximately 634,000 tonnes per year. Addressing these significant peaks in wind energy waste will necessitate a substantial nationwide expansion of decommissioning and recycling infrastructure. Cumulatively, wind EoL waste through to 2080 is estimated at 6,125,000 tonnes, assuming current capacity expansion trajectories are realised indicating a substantial, long-term material waste stream (see Figure 2).

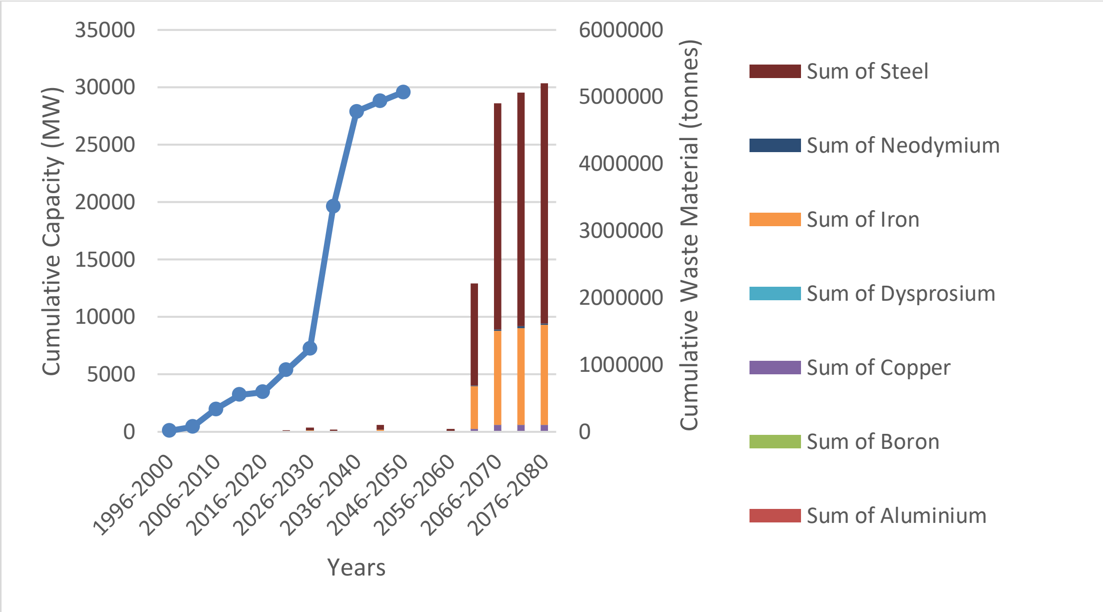

Figure 2. Cumulative installed and projected wind capacity and EoL waste material in Aotearoa New Zealand (1996–2080)

The end-of-life waste generated by renewable energy installations offers considerable economic promise, driven by the high recovery potential and strong market demand for materials such as aluminium, copper, and steel (Suyanto et al., 2023). These estimates highlight the need for a deliberate, long-term commitment to developing a specialized recycling sector, one that can generate employment, bolster resource security, diminish import dependence, and reduce landfill burdens (International Renewable Energy Agency & IEA-PVPS, 2016; Sustainability Victoria, 2021).

These forecasts confirm that Aotearoa New Zealand faces a delayed but pronounced waste burden from both technologies. The difference in timing between solar and wind waste surges also suggests the need for staggered infrastructure and investment planning. Policy frameworks and recycling systems must anticipate these peaks in waste generation to avoid delayed responses or overreliance on offshore disposal pathways.

4.2. Material composition and technical recovery feasibility

Understanding the material composition of end-of-life (EoL) solar and wind infrastructure is essential for identifying which components can be recovered efficiently, which offer economic value, and which pose significant recycling challenges. Disaggregating these waste streams by component type provides a clearer view of technical recoverability and economic viability.

Solar PV panels are primarily composed of glass, aluminium framing, polymers including encapsulants and backsheets, and smaller fractions of silicon, silver, copper, and other trace materials (IEA-PVPS, 2022; Sustainability Victoria, 2021), as outlined in Table 1. Mechanical recycling can recover the vast majority of glass and aluminium with high efficiency and market value, whereas polymers such as EVA encapsulants require energy-intensive delamination processes that reduce cost-effectiveness (Latunussa et al., 2016).

