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SOLAR AND WIND ENERGY IN CANADA
VALUE RECOVERY AND END-OF-LIFE CONSIDERATIONS

PART 3.
Policy options to minimize waste generation and encourage value recovery and circularity of materials

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A Policy Brief Summary, and two other working papers with more details on the findings in this research project are available at www.institute.smartprosperity.ca:

Policy Brief: *Solar and Wind Energy in Canada – Value Recovery and End-of life Considerations*

Working Paper 1: *Solar and Wind Energy in Canada – Value Recovery and End-of life Considerations: Material needs and end-of-life resource flow implications under Canada's climate change objectives, and data gaps.*

Working Paper 2: *Solar and Wind Energy in Canada – Value Recovery and End-of life Considerations: Pathways to reduce resource consumption, extend the life of products and recover value, and associated Canadian capacity*

About Smart Prosperity Institute

Smart Prosperity Institute is a national research network and policy think tank based at the University of Ottawa. We deliver world-class research and work with public and private partners – all to advance practical policies and market solutions for a stronger, cleaner economy.

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Foreword

The global transition to a low-carbon future is expected to have a profound effect on primary material demand and will also change the waste profile of the energy sector. Low-carbon energy technologies have a larger material requirement per unit of energy generation (t/MW) relative to fossil-fuel-based counterparts. Thus, as global ambition on climate action ramps up, there is bound to be a rapid increase in material demand, including demand for several strategically critical minerals and metals.[1]

While there is a growing body of research into potential supply constraints for key minerals and metals for low carbon energy technologies,[2] work on green industrial policy has paid less attention to managing the end-of-life implications of the large-scale transition to these new technologies. It has only begun to look into the potential role of circular economy strategies to reduce material intensity of low-carbon energy technologies, minimizing waste along technology life cycles, and recover value at end of life.

In Canada's transition to a low-carbon economy, it is important that the flow of material in renewable energy technologies be managed sustainably and in an environmentally sound manner. Circular policies will likely be needed to close and extend the related material loops so different components of these technologies are re-used or remanufactured, end-of-use material and scrap is recycled to the greatest extend possible to maximize retained value and minimize waste, and any remaining residual waste is disposed of safely.

The objective of this project is to use the example of solar PV and wind technologies to explore emerging waste management considerations and opportunities for value recovery associated with Canada's commitment to transition to a low carbon economy, with the dual goals of:

- Identifying potential strategic industrial opportunities and challenges related to the management of and innovation around anticipated resources and material flows involved in a transition to a low carbon economy; and
- Identifying policy approaches that support circularity to minimize waste and support sustainable material management in a transition to a low carbon future

Note, other non-fossil fuel solutions important to Canada's low-carbon transition (e.g. hydro, run-of-river, geothermal, bio-based fuels, etc.) are not included.

The research included a review of literature and policy experience and interviews with selected experts. Furthermore, the project has also developed a model to estimate potential magnitudes of future end-of-life material volumes and content stemming from Canadian installed wind and solar energy sources to 2050, and to assess preliminary scenarios with factors that may affect this end-of-life material generation potential.[*] This drew on installed capacity projections from the 'Evolving Scenario' of Canada Energy Regulator (CER)'s Canada's Energy Future 2020 report,[3] with methodologies to project solar PV waste developed by IRENA[4] and Santos et.al.[5] The findings presented have two major limitations. First, the CER's 'Evolving Scenario' of installed capacity is not a scenario for net zero emissions in 2050. Second, due to numerous data gaps and uncertainties, this first effort at a Canadian forecast should be interpreted as illustrative in scope, not in detail.

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[*] The modelling approach developed for this project uses data on installed capacity for solar PV and wind from the "Evolving Scenario" of the Canada Energy Regulator (CER)'s report on *Canada Energy Future 2020*, and includes estimates of waste generation for both "Regular Loss" and "Early Loss" scenarios to capture different rates of component failure for installed solar energy capacity. More details on scenario assumptions, and model limitations, are included in Section 4 and Appendices to Part 1.

The findings from these related streams of work are presented in three parts (listed below), with part 3 presented in the document which follows:

Part 1: Material, resource, and waste generation implications for wind and solar energy sources under Canada’s climate change objectives, and associated data gaps;
Part 2: Pathways for waste minimization, product life extension or value recovery, and associated Canadian capacity; and
Part 3: Policy options to minimize waste generation and encourage circularity of materials.

1. Introduction

Non-hydro renewables are relatively new in the Canadian energy landscape, proliferating only during the past two decades, and due to their long lifespans are only now reaching end-of-life at sufficient scale to bring attention to their emerging waste streams. The vast majority of installations are still a decade away from end-of-life. Modelling for this study suggests that annual end-of-life solar PV waste is projected to grow exponentially post 2025, from 2,700 tonnes today to 9,000 tonnes/year by 2030 and 13,500 tonnes/year by 2035.[†] Similarly, annual end-of-life wind waste is projected to reach 161,000 tonnes/year by 2035 - a 571 % increase from a 2020 baseline of approximately 24,000 tonnes.

Canada therefore has a modest lead time to develop and implement strategies, capacity, and the required policies and regulatory frameworks to minimize waste generation and encourage circularity of materials for these two non-hydro renewables. In doing so, we can learn from the experiences of other jurisdictions with a lead in introducing policies to reduce and manage the end-of-life materials generated from renewable energy technologies; while also undertaking new research to fill knowledge gaps, putting in place data collection, and planning for future infrastructure requirements -- to develop our own policies.

Part 3 of this research provides an overview of policy options to support this. It first summarizes current and proposed policies, in other jurisdictions and in Canada, and their potential to enhance circularity and minimize waste. Then, building on evidence gathered to this point of our research, it proposes objectives for public policies to support the circularity of materials used in renewable energy technologies in Canada. A menu of potential policy instruments is listed, but deliberately stops short of recommending specific policy instruments for Canada, as this seems premature in light of crucial data gaps, further technical assessment, and stakeholder input. To guide policy timing, the report then discusses some temporal and volume threshold considerations. Finally, it lays out additional research needs to build further evidence for more effective policy making. The report concludes with a summary of findings.