Table 1. Composition and recyclability of solar PV panel components

Material	Approx. Share by Weight (%)	Recyclability Status	Notes
Glass	~75%	High (via mechanical recycling)	Contamination can lower reuse potential
Aluminium Frame	~10%	Very High (>90% recovery)	Easily dismantled and processed in current recycling streams
EVA Encapsulant	~10%	Low	Requires thermal or chemical separation; hinders recovery of others
Silicon	~5%	Moderate	Recoverable with treatment; often degraded at EoL
Silver	<1%	Low	High value, but present in trace amounts; costly recovery
Other Metals	<1%	Varies	Includes copper, tin, and lead in small amounts

On the other hand, wind turbines consist mainly of steel and cast iron in towers and support structures, which integrate readily into existing metal recycling streams (NREL, 2023), as outlined in Table 2. Nacelles and hubs contain copper, aluminium, electronics, and cast iron, all of which are economically attractive for recovery. Generator modules include rare earth elements (neodymium, dysprosium) accounting for 2–5 % of mass. These materials are high value, but technically difficult and costly to extract at scale (NREL, 2023). The most challenging fraction is fibreglass-reinforced polymer blades, which resist thermal and mechanical processing and are typically relegated to landfill or low-value co-processing (Clean Energy Council, 2023).

While most of the material mass from both technologies is theoretically recoverable, in practice the technical and economic recoverability varies by component. Policy and industry focus should initially target high-volume, high-value, and technically accessible materials such as aluminium, copper, and steel while supporting innovation in the treatment of complex materials like silicon and turbine blades.

Table 2. Composition and recyclability of wind turbine components

Component	Primary Materials	Approx. Share by Weight	Recyclability Status	Notes
Tower	Steel	60–70%	Very High	Standard steel recycling processes apply
Nacelle & Hub	Cast iron, copper, aluminium, electronics	15–20%	High	Copper and aluminium are economically recoverable
Generator	Rare earth magnets (NdFeB), steel	2–5%	Moderate	Rare earth recovery possible but not yet widespread
Blades	Fibreglass-reinforced thermoset polymers	10–15%	Low	Difficult to recycle; landfill or co-processing most common
Cables & Wiring	Copper	<1%	Very High	Easily separated and recovered
Control Systems	Mixed metals, plastics, semiconductors	<1%	Low–Moderate	Complex disassembly; often downcycled or discarded

4.3. Economic feasibility of material recovery

The economic feasibility of recycling end-of-life (EoL) waste from solar and wind technologies hinges on the balance between material recovery values and processing costs. Using value estimates adapted from Deng et al. (2024), aluminium recovery accounts for between NZ$ 5.1 billion to NZ$ 8.5 billion between 2052 and 2080. Although glass accounts for the largest mass share, its low market value limits its contribution to a maximum of NZ$ $571 million. Therefore, aluminium stands out as the key economic contributor in the assessment of materials salvaged from decommissioned solar and wind installations. Materials such as EVA encapsulant and polymeric backsheets offer negligible returns and face technical barriers to processing (Sustainability Victoria, 2021; IEA-PVPS, 2022). The high value of aluminium and copper across both technologies supports the prioritisation of these materials in policy and infrastructure development (see Figure 3).

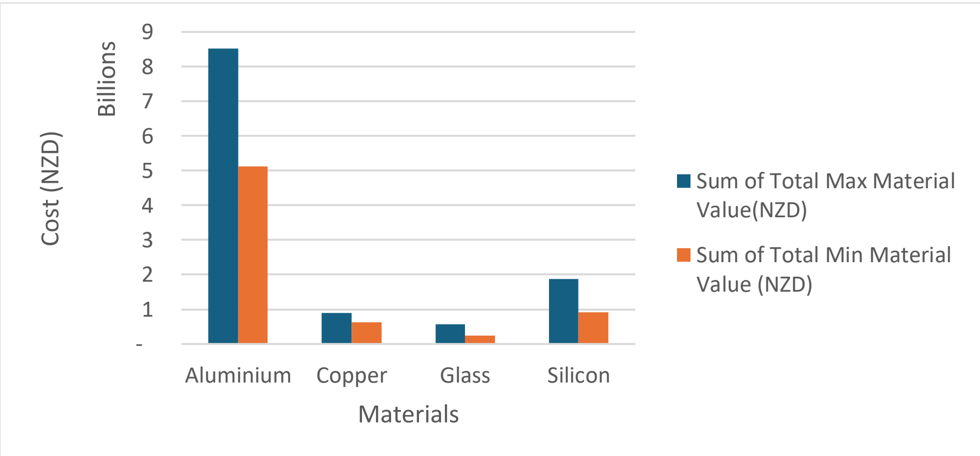

Figure 3. Estimated material recovery value by material type (2052–2080)

As shown in Table 3, only a full-recovery facility (Option 2) operating at ≥4 000 t/yr yields economic viability, requiring about NZ$ 19 million in capital and NZ$ 963–1, 177 / tonne in operating costs while smaller-scale options and reuse testing facilities involve lower upfront investment but recover fewer high-value materials.

Table 3. Estimated recycling costs by method

Facility Scale (tonnes/year)	Capital Investment (AUD)	Capital Investment (NZD)	Operating Cost (AUD/tonne)	Operating Cost (NZD/tonne)	Minimum Economic Scale (tonnes/year)
Delamination Only (Option 1)	AUD 1.1 million	NZD 1.2 million	AUD 500-550	NZD 535-589	2,500
Full Recovery (Option 2)	AUD 17.8 million	NZD 19 million	AUD 900-1100	NZD$ 963-1177	4,000
Frame and Junction Box Only (Option 3)	AUD 0.22 million	NZD 0.24 million	AUD 350-450	NZD 375-482	3,000
Reuse Testing Facility (Option 4)	AUD 0.4 million	NZD 0.43 million	AUD 250-300	NZD 268-321	N/A

(Source: Deng et al., 2024)

Projecting material flows over a 30-year lifespan yields annual revenue estimates from NZ$ 6.91 billion in a conservative recovery scenario to NZ$ 11.87 billion under high efficiency assumptions as illustrated in Figure 4. Revenues rise steeply after 2055 and peak between 2076 and 2080, reflecting the retirement curve of installations deployed in the 2020s and 2030s. Notably, these gross values do not account for discounting or inflation adjustments required for net present value calculations.

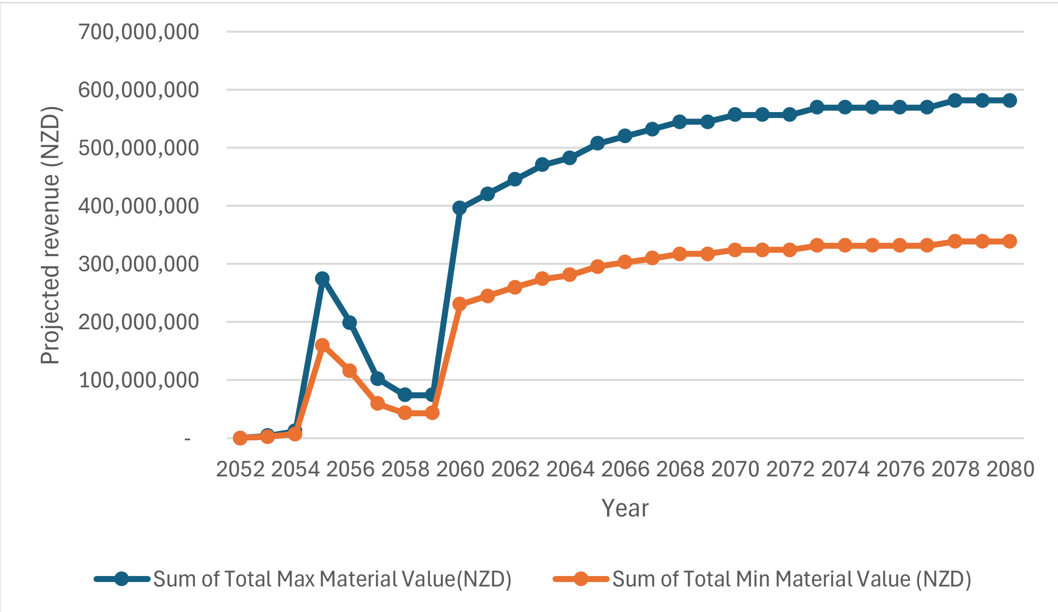

Figure 4. Estimated annual economic value from recovered materials (2052–2080)

These results illustrate the significant economic upside of establishing a local recycling system. However, they also mask important financial caveats. For instance, cost estimates do not account for logistics, land acquisition, skilled labour development, or regulatory compliance, all of which will affect actual investment returns. Furthermore, many of the most valuable components, such as silicon and rare earths, require specialised processing infrastructure that does not yet exist in Aotearoa New Zealand.

Nevertheless, a shared solar and wind recycling facility targeting aluminium, copper, and steel could achieve economies of scale, especially given the overlapping timelines of waste generation. If supported by landfill levies, producer contributions, and reuse incentives, such a facility could become financially viable.

4.4. Policy gaps and opportunities for reform

Currently, Aotearoa New Zealand has no formal policy mechanisms tailored to the recycling of renewable energy technologies. The Waste Minimisation Act (Parliamentary Counsel Office, 2008) provides a legal basis for product stewardship, but lacks enforceable provisions for solar and wind infrastructure (Blake et al., 2019). By contrast, the European Union mandates recovery and reuse targets under the WEEE Directive, and Australia has committed to a national extended producer responsibility (EPR) scheme for PV waste by 2025 (Chowdhury et al., 2020; WMRR, 2024).

This policy vacuum in Aotearoa New Zealand introduces uncertainty for investors and manufacturers, and inhibits coordinated infrastructure development. At the national level, Germany, Austria, Finland, and the Netherlands have banned the landfilling of composite materials (WindEurope, 2020). The introduction of EPR obligations, landfill restrictions, and national recovery targets could dramatically alter the viability of recycling initiatives by embedding circular economy principles into system design and supply chain responsibilities.