2. Global Policy Review

2.1. Solar PV

In most countries worldwide, solar PV is still classified as general or industrial waste. Specific solar PV waste regulations are present in only a few jurisdictions. However, with the rapidly increasing global installed capacity of solar power, many jurisdictions are now beginning to consider, research and propose regulations to deal with the end-of-life materials generated by solar PV. This section reviews policies in the European Union, Japan, the United States, and Canada.

European Union

The European Union (EU) is currently the only global jurisdiction with regional and national waste regulations that specifically apply to solar PV. With the first significant installations of solar energy taking place in the early 1990's, by the early 2000's solar PV waste became a growing concern. Solar panel manufacturers started to devise PV life cycle management initiatives, a prominent example being the pan-

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[†] See Part 1 for assumptions and scenarios

European PV CYCLE initiative. However, with increasing global supply chains, pan-Europe voluntary initiatives were challenging to implement. This prompted Europe to adopt a regulatory approach to solar PV waste management, revising their Waste Electrical and Electronic Equipment (WEEE) Directive in 2012.[6]

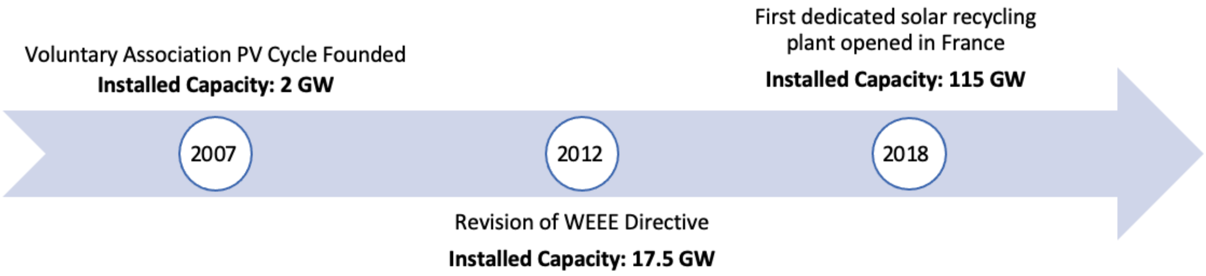

Figure 1: Timeline of EU's solar PV waste management initiatives.

The revised WEEE Directive which came into implementation in 2014 placed the principle of extended producer responsibility (EPR) at its core. Under this directive, all producers (regardless of location of manufacturing) selling solar PV in the EU are liable for the costs of collecting, treating and monitoring of the ensuing waste. Their responsibilities include:[7]

- **Financing responsibility**: Producers are liable through a financial guarantee to cover the cost of collecting and recycling of products by financing public collection points and first-level treatment facilities. They also need to either become a member of a collective compliance scheme or develop an individual scheme.

- **Reporting responsibility**: Producers are obliged to report monthly or annually on panels sold, taken back (through individual or collective compliance schemes) and forwarded for treatment. They must also report on the results from the waste treatment of products (tonnes treated, recovered, recycled, and disposed of by fraction, e.g., glass, mixed plastic waste, metals).

- **Information responsibility**: Producers are accountable for labeling panels in compliance with the WEEE Directive. They must inform buyers that the panels have to be disposed of in dedicated collection facilities and should not be mixed with general waste, and that takeback and recycling are free. They are also responsible for informing buyers of their PV panel end-of-life procedures. Lastly, producers are required to give information to waste treatment companies on how to handle PV panels during collection, storage, dismantling and treatment. This information contains specifics on hazardous material content and potential occupational risks as well as electrocution risks when handling panels exposed to light.

To ensure compliance, the WEEE Directive set firm targets for collection, recovery and recycling that have increased over the years (Table 1). The collection target has risen from 45% (by weight) of equipment put on the market in 2016 to 65% of equipment put on the market or 85% of waste generated from 2018.

Meanwhile, the recovery[‡] and recycling[§] targets have risen from 75% recovery/65% recycling in 2016 to 85% recovery/80% recycling from 2018 onwards.[8] This along with supplementary standard and technical specification for PV panel collection and treatment released in 2017[9], has resulted in the implementation of a high-value recycling processes[**] in the EU.

Table 1: WEEE Collection, Recovery and Recycling Targets.

	2012-2015	2015-2018	2018 onwards
Annual Collection Target	At least 4 kg / inhabitant of WEEE **OR** the average amount of WEEE collected in the three preceding years	45% of EEE put on the market	65% of EEE put on the market, **OR** 85% of WEEE generated
Annual Recycling Target	65%	70%	80% for reuse and recycling
Annual Recovering Target	75%	80%	85%

In addition, the revised WEEE Directive also put in place specific measures to prevent illegal shipments of panels and new obligations for trade. These measures include the requirement for every load (e.g., shipping container, lorry) to provide documentation that proves that it is carrying used EEE and not WEEE, in the absence of which authorities consider the shipment illegal.

The revised WEEE Directive applies to all 28 EU member states and their wider economic area but allows member states to make adjustments when they transpose the directive into their legislation. This has posed some challenges for producers because member states have implemented slightly varying definitions of EPR.[10] For example, solar PV is classified under different waste streams by various member countries, such as 'waste from private households' in France versus 'waste from other users than private households' in the UK.

These differing definitions have implications for collection and recycling financing as well as waste responsibilities. The WEEE Directive allows for two financing approaches depending on the end use (private household or not) of the product:[11]

- Private households (B2C transactions): Where the end user is a private household, the producer cannot enter into a contractual arrangement with the customer on financing. Here producer pay-

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[‡] Recovery is defined as any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy.

[§] Recycling is defined as any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations

[**] High-value recycling ensure that potentially harmful substances (e.g., lead, cadmium, selenium) will be removed and contained during treatment; rare materials (e.g., silver, tellurium, indium) will be recovered and made available for future use; materials with high embedded energy value (e.g. silicon, glass) will be recycled; recycling processes will consider the quality of recovered material (e.g. glass).

as-you-go (PAYG) approaches[††] combined with last-man-standing insurance[‡‡] and joint-and-several liability producer schemes[§§] are considered more efficient and viable.