Moreover, establishing a regulatory timeline would enable industry and government to collaborate on infrastructure development without abrupt enforcement; for example, requiring phased compliance starting in 2035. A regulatory approach that combines producer accountability, incentives for modular design, and public funding for pilot facilities would position Aotearoa New Zealand to lead on sustainable energy policy in the region.

4.5. Infrastructure considerations and regional adaptation

Aotearoa New Zealand's relatively small market and geographic isolation pose logistical challenges for the recycling of renewable energy components. However, these constraints can be addressed through decentralised infrastructure planning. Establishing regional recycling hubs in the North and South Islands, strategically located near freight corridors or major generation sites, could reduce transport costs and increase system accessibility.

International experience suggests that small economies can overcome scale limitations through regional partnerships. Coordinated processing agreements with Australia and Pacific Island nations, for instance, could allow cost-sharing and cross-border material flows, making otherwise unviable recycling streams more efficient. This is especially relevant for hard-to-recycle components such as wind turbine blades, which require high-volume throughput to justify investment in pyrolysis or co-processing technologies.

Furthermore, timing is on Aotearoa New Zealand's side. Unlike the EU or Australia, which are already experiencing rising waste volumes, Aotearoa New Zealand's renewable energy waste curve offers a proactive window for policy design and infrastructure planning. Planning for future waste streams would enable smoother scaling of facilities and workforce development, rather than relying on late-stage remediation.

4.6. Geographic and temporal variations

Aotearoa New Zealand's renewable energy sectors remain relatively nascent compared with the European Union and Australia, which in turn shapes the country's unique waste timeline. Wind power in the country dates back to the late 1990s and has grown to approximately 1.3 GW of installed capacity as of 2023 (New Zealand Wind Energy Association [NZWEA], 2023). In contrast, large-scale solar deployment has only gained momentum over the past decade, driven by sharply falling PV module costs (Energy Efficiency and Conservation Authority [EECA], n.d.) and government proposals to streamline consenting under the Resource Management Act (MinterEllisonRuddWatts, 2024). Consequently, Aotearoa New Zealand will not experience significant solar waste until well into the 2050s, reflecting the 30-year design life of modules installed today.

By contrast, the European Union began deploying large volumes of both solar PV and wind turbines in the early 2000s. More recent work by the European Environment Agency (2024) reveals that first-generation PV panels are already reaching end-of-life, prompting implementation of the WEEE Directive's binding targets of 85 percent material recovery and 80 percent recycling or reuse. However, compliance remains uneven, with only half of reporting nations meeting these thresholds in 2021. This outcome is attributed to infrastructure bottlenecks and the complexities of processing composite turbine blades made of glass fibre–reinforced polymers.

Similarly, Australia's rapid uptake of residential and utility-scale solar over the past decade has foreshadowed an imminent waste surge. Research by Suyanto et al. (2023) shows that when capital, logistics, and processing costs are accounted for, advanced recycling pathways for PV panels can exceed landfill disposal costs, despite Victoria's pioneering landfill ban on solar modules. Nevertheless, Australia's commitment to a national EPR scheme by 2025 (Waste Management and Resource Recovery Association of Australia [WMRR], 2024) underscores the effectiveness of coupling regulatory mandates with economic incentives to stimulate industry investment.

A comparative assessment of these regions' deployment histories and technology lifespans highlights starkly different e-waste waves. The EU's first major e-waste volumes materialized in the 2020s, Australia's are projected in the 2030s, and Aotearoa New Zealand's peak will not occur until the 2050s. These temporal differences present the country with a strategic opportunity. By anticipating future e-waste flows, the country can enact targeted policy measures such as early EPR adoption, landfill restrictions, and clear recovery targets before e-waste volumes stress existing infrastructure. Moreover, aligning this proactive roadmap with circular economy principles and industry capacity-building will allow Aotearoa New Zealand to avoid the reactive challenges faced by early adopters and establish a resilient, scalable recycling system.

5. Discussion

The projected trajectories reveal that Aotearoa New Zealand faces an impending surge in renewable energy waste, with material flows concentrated in high-value metals and bulk recyclables. The material composition of renewable energy technologies dominated by recoverable metals such as aluminium, copper, and steel offers a strong basis for local value creation. Research by Suyanto et al. (2023) and others has shown that these materials can support robust secondary markets while simultaneously reducing reliance on imports and mitigating landfill dependency. Moreover, disaggregated analysis of component recoverability confirms that while high-volume metals are technically and economically feasible to reclaim, materials such as polymers, silicon, and rare earth elements present significant challenges. These complexities reinforce the case for a phased approach: prioritizing bulk recoverables initially while supporting innovation to unlock more advanced processing solutions in the long term.

More recent work by Deng et al. (2024) demonstrates that aluminium alone could yield between NZ$ 5.1 and 8.5 billion in recoverable value, with copper and steel contributing additional financial returns. However, capital investment requirements are substantial, and viability is highly dependent on scale. A full recovery facility, for instance, would require an annual input of 4,000 tonnes and upwards of NZ$ 19 million in capital. These figures suggest that while economic potential is high, realizing it will require coordinated public and private investment, as well as supportive policy instruments such as landfill levies and producer contributions.

Moreover, the timing of this waste growth presents a strategic window for Aotearoa New Zealand. In contrast to the European Union and Australia, where policy responses often lagged behind waste accumulation, Aotearoa New Zealand has the opportunity to design and implement regulatory mechanisms ahead of the projected surge. Comparative timeline analysis shows that the EU's first major wave of solar and wind waste occurred in the 2020s, with Australia's projected in the 2030s. Aotearoa New Zealand, by contrast, will not see peak volumes until the 2050s and beyond. This temporal advantage allows for the deliberate planning of recycling infrastructure, regulatory frameworks, and workforce development programs. Continued reliance on offshore processing will likely become less viable as international regulatory frameworks tighten and the costs of transporting end-of-life materials rise (Ilankoon et al., 2021).

Policy lessons from other countries provide a robust foundation for this. The European Union, through the WEEE Directive, has implemented binding recovery targets mandating 85% material recovery and 80% recycling or reuse of photovoltaic waste. Additionally, the Waste Framework Directive embeds the waste hierarchy into law (see Figure 5), prioritizing prevention, reuse, and recycling before energy recovery or disposal. These principles are not merely theoretical; they have been shown to enhance recovery rates and improve participation from industry stakeholders (SolarPower Europe, 2024). Similarly, Australia's land lease regulations and upcoming national EPR scheme for PV panels demonstrate alternative mechanisms for assigning responsibility without formal producer organizations.

Furthermore, the integration of circular economy design principles into product standards is gaining momentum globally. Research by the Clean Energy Council (2023) highlights innovations such as Siemens Gamesa's RecyclableBlade and Vestas' chemical disassembly pilots as promising examples of design-for-recyclability. While such technologies are still nascent, they offer a critical pathway for addressing difficult-to-recycle components such as thermoset composites in wind blades. Encouraging the adoption of these innovations through eco-design regulations could reduce lifecycle emissions, improve recovery rates, and delay obsolescence.

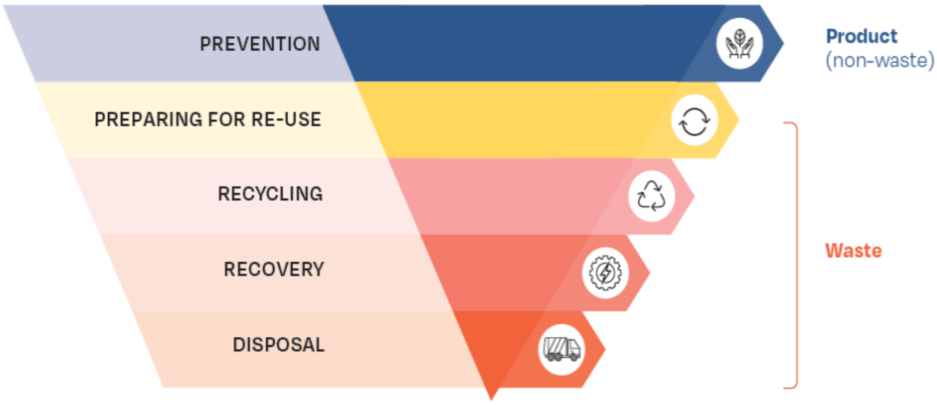

Figure 5. Waste hierarchy for end-of-life management of solar and wind technologies
(Source: SolarPower Europe, 2024:13)

Finally, the establishment of shared solar and wind waste recycling facilities could leverage economies of scale and overlapping retirement curves, particularly if underpinned by policies such as extended producer responsibility, phased regulatory timelines, and infrastructure co-investment. Research by Xu et al. (2018) and IRENA & IEA-PVPS (2016) suggests that combining EPR with public financing and market-based incentives can catalyze private sector participation and help overcome early-stage cost barriers.

The material and economic analyses underscore the need for a multi-dimensional strategy that aligns policy, investment, and design innovation. Aotearoa New Zealand is uniquely positioned to lead on this front. By learning from international precedents and acting ahead of its own e-waste curve, the country can develop a resilient, circular renewable energy e-waste management system that delivers environmental, economic, and social benefits.

Recycling end-of-life solar and wind infrastructure is not only a waste management issue; it is a climate and economic opportunity. Proper recovery reduces emissions associated with primary material extraction, conserves resources, and minimises landfill dependency. It also supports broader circular economy goals by reintegrating valuable materials into supply chains.

In Aotearoa New Zealand's renewable energy and climate ambitions, these practices strengthen the country's commitment to sustainable development. They also enhance energy sovereignty by reducing dependence on imported materials and create new avenues for green employment. As international markets increasingly reward circularity and carbon transparency, the ability to demonstrate full lifecycle management of clean technologies will become a strategic advantage.