- Non-private households (B2B transactions): In B2B transactions, both customer and producer may be capable of collecting and recycling end-of-life e-waste. In this case the customer can use project cash flows, hire the original producer or hire a professional third party to recycle. Here a regulatory framework ensuring collection and recycling to common standards for all industry players and allowing contractual arrangements between producer and customer for financing end-of-life obligations is considered most effective.

In addition to the WEEE Directive, other EU regulations relevant for PV modules and the end-of-life treatment are summarised in Table 2.

Table 2: EU Regulations relevant for End-of-life treatment PV modules

Regulation	Description
European Waste Framework Directive 2008/98/E (WFD)[12]	The key legislative document on waste at the EU level. This directive specifies properties that render waste hazardous and provides information about handling waste and end-of-waste criteria. Reference modules plus their defined waste streams are assessed according to the requirements of the WFD.
Commission Decision 2000/532/EC **List of Waste (LoW)**[13]	The key document for the assessment of hazardous properties and the classification of waste. Full and compliant classification enables businesses and competent authorities to determine if waste is classified as hazardous or not.
Persistent Organic Pollutant (POP) Regulation[14]	Aimed at protecting the environment and human health from persistent organic pollutants. The hazardous classification is based on the relevant threshold listed in the Annex of the POP Regulation but lists none of the substances used in PV modules.
Restriction of Hazardous Substances Directive (ROHS)[15]	Closely linked to the WEEE Directive, lays down rules on the restriction of the use of hazardous substances in EEE with a view to contributing to the protection of human health and the environment, including the environmentally sound recovery and disposal of EEE waste. The use of hazardous substances in photovoltaic modules intended to be used in systems that are designed, assembled, and installed by professionals for permanent use at defined locations to produce energy from solar light for public, commercial, industrial, and residential applications are not (yet) in the scope of this Directive.
The Battery Directive[16]	Covers the handling of batteries, accumulators, waste batteries, and waste accumulators. Applies to the decommissioning a PV plant if batteries are used as energy storage systems.
Eco-Design Directive [17]	A framework for the setting of eco-design requirements for energy related products. This Directive obliges the supplier or the manufacturer to assess possibilities for reuse, recycling, and recovery of materials or energy. The supplier has to provide information about treatment facilities concerning disassembly, recycling, or disposal at the end-of-life. A similar regulation may be developed for PV modules in the future.

[††] Pay-as-you-go (PAYG): Cost of collection and recycling is borne by the producer.

[‡‡] Last-man-standing insurance: Covers the costs of collection and recycling if all producers disappear from the market by the time the product's end of life is reached.

[§§] Joint-and-several liability: Producers agree to jointly accept the liabilities for waste collection and recycling.

Product Environmental Footprint (PEF)[18]	A harmonized methodological approach to assess, display, and benchmark the environmental performance of products, services, and companies by doing an assessment of the environmental impacts over the life cycle. The life- cycle approach includes resource extraction and preprocessing, design, manufacturing, and retail, distribution, use, collection and reuse, recycling, energy recovery and disposal.

Japan

Japan does not currently have specific regulations on the end-of-life management of solar PV; this falls under the general regulatory framework for waste management (the Waste Management and Public Cleansing Act). However, PV panels integrated with building material could be subject to their Construction Waste Recycling Law, which prescribes how to manage construction and decommissioning waste and requires recovery and recycling of concrete, wood and construction materials.[19]

The Japanese Government has been looking into end-of-life management for renewable energy equipment such as PV, solar water heaters and wind turbines. In 2015, it released a roadmap for collection, recycling and proper treatment, which highlighted technology R&D, environmentally friendly designs, and guidelines for dismantling, transportation, and treatment.[20] In 2016, it published guidelines for promoting proper end-of-life treatment, including recycling.[21] It is expected that this will lead to further policies on end-of-life management of solar PV.

United States

The United States does not currently have any federal laws or regulations on the end-of-life management of solar PV. Where there are no specific regulations on PV modules in a state, solar PV is governed by the federal Resource Conservation and Recovery Act (RCRA), the legal framework for managing all hazardous and non-hazardous solid waste. Under this Act, solar PV is evaluated using the characteristic hazardous waste method (Toxic Characteristic Leaching Procedure (TCLP) test) to determine if they exceed the regulatory levels of hazardous waste. They are then classified as hazardous or non-hazardous, depending on the materials in the used module and the test methods. In most cases, they are deemed hazardous and as a result, cannot be disposed of in landfills.[22]

At the subnational level, some US States have recently developed or are in the process of developing regulations for the end-of-life management of solar PV. These regulations must at a minimum meet the RCRA requirements. Interestingly, the presence of these regulations does not always correlate with the installed PV capacity in the state. For instance, Illinois is not featured in the top 10 states by installed capacity but started a Solar Module Recycling Initiative in 2017. Similarly, Minnesota which also does not have a high installed capacity set up, a Solar Module Recycling Strategy Working Group in 2019. On the other hand, states like California and New York which have the 1st and 9th highest installed capacity respectively are still in the process of developing regulations.[23]

Of particular note is the State of Washington, which in 2017 passed a bill to promote a sustainable, local renewable energy industry. This bill created the Photovoltaic Module Stewardship and Takeback Program, which requires manufacturers of solar PV to provide the public a convenient and environmentally sound way to recycle all modules purchased after July 1, 2017. Under this program manufacturers must finance the takeback and recycling system at no cost to the PV module owner. A product stewardship organization may act on behalf of a manufacturer or group of manufacturers to operate and implement the stewardship program.[24] In 2019, the State released further guidance for manufacturers which:[25]

- Defines PV modules covered in the program to include those directly connected to the grid or utility service;
- Directs each manufacturer to submit a recycling plan by July 1, 2022; and
- Requires that no manufacturer, distributor, retailer, or installer may sell, or offer for sale, a PV module for which a recycling plan has not been approved, beginning July 1, 2023.