6. Conclusion and recommendations

This section draws together the study's key insights and charts a path forward for Aotearoa New Zealand's end-of-life management of solar and wind infrastructure by presenting the main outcomes, examining the study's limitations, offering targeted recommendations for policy, infrastructure and workforce development, and identifying areas for future research.

6.1. Main outcomes

This study has demonstrated that Aotearoa New Zealand is approaching a critical juncture in its clean energy transition, where the environmental and economic implications of end-of-life (EoL) solar and wind infrastructure should be addressed through coordinated planning and policy action. The research offers the first estimate of renewable energy waste volumes in the country, projecting a cumulative total of approximately 1.68 million tonnes by 2080. These findings underscore the scale of the challenge, as well as the urgency of integrating EoL waste strategies into national energy planning.

By combining quantitative modelling of waste generation with a detailed assessment of material composition and recoverability, the study has established a strong technical foundation for informed decision-making. High-value materials such as aluminium, copper, and steel, which are present in both solar and wind systems, were identified as key materials for economic recovery, with an estimated potential value of up to NZ$ $11.8 billion. These materials represent a compelling opportunity to support domestic resource security and green economic development.

The analysis also explored the policy and infrastructure conditions required to realise this potential. Drawing on international case studies from the European Union and Australia, the research identified practical, transferable strategies that could be adapted to Aotearoa New Zealand's unique market size and geographic context. In particular, extended producer responsibility (EPR) schemes, regional recycling hubs, and regulatory targets emerged as critical enablers of system-level change.

Through this integrated approach, the study provides a viable roadmap that balances technical feasibility with policy innovation. It shows that the effective management of waste from solar and wind technologies is not only achievable, but essential to ensuring that the renewable energy transition aligns with the principles of sustainability, circularity, and long-term resilience. By acting early, Aotearoa New Zealand could lead by example in the responsible stewardship of renewable energy technologies.

6.2. Limitations

This study has several limitations including:

- Logistics and operational factors were not incorporated, such as transportation costs, waste-collection challenges, and cross-regional recycling dynamics, which may lead to over- or underestimation of implementation expenses.
- Economic projections were derived from Australian cost data converted at a fixed rate (1 AUD = 1.07 NZD), potentially misrepresenting country-specific labour rates, regulatory fees, and currency fluctuations.
- The cost-benefit assessment focused exclusively on aluminium, silicon, copper, and glass, omitting other valuable or hazardous materials such as rare earth elements, carbon-fibre composites, and fluoropolymers, owing to insufficient data, thereby narrowing the scope of resource recovery.
- Recovery rates were held constant throughout the projection period, without accounting for anticipated technological advances, policy reforms, or process-efficiency improvements that could alter long-term material-yield estimates.
- The analysis omitted the time value of money, which may overstate economic returns for materials reaching end-of-life in the 2060s and beyond.
- The assumed feasibility of an integrated solar–wind recycling facility depends on the future development of coordinated supply chains, stakeholder collaboration,

and enabling policy frameworks, none of which currently exist in Aotearoa New Zealand.

These limitations underscore the importance of conducting further region-specific studies, collaborating with industry partners, and launching pilot projects to confirm the practicality of the suggested recycling strategies under real-world conditions.

6.3. Recommendations

To ensure that Aotearoa New Zealand manages the emerging waste from solar and wind infrastructure responsibly and sustainably, a coordinated and forward-looking strategy is required. Firstly, introducing a national extended producer responsibility (EPR) scheme would be foundational in embedding accountability across the renewable energy supply chain. Moreover, embedding the waste hierarchy into that scheme so that prevention, reuse, and recycling are legislated as priorities before recovery and disposal will align New Zealand's regulatory framework with circular economy principles.

Secondly, sector-specific recovery targets should be legislated for photovoltaic modules and wind turbines (for example, an 85 % material-recovery and 80 % recycling or reuse threshold). Research by SolarPower Europe (2024) and the EEA (2024) demonstrates that such targets drive both infrastructure investment and industry participation. Additionally, aggregating waste streams from solar and wind installations will help achieve the minimum throughput needed estimated at 4,000 tonnes per annum for full-scale feasibility thus overcoming the scale limitations of New Zealand's smaller market (Deng et al., 2024).

Parallel to these policy reforms, there is a critical need to invest in local infrastructure capable of handling projected volumes of recyclable material. More recent work by Shrestha and Zaman (2024) suggests that regional recycling hubs in both the North and South Islands should be sited near freight corridors and generation centres to reduce transport burdens and improve access for remote or smaller-scale installations. Such hubs would initially prioritise high-value, technically accessible streams (aluminium, copper, steel), while leaving room for future expansion into complex fractions like silicon, rare earths, and composite turbine blades.

Furthermore, workforce development is essential. Recycling processes are labour-intensive, and research by Macher and Szigeti (2024) shows that upskilling technicians in dismantling, material separation, and advanced recycling techniques not only improves operational efficiency but generates local employment in engineering and materials recovery sectors.