In addition, the United States has several voluntary collection and recycling initiatives. For instance, the company First Solar operates a commercial-scale recycling facility with a daily capacity of 30 t in Ohio for its own CdTe solar panels. First Solar is able to recover over 90 % of the semiconductor and 90 % of the glass from end-of-life panels. The glass cullet is reused in new glass products and the unrefined semiconductor material is sent for further processing to be reused in new First Solar modules.[26] In 2018, Recycle PV opened the first dedicated solar panel recycling facility in the USA.[27]

Canada

Canada does not have any specific end-of-life solar PV regulations; PV modules are regulated by common waste legislation. Solar PV is neither classified as hazardous waste nor electronic waste (e-waste) in any province or territory. This is likely due to the still relatively small volumes of panels reaching end-of-life, as well as the fact that the majority of solar PV historically installed in Canada used first-generation technologies which do not contain hazardous materials; and private take-back schemes offer voluntary end-of-life management for second-generation thin-film PVs. In provinces like British Columbia and Quebec where solar PV is largely used in the residential sector, they are considered construction waste.[28] Solar PV is also not included in any provincial and territorial EPR programmes, nor in the 2009 Canada-wide Action Plan for Extended Producer Responsibility, adopted by the Canadian Council of Ministers of the Environment (CCME).[29]

Box 1: Hazardous materials in second generation thin-film solar PV

Hazardous materials in second generation thin-film solar PV

Second generation thin-film solar PV contain toxic chemicals such as cadmium telluride, copper indium selenide, cadmium gallium (di)selenide, copper indium gallium (di)selenide, hexafluoroethane, lead, and polyvinyl fluoride. As these become more widely adopted in Canada, it may become necessary to designate these panels as hazardous waste.

Currently, end-of-life solar PV in Canada are either being landfilled, stockpiled awaiting recycling systems, or voluntarily collected and shipped to recycling facilities in the USA.[30] First Solar which owns solar farms in Ontario has recycled over 2,000 metric tonnes of end-of-life PV modules from Canadian installations in their recycling facility in Perrysburg, Ohio.[31]

The growing stream of solar PV waste has led some provinces to begin examining end-of-life management options. In 2020, the Government of Alberta approved a two-year $43 million pilot project, which will allow the Alberta Recycling Management Authority (ARMA) to use reserve funds to recycle up to 24,600 tonnes of electronic products, that were not accepted previously in the program, including solar panels. Under this pilot, municipalities will receive funding for collecting the additional electronics included in the recycling expansion.[32]

That same year, the a policy intentions paper published by the B.C. Ministry of Environment and Climate Change Strategy acknowledged that while solar panels are recyclable, "producers need to establish collection and recycling programs for homeowners and communities, particularly rural and remote, that otherwise will have limited options to divert from disposal", and asked for comments or suggestions on whether this product type should be included in the existing EPR program.[33] This was largely prompted by the B.C. Government's focus on reducing local government costs and shifting the burden of waste management away from taxpayers and Indigenous communities. Inclusion of solar panels received unanimous stakeholder support and in 2021, the government formally announced its intention to include solar panels in its Recycling Regulation and EPR strategy.[34]

2.2. Wind

To date there is little legislation and regulation of end-of-life wind turbines globally. This may be because 85%-90% of a wind turbine's total mass can be recycled through existing industrial recycling facilities. Most of the mass that is not easily recycled comes from the turbine's rotor blades. As a result, regulation on wind turbine waste tends to focus on this component. However, with wind markets developing at different paces, regulations on blade waste are not aligned internationally. Section 2.2 reviews policies in the Europe (Germany, Netherlands, France), and Canada.

Europe

Unlike solar PV panels, wind turbine waste does not come under the ambit of the revised WEEE Directive, which explicitly excluded 'large-scale fixed installations', such as wind turbine stations (including their cabin, wings, equipment in tower, cranes) from its scope from 2018 onwards.[35]

However, some European nations have introduced regulations that have a bearing on wind turbine blade waste. For instance, in 2009, Germany banned direct landfilling of waste with an organic content higher than 5%. This ban is applicable to wind turbine blade waste which contains organic matter. In response to this regulation, a cement co-processing plant to handle large amounts of glass fiber-reinforced polymers waste has been set up. With a capacity of 30,000 tons/year, this plant currently uses around 15,000 tons of composite waste annually. Of this, 10,000 tons comes from wind turbine blades, processed at a gate fee of around 150 EUR/t.[36]

In 2017, Netherlands released the 3rd edition of its National Waste Management Plan which banned the landfilling of composite waste. However, it allows for exemptions where the cost of alternative treatment is higher than 200 EUR/t. In the Netherlands, the cost of mechanically recycling wind turbine blades ranges between 500-1,000 EUR/t including onsite pre-cutting, transport and processing. As a result, most wind farm operators can get this exemption and practice landfilling of wind turbine blades.[37]

In addition, some European countries have commissioned studies to understand wind turbine waste implications and explore policy recommendations for mitigation. In 2019, the German Government commissioned a study on wind turbine decommissioning and waste management. This report made recommendations for setting up an efficient dismantling system in Germany, and included specific elements of product responsibility including: [38]

- Information and labeling obligations regarding the material composition of the rotor blades;
- Separate processing with the aim of quality assurance of recyclates and substitute fuels;
- Obligation for high-quality recycling or guarantee of disposal safety;
- Inclusion of manufacturer's knowledge and processing technologies adapted to product related technological change; and
- Cause-related allocation of disposal costs and organizational obligations during disposal.

That same year, the French Government commissioned a study on wind turbine circularity. The report recommended introducing EPR for wind turbine blades. However, this was not done when the new law on circular economy was adopted in 2020, as it was deemed that joint efforts between authorities and the industry were more likely to be successful in increasing blade recycling.[39]

Canada

There are currently no specific end-of-life management regulations in place for decommissioned wind turbines.