Finally, policy measures such as phased landfill restrictions on recoverable components, targeted financial incentives (grants, tax credits), and public–private partnerships can help shift the economics of recycling. Embedding renewable energy waste within broader climate and energy strategies will also ensure alignment with national emissions-reduction goals and sustainability commitments.

In conclusion, further research should investigate advanced processing for rare earths and composites, model optimal facility locations and material flows, and evaluate the long-term environmental benefits of circular practices. Such work will strengthen the evidence base for decision-making and help position Aotearoa New Zealand as a regional leader in responsible clean energy deployment.

References

Artaş SB, Kocaman E, Bilgiç HH, Tutumlu H, Yağlı H, Yumrutaş R, 2023. Why PV panels must be recycled at the end of their economic life span? A case study on recycling together with the global situation. Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers, Part B, 174, 63–78, doi:10.1016/j.psep.2023.03.053.

Blake V, Farrelly T, Hannon J, 2019. Is voluntary product stewardship for e-waste working in New Zealand? A Whangarei case study. Sustainability, 11(11), 3063, doi:10.3390/su11113063.

Chowdhury MS, Rahman KS, Chowdhury T, Nuthammachot N, Techato K, Akhtaruzzaman M, Tiong SK, Sopian K, Amin N, 2020. An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews, 27, 100431, doi:10.1016/j.esr.2019.100431.

Clean Energy Council, 2023. End-of-life management for solar and wind systems. Accessed 2 August 2025 from: https://cleanenergycouncil.org.au.

Deng R, Tan V, Niu C, Egan R, 2024. Scoping study: Solar panel end-of-life management in Australia. Australian Centre for Advanced Photovoltaics, University of New South Wales, Sydney, accessed 2 August 2025 from: https://apvi.org.au/scoping-study-solar-panel-end-of-life-management-in-australia/.

EECA, no date. Solar energy. Energy Efficiency and Conservation Authority, Wellington, accessed 3 August 2025 from:
Available at: https://www.eeca.govt.nz/insights/energy-in-new-zealand/renewable-energy/solar/.

Electricity Authority and Concept Consulting, no date. Generation Investment Pipeline: Proposed Utility-Scale Solar PV Capacity (2024–2029) [Dataset]. Electricity Authority and Concept Consulting, Wellington, accessed 4 June 2025 from: https://www.emi.ea.govt.nz/Wholesale/Datasets/Generation/GenerationFleet/Proposed.

European Commission Joint Research Centre, 2022. Wind energy circularity challenges. Publications Office of the European Union, Luxembourg, accessed 3 August 2025 from: https://setis.ec.europa.eu/document/download/6dfe5811-a603-42da-8298-2cc636ae1579_en?filename=JRC131723_wind_energy_circularity_challenges_v7.pdf.

European Environment Agency, 2024. Recycling from green technology. European Environment Agency, Copenhagen, accessed 3 August 2025 from : https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/recycling-from-green-technology.

Heath GA, Silverman TJ, Kempe M, Deceglie M, Ravikumar D, Remo T, Wade A, 2020. Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nature Energy, 5(7), 502–510, doi:10.1038/s41560-020-0645-2.

IEA-PVPS, 2022. End-of-life management of photovoltaic panels: Trends in PV module recycling technologies. International Energy Agency – Photovoltaic Power Systems Programme, Paris, accessed 3 August 2025 from: https://iea-pvps.org/key-topics/end-of-life-management-of-photovoltaic-panels-trends-in-pv-module-recycling-technologies-by-task-12/.

Ilankoon IMSK, Ghorbani Y, Chong MN, Herath G, Moyo T, Petersen J, 2021. E-waste recycling and resource recovery: A review on sustainability and circular economy. Metals, 11(8), 1313, doi:10.3390/met11081313.