In the case of off-shore wind turbines however, some international and regional agreements may apply.[40] For instance, the United Nations Convention on the Law of the Sea (UNCLoS) applies to offshore wind farms in Ontario. This agreement, ratified by Canada in 2003, states in regard to installations and structures that "*Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation, taking into account any generally accepted international standards established in this regard by the competent international organization. Such removal shall also have due regard to fishing, the protection of the marine environment and the rights and duties of other States. Appropriate publicity shall be given to the depth, position and dimensions of any installations or structures not entirely removed.*"

Decommissioning of wind farms is an expensive activity (ranging from between $30,000 to $80,000 per turbine[41]), the burden of which falls on the project developer. Where these are built on crown land, municipalities are at risk of having to fund eventual clean up if project developers go bankrupt during the long lifespan of the wind turbines. Recognizing that this risk can be mitigated if funds are set aside as part of the approval process, some authorities in Ontario and Alberta have begun requesting letters of credit or decommissioning bonds to be furnished by project developers.[42] Recently, the Alberta Utilities Commission also proposed a revision of its rules on 'Applications for Power Plants, Substations, Transmission Lines and ISDs' (Rule 007), which if approved will require an operator to demonstrate how sufficient funds will be available at the project's end-of-life to cover the cost of decommissioning and reclamation.[43] This does not, however, specify recovery nor how the decommissioning should be done.

3. Proposed Policy Objectives and Menu of Potential Policy Instruments

As governments at all levels introduce policies to increase the uptake of renewables, the eco-efficiency, value recovery opportunities and end-of-life considerations of this transition require parallel policy attention.

These approaches will support climate change as well as circular economy objectives:

- More eco-efficient material choices, product manufacturing and product design can decarbonize the material footprint of solar PVs and wind turbines;
- End-of-life solar PVs and wind turbines represent a valuable resource, containing substantial amounts of critical and strategic minerals essential for the transition towards a low carbon future and subject to potential supply bottlenecks in the near future. Value recovery of these critical minerals and metals can help to mitigate potential market shocks associated with their use;
- The useful life of solar PVs and wind turbines can be extended, and it can be easier to recover value recovery and close material loops, while diverting waste from landfills.

3.1. Proposed Policy Objectives

The technical, financial, and regulatory barriers outlined in Part 2 of this report establish the case for public policy action to support the circularity of materials used in solar PV and wind technologies. Such action should ultimately aim to reduce primary resource consumption, extend the life of renewable energy products and recover valuable materials at their end-of-life. This can help mitigate some of the unintended environmental consequences of technologies deployed for the transition to a low-carbon economy, as well as contribute to the circular economy transition.

To achieve those outcomes, five policy objectives are proposed:

i. **Divert waste from renewable energy technologies from landfill**: Based on the modelling conducted for this study, by 2030 between 4,000 and 10,000 tonnes of solar PV WEEE waste and approximately 160,000 tonnes of wind waste will be generated annually in Canada. In the absence of policy interventions, much of this will end up in landfill. Many landfills are already operating at or near capacity.[44] Finding sites for new landfills is a lengthy and contentious process and building and operating landfills is expensive. Hence public policy should focus on easing the pressure on landfills and make every effort to divert valuable waste from it.

ii. **Recover critical minerals and metals used in renewable energy technologies and support the creation of markets for the secondary materials**: Solar PV and wind turbines are material intensive. Solar panels contain nineteen mineral products and metals,[***] while wind turbines contain at least nine.[†††] Many of these are deemed to be critical, valuable, and with demand projected to escalate under low-carbon energy scenarios (see Part 1). The use of secondary rather than primary materials will also reduce the embedded energy of these technologies.

iii. **Shift the onus of end-of-life management of renewable energy technologies from the public to the producers of the products:** Management of renewable energy technologies at their end-of-life could become an expensive burden on taxpayer funded municipalities and regional waste authorities. Moreover, placing the onus of end-of-life management onto the consumer can create equity concerns for rural, remote and indigenous communities who will inherently face more difficulty managing complex waste streams. Shifting this responsibility to the producers of these products integrates end-of-life costs into market prices, and assigns responsibility to those who have the greatest control over product design, and the greatest ability and responsibility to reduce toxicity and waste.

iv. **Encourage the consideration of lifecycle impacts in the procurement of renewable energy technologies:** Despite being a low polluting source of energy, the production, use and disposal of renewable energy technologies is not without environmental impact. These technologies can be produced with varying lifecycle carbon intensities which impacts their embodied carbon as well as their carbon payback time.[‡‡‡] Public policy should incentivize suppliers to adopt resource-efficient processes and support consumers to make purchase decisions that factor in these lifecycle impacts.

v. **Align with emerging international policies and practices:** As outlined in Part 1 of this report, the value chains for both solar PV and wind turbines are truly global. And as outlined in Part 2 of this report, standardizing product design and manufacturing processes globally, can enable potential

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[***] Copper, Indium, Lead, Phosphate rock, Silica, Selenium, Iron ore, Molybdenum, Cadmium, Tellurium, Titanium dioxide, Gallium, Metallurgical coal, Silver, Germanium, and Tin.

[†††] Iron, Copper, Aluminum, Chromium, Lead, Molybdenum, Manganese, Neodymium, Nickel

[‡‡‡] Carbon payback time refers to the time it takes for a final product (in this case solar PV panel or wind turbine) to offset the carbon emissions from its lifecycle (extraction, manufacturing, and operation)

recyclers to use fewer techniques to recycle different product types. Further, while existing Canadian steel, glass, and e-waste recycling facilities could recycle some of the materials from end-of-life solar PV and wind turbines, recovery and recycling of solar PV semiconductor materials require dedicated facilities which are only economic above certain volume thresholds. Thus, for the recovery of critical minerals and metals, export of scrap solar PV for recycling will be necessary until domestic (or, more likely, regional) volumes reach these thresholds. Alignment with emerging international policies and practices, as described in Section 2 above, while protecting domestic interests, will facilitate this.

3.2. Menu of Potential Policy Instruments

A menu of policy instruments that can be deployed along the lifecycle of wind and solar energy technologies to minimize waste generation and support circularity of materials used in low carbon technologies is presented below.

This listing deliberately stops short of recommending specific policy instruments for Canada, as this seems premature in light of crucial research and data gaps. The list is also agnostic to level of government having jurisdiction to employ the policy tool.

The list is organized according to three categories: (1) stimulating better end-of-life management of renewable energy technologies; (2) supporting businesses that develop and provide circular practices; and (3) support for the circular innovation system as a whole.

3.2.1 Stimulating better value recovery and end-of-life management of renewable energy technologies

Canada does not have any guidelines, regulations or policies in place today to encourage repair, reuse, recyclability in solar PVs and wind turbines, or specific to their end-of-life management.

To encourage ecodesign, repair and reuse the following policy instruments can be applied:

- **Ecodesign regulations**: It is estimated that 80% of a products environmental impacts are determined during its design phase.[45] Currently solar PV and wind turbines are not designed with end-of-life management considerations. Recognizing this, some jurisdictions are considering a regulatory approach to encouraging more environmentally friendly designed technologies. For instance, the EU included solar PVs in the Eco-design Working Plan 2016-2019 and are expected to introduce legislation based on the findings of a preparatory study published in 2019.[46] Eco-design regulations have a broad scope, and can for example set minimum requirements for recycled and non-hazardous materials composition, and/or create standards or guidelines for design that support higher energy efficiency, enhanced performance, reparability, dismantlability, recyclability, etc. Such regulations can improve the standardization of these technologies across the industry and thereby facilitate better end-of-life management. International cooperation may be needed to create consistent eco-design requirements between various jurisdictions in order to influence multinational brand-owners.

- **Tax incentives:** Pricing tools allow businesses the flexibility to take actions that best suit their situation. Tax incentives can be developed across the lifespan of solar PV and wind turbines technologies to encourage more repair, reuse, and recycling activities. For instance, major repairs that prolong the life of solar PV are generally considered economically unfeasible given the rapidly falling prices and increasing efficiencies of new technologies. Introducing tax incentives for repair could change the economics of repair and keep panels in use longer. Tax incentives could also be given to purchase secondary raw material recovered through recycling processes thereby increasing their demand. On the other hand, tax incentives intended to increase the uptake of new and more efficient technologies may inadvertently create perverse incentives to accelerate capital stock turnover of otherwise still productive existing installations, resulting in earlier end-of-life.

- **Labeling and certification:** The lifecycle impacts of solar PV and wind turbines are often unknown to purchasers. Labeling or certification schemes can help consumers make more informed purchasing decisions and encourage producers to develop products that minimize lifecycle impacts. Such schemes can take many forms including requiring the disclosure of energy intensity, material composition, hazardous substance use, degradation rates, durability, repairability, recyclability etc. These are currently under consideration in the EU.

  A separate certification issue relates to second-hand panels. Depending on age, solar PV and wind turbines may still retain sufficient efficiency rates at the time of utility decommissioning to make them attractive for reuse. As a result, there is a growing second-hand market for these technologies, particularly in developing countries where customers are willing to forego a manufacturer's warranty in lieu of lower prices. In the domestic market, second-hand solar PVs for instance are resisted by both producers and consumers due to a lack of accountability for performance as well as liability concerns for health and safety. To stimulate a domestic second-hand market, guidelines could be developed for testing and certification of used solar PV and wind turbines. See Box 2 for more details.

Box 1: Recommended steps to testing and certification of used solar PV panels[47]

Recommended steps to testing and certification of used solar PV panels

According to a 2020 study by the CSA group which interviewed authorities, manufacturers, certification organizations, and installers in North America, the following steps are recommended for carrying testing and certification of used solar PV panels:

- A visual inspection and cleaning should be carried out
- A current-voltage (IV)-curve should be recorded
- For product and electrical safety reasons, a ground continuity and an electrical isolation test should be performed, and the system voltage of future applications should be limited according to the test results
- The results shall be documented and a new label with the results should be placed on the back of the module
- A warranty of 6 or 12 months should be provided at minimum

Landfill is now the cheapest option for end-of-life disposal: according to one study based on stakeholder consultations, it costs USD$1–$2/ solar module to landfill versus USD$25/solar module to recycle in North America.[48] In this model, end-of-life responsibility is borne by municipalities and waste authorities. To shift this responsibility to producers of these technologies and encourage them to internalize the full cost of environmental damage from the waste they generate, the following policy instruments can be applied:

- **Extended Producer Responsibility:** EPR is considered a regulatory cornerstone of the transition to a circular economy. Under this model, producers are assigned full financial and physical responsibility for managing their products at their end-of-life. Depending on how producers are defined they can include domestic and/or international manufacturers, resellers, importers of technology products. These regulations could be designed to incentivize improvements along the whole value chain from design to manufacturing to post-consumer waste management. These incentives are highest in the Individual Producer Responsibility where individual producers are made both financially responsible and liable for end-of-life management of their products. EPR models are currently the most popular instrument for end-of-life solar PV management (both residential and utility scale applications). The most comprehensive application of EPR for solar PV can be seen in EU's revised WEEE Directive. A North American application is State of Washington's Photovoltaic Module Stewardship and Takeback Program. While being considered for wind turbines in some jurisdictions, EPR is generally not preferred for end-of-life management of wind turbines where market incentives for recycling these are already strong. It could however be considered for specific components of wind turbine such as their rotor blades (which currently has a weak business case for recycling) or for the oil used in them (since used oil EPR programs are already present in Canada).

- **Legally binding end-of-life standards/guidelines/regulations:** As described in Part 2, lack of recycling and value recovery regulations hinder the uptake of more circular practices. The development of specific collection and recycling regulations for solar PV and wind turbines at end-of-life, such as recycling and treatment standards is a cornerstone for consistently, efficiently and profitably dealing with increasing waste volumes. End-of-life value recovery regulations can also promote more circular life-cycle practices.[49] Regulations can also require project developers to provide details on how they plan to manage their waste on decommissioning, and/or to post bonds to ensure funding is available to implement these plans if the company goes bankrupt.

- **Waste Classification:** Currently solar PV and wind turbines are considered and managed as general waste. Some sub-technologies however are known to contain hazardous substances, which could pose a risk to environmental and human health during end-of-life management. As these become more prevalent in Canada and their compositions and impacts become better understood, an assessment could be made of whether to re-classify these in line with relevant provincial and federal laws and regulations. This could include the *Canadian Environmental Protection Act,* 1999, the *Export and Import of Hazardous Waste and Hazardous Recyclable Material Regulations* and Canada's Toxic Substances List among others.[50] Further research is required to determine at what point these technologies should be considered hazardous, and how this might impact any necessary cross border movement for end-of-life management.