International Energy Agency, 2024a. Renewables 2024: Analysis and forecast to 2030. International Energy Agency, Paris, accessed 3 August 2025 from: https://www.iea.org/reports/renewables-2024.
International Energy Agency, 2024b. World Energy Outlook 2024. International Energy Agency, Paris, accessed 3 August 2025 from: https://www.iea.org/weo.
International Renewable Energy Agency (IRENA) and IEA-PVPS, 2016. End-of-life management: Solar photovoltaic panels. Accessed 14 July 2025 from: https://www.irena.org/publications.
Latunussa CEL, Ardente F, Blengini GA, Mancini L, 2016. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Solar Energy Materials and Solar Cells, 156, 101–111, doi:10.1016/j.solmat.2016.03.020.
Liu P, Barlow CY, 2017. Wind turbine blade waste in 2050. Waste Management, 62, 229–240, doi:10.1016/j.wasman.2017.02.007.
Macher GZ, Szigeti C, 2024. The role of the circular economy in the labour market and employment rate in the European Union. University of Maribor, doi:10.18690/um.epf.5.2024.31.
Ministry of Business, Innovation and Employment (MBIE), 2023. Energy in New Zealand 2023. Wellington, accessed 14 July 2025 from: https://www.mbie.govt.nz.
MinterEllisonRuddWatts, 2024. Government moves to streamline consenting for renewable energy. Wellington, accessed 3 August 2025 from: https://www.minterellison.co.nz/insights/government-moves-to-streamline-consenting-for-renewable-energy.
Mousavian S, Mahmoudi S, Behnia M, 2023. The influence of circular economy in renewable energy systems: EoL solar module management. In: Fathi F, Zio E, Pardalos PM (Edss): Handbook of Smart Energy Systems. Springer, Cham, doi:10.1007/978-3-030-97940-9_103.
Nain P, Kumar A, 2020. Initial metal contents and leaching rate constants of metals leached from end-of-life solar photovoltaic waste: An integrative literature review and analysis. Renewable and Sustainable Energy Reviews, 119, 109592, doi:10.1016/j.rser.2019.109592.
National Institute of Water and Atmospheric Research, no date. Nowcasting and short-to-medium-range forecasting for solar and wind energy. NIWA, Wellington, accessed 28 May 2025 from: https://niwa.co.nz/climate-and-weather/nowcasting-and-short medium-range-forecasting-solar-and-wind-energy.
National Renewable Energy Laboratory, 2023. Materials used in U.S. wind energy technologies. National Renewable Energy Laboratory, Golden, Colorado, accessed 3 August 2025 from: https://www.nrel.gov/docs/fy23osti/81483.pdf.
New Zealand Wind Energy Association, 2023, Wind energy in New Zealand. Wellington, accessed 3 August 2025 from: https://www.windenergy.org.nz/.
New Zealand Wind Energy Association, no date. Operating onshore windfarm projects. Wellington, accessed 4 June 2025 from: https://www.windenergy.org.nz/onshore-wind/operating-onshore-windfarm-projects/.
Pimentel Pincelli I, Brent AC, Hinkley JT, Sutherland R, 2025. Scaling up solar and wind electricity: Empirical modelling and a disruptive scenario for their deployments in Aotearoa New Zealand. Journal of the Royal Society of New Zealand, 55(4), 775–797, doi:10.1080/03036758.2024.2381750.
Shrestha N, Zaman A, 2024. Decommissioning and recycling of end-of-life photovoltaic solar modules in Western Australia. Sustainability, 16(2), 526, doi:10.3390/su16020526.

SolarPower Europe, 2024. End-of-life management best practice guidelines for solar PV systems (Version 1.0). Brussels, accessed 3 August 2025 from: https://solarbestpractices.com/guidelines/detail/foreword-5.
Sustainability Victoria, 2021. PV panel product stewardship and recycling: Scoping study report. Melbourne, accessed 3 August 2025 from: https://assets.sustainability.vic.gov.au/susvic/Report-Waste-PV-system-materials-flow-analysis-public.pdf.
Suyanto ER, Sofi M, Lumantarna E, Aye L, 2023. Comparison of waste photovoltaic panel processing alternatives in Australia. Journal of Cleaner Production, 418, 138128, doi:10.1016/j.jclepro.2023.138128.
Transpower, 2022. Integrated Report FY22. Wellington, accessed 3 August 2025 from: https://www.transpower.co.nz/publications/integrated-report-fy22.
Trypolska G, Kurbatova T, Prokopenko O, Howaniec H, Klapkiv Y, 2022. Wind and solar power plant end-of-life equipment: Prospects for management in Ukraine. Energies, 15(5), 1662, doi:10.3390/en15051662.
Waste Management and Resource Recovery Association of Australia (WMRR), 2024. National PV product stewardship roadmap. Accessed 14 July 2025 from: https://www.wmrr.asn.au.
Parliamentary Counsel Office, 2008. Waste Minimisation Act 2008. Public Act 89, Wellington, accessed 3 August 2025 from: https://www.legislation.govt.nz/act/public/2008/0089/latest/DLM999802.html.
WindEurope, Cefic and EuCIA, 2020. Accelerating wind turbine blade circularity. Brussels, accessed 3 August 2025 from: https://windeurope.org/intelligence-platform/product/accelerating-wind-turbine-blade-circularity/.
Xu M, Yang J, Ji H, Wu Y, Li J, Di J, Meng X, Jiang H, Lu Q, 2024. Recovering high-quality glass fibers from end-of-life wind turbine blades through swelling-assisted low-temperature pyrolysis. Waste Management, 187, doi:10.1016/j.wasman.2024.07.020.
Xu Y, Li J, Tan Q, Peters AL, Yang C, 2018. Global status of recycling waste solar modules: A review. Waste Management, 75, 450–458, doi: 10.1016/j.wasman.2018.01.036.