- **Landfill disposal bans:** Landfill bans on select products or materials have proven effective in increasing recovery and recycling rates of solar PV and wind turbine components in some jurisdictions. Examples include the EU's landfill ban on electronic products, including solar panels, in 2014 and Germany's landfill ban on waste with organic content higher than 5% (affecting wind turbine blade waste) in 2009. However, such regulation should only be put in place after the creation of alternative end-of-life material management pathways.

3.2.2 Policy instruments to support businesses that develop and provide circular practices

- **Financial support to businesses that provide circular service:** While significant, the volumes of installed solar and wind capacity are still relatively small in Canada. However, as installed capacity continues to grow, so will opportunities for new businesses in related energy and waste sectors, including those providing repair and recycling services. Setting up dedicated recycling infrastructure, in particular, is likely to be capital intensive. Financial support can help overcome financial barriers described in Part 2 and can encourage the growth of these businesses domestically, especially during their early years, through instruments such as grants or loans, tax credits for capital investments, risk-pooling fund models for waste service providers, soft loans, and green bonds.

- **Public Procurement:** Public procurement, which accounts for about 13% of GDP in Canada,[51] can be a powerful tool to stimulate circular economy practices. It offers the dual benefit of allowing governments to lead by example and providing a testbed for innovations in the market. In 2016, the federal government announced that by 2025, 100% of electricity used in federal buildings and operations will be from renewable energy sources. Where renewable energy technologies are procured by government authorities, public procurement guidelines/criteria could be issued/updated to minimize lifecycle cost and environmental impacts.

- **Non-financial support to businesses that provide circular service:** Non-financial support to businesses such as technical support, advisory, training, demonstration of best practices, etc. is another dimension of encouraging the growth of domestic solar PV and wind turbine repair and recycling services.

3.2.3 Policy instruments to support the system as a whole

- **Climate Change and Circular Economy Policy Coherence:** create synergies between climate change and circular economy policies and programming, where circular economy measures address or prioritize creating closed material loops for resources with high carbon footprint, and climate change policies that (1) integrate circular solutions to minimize the embedded carbon in and supply bottlenecks for the material needed to enable the transition to a low carbon economy and (2) assess the potential and incorporate circular strategies as incremental measures to achieve Canada's mid-century net zero target.

- **Targets:** Setting binding and measurable recovery and recycling targets from end-of-life solar PV and wind turbines in future renewable energy polices, strategies, plans and programs could bring attention to this need and help mobilize private sector initiatives.

- **Policy Coherence:** Canada’s current provincial patchwork of product stewardship, partial EPR, and full EPR programs, covering different materials and use of different definitions, reporting mechanisms, and governance structures has been a barrier to efficient and cost-effective recovery and recycling of other materials. This can be avoided for end-of-life management for renewable energy technologies like solar PV and wind turbines, by striving for a harmonized, or at least coordinated approach across the provinces and territories. In addition, given the global nature of solar and wind energy supply chains, alignment with international standards and best practice guidelines for end-of-life management would support resource and cost savings.

- **Partnerships:** End-of-life management of solar PV and wind turbines is a global inter-disciplinary issue that will require the cooperation of a wide array of stakeholders across the lifecycle and value chain of these technologies (project developers, manufacturers, consumers, recyclers etc.). Strong partnerships between the energy and waste sectors, the government and private sector as well as between countries can be facilitated through industrial clusters (see Box 3), working groups, committees, and international dialogue, etc.

Box 2: 600W+ Photovoltaic Open Innovation Ecological Alliance [52]

600W+ Photovoltaic Open Innovation Ecological Alliance

In 2020, 39 photovoltaic companies in China came together to form the 600W+ Photovoltaic Open Innovation Ecological Alliance. This alliance aims to create a new collaborative and innovative ecosystem through open collaboration, synergising the main resources of the industry chain and integrating core processes such as R&D, manufacturing and applications. Companies in this alliance come from upper, middle and lower streams of the industrial value chain, such as silicon, wafers, cells, modules, trackers, inverters, materials and equipment manufacturers. They believe that open innovation is critical for the sustainable development of the PV industry and have committed to work together to build products, systems and standards for a next-generation technology platform.

- **Skills, Training & Workforce Development:** A new industry of end-of-life management of solar PV and wind turbines will require the development of new skills and jobs. Research and education programmes can train the next generation of scientists, engineers, technicians, managers etc. needed to develop the technical, regulatory, logistics and management systems necessary to maximize value extracted from growing waste streams. In addition, specific education and training on repairs, maintenance and refurbishment can help to extend the lifetime of these technologies.

- **Data Collection and Monitoring:** There is currently a dearth of detailed and harmonized data on issues such as the volume of installed units, material content, end-of-life collection, reuse, recycling, material recovery and disposal of solar PV and wind turbines, although some work on this has begun. This data collection can be facilitated by requiring producers to disclose this data and by developing a data inventory or registry to track it.

3.3. Temporal and volume threshold considerations to policy timing

There may be logical, temporal or volume threshold sequences to the adoption or phase-in of these policies.

Policies should distinguish between legacy stock (i.e., stock in place as of 2020) and future stock. In absence of market-driven recycling opportunities, municipalities and regional waste authorities bear the onus for end-of-life management for legacy stock. In the case of solar PV, depending on the differing rates of panel degradation under the two modelled scenarios, the annual end-of life volumes from the legacy stock of solar peak at 2037 at 9,550 tonnes or in 2042 at 17,347 tonnes. For wind, annual end-of-life volumes from legacy stock peak in 2034 at 125,000 tonnes (see Figures 37 - 40, Part 1).

Some policies, such as tax incentives for repair and reuse, testing and certification for used panels, end-of-life recovery standards or landfill bans can apply to both legacy and future stock.

Other policies, such as eco-design, labelling, and EPR may only be applied to future stock, but should be put in place now to establish the design expectations, create the value recovery opportunities and manage the end-of-life practices of tomorrow.

Hence, forward-looking policies that push towards solar PV and wind turbine design standardization and modularization, material passports that are accompanied with global databases on panel and turbine contents, EPR regulations that transfer the onus of end-of-life management to product producers, etc., require immediate attention.

However, Canada is more than a decade away from seeing the volume threshold necessary to establish dedicated domestic end-of-life solar PV recycling facilities, and policy intervention in this space may not be immediately necessary. For instance, the annual end-of-life volume of 10,000 tonnes was identified to authors as the threshold for a dedicated solar recycling facility. The modelling for this study suggests that Canada as a whole may not generate this kind of flow rate until somewhere between 2030 and 2035,[§§§] and even at that time, the jurisdictional distribution of current solar capacity suggests that north-south Canada-US specialized regional recycling clusters would remain logical, except in Ontario.

3.4. Research needs to improve evidence for policy making

Solar and wind energy have only become a significant energy source in Canada in the past decade or so and are still a decade away from emerging as a major source of waste. Hence this area is still under-researched. However, preliminary discussions with key stakeholders have revealed growing interest in understanding the scale of the challenge, the technical options and the policy options. This information is also needed to improve evidence for policy making. Specific research areas identified during this project are presented in Table 3.

Table 3: Future Research Areas Identified

Area of Research	Expected outcome
To address data gaps for modelling	
Projections for solar and wind capacity growth that align with Canada's commitment to achieving net-zero emissions by 2050.	To gauge a more precise timeline and expected volumes of future waste streams.
Empirically estimating Canada specific parameters for evolution of losses in solar PV and wind turbines.	To account for regional variations and to improve accuracy of projections for future end-of-life streams.
Evaluating the material requirements for storage and transmission infrastructure necessary to distribute energy generated by solar PV and wind turbines.	To avoid underestimating the total material requirement and waste implications of low carbon infrastructure.
Detailed energy profiles and projections for growth of solar and wind capacity at a subnational level.	To gauge regional priorities.
Landscape review of how solar and wind energy technologies are evolving.	To understand how these may deliver more energy and material efficiency, drive material innovation and substitutions to enable higher recovery rates, and make it technically and economically feasible to repair, reuse, refurbish, recover and recycle them.

[§§§] Based on differing rates of panel degradation under the two modelled scenarios

Materials used in existing and under-development solar and wind energy technologies that are produced domestically or imported into Canada.	To gauge the nature and volume of specific materials that can potentially be recovered and reintroduced into the Canadian economy.
To build evidence for policy making	
Market analysis on existing and anticipated circular economy practices (such as eco-design, repair and maintenance, reuse, recycling etc.) being undertaken by the private sector in Canada.	To identify barriers and better inform policy interventions required to overcome these.
Disassembly and high-value recycling processes for solar PV panel and wind turbines currently available or under development.	To plan for the recovery of rare, valuable and potentially hazardous materials.
Identification of new uses and markets for materials used in solar PV panel and wind turbines as well as Canada's capacity to recover these.	To identify how policy instruments can stimulate demand for their end-of-life recovery.
Identification of cross-continental barriers and opportunities for joint recovery and recycling operations.	To enable international collaboration that can take advantage of economies of scale.
Identification of cross-sectoral opportunities for industrial symbiosis for joint recovery and recycling operations.	To enable inter-sectoral collaboration that can take advantage of economies of scale.

4. Conclusion

As governments at all levels introduce policies to increase the uptake of renewables, the eco-efficiency, value recovery opportunities and end-of-life considerations of this transition require parallel and intermeshed policy attention.

There exist deep synergies between climate change and circular economy policies: decarbonizing wind and solar technologies contributes towards circular economy goals of designing out pollution and waste energy, while circular economy policies can support more efficient use of, and value recovery of the critical minerals and metals needed for the transition to a low carbon future and extend the useful lives of solar PV and wind technologies. Despite these synergies, these two agendas in Canada are siloed.

These considerations are largely missing in Canada yet are crucial to ensuring that Canada's renewable energy transition also incorporates broader concerns about overall environmental sustainability, including material flow and materials management perspective. Renewable energy technologies are material intensive and retain value at end-of-life. Recovering these materials including critical minerals and metals can support the growing demand for these materials, reduce potential supply bottlenecks in the future, while also reducing environmental and energy costs. The modelling results for this study suggest that cumulative end-of-life solar PV waste in Canada will grow to approximately 15,000-65,000 tonnes by 2030 and 363,000-470,000 tonnes by 2050 (dependent on differing rates of panel degradation under the two modelled scenarios). Similarly, cumulative end-of-life wind waste is expected to grow to 831,000 tonnes by 2030 and 4,500,000 tonnes by 2050.

Currently, much of the resource-rich value embedded in solar PV and wind technologies (particularly blades for the latter) is lost to landfill. This places the burden of end-of-life management on municipalities and waste management agencies, many in rural, remote, and Indigenous communities where these technologies are sited. EPR models can shift this burden to the producers. This has the dual benefit of reducing the public cost of management, and incentivizing producers to make upstream changes in design that can reduce waste volumes and facilitate better management of these.

The small portion of solar PV waste that is diverted from landfill is largely being exported to other countries for reuse or recycling; while Canada is not retaining this value, the materials are being cycled in the global economy. For materials now being sent to landfill, and particularly legacy stock that will not be covered under possible future EPR policies, Canada could consider various policy instruments noted in this report and strive to enhance its recycling capacity for material streams emerging from the end-of-life of these technologies. As of now, there are opportunities to use recycling channels that are in place for electronic waste, glass, and steel more generally. While these can recover the bulk materials found in these technologies, they are unsuitable for more high-value recycling. Domestic volumes of these materials are not high enough to set up dedicated recycling facilities, and likely will not be until 2030-2035. To bridge this capacity gap, Canada could explore a joint solar PV end-of-life management approach with the United States, thereby taking advantage of economies of scale from the combined waste volumes in the two countries.

The Canadian wind fleet is relatively young and as such there is limited experience dealing with end-of-life wind turbines. However, while international experience suggests that there is still a lack of established economically viable recycling channels for wind blades, a significant portion of end-of-life wind turbines can be recycled. Similar to end-of-life solar PV recycling, certain existing recycling facilities in Canada can potentially be adapted to recycle end-of-life wind turbines. However, while these facilities can recover bulk materials like steel, specialized processes may be required to recoup critical materials such as rare earths – whose demand is expected to grow exponentially as wind sub-technology shifts away from geared turbines to direct drive. Specifically, neodymium, praseodymium, and dysprosium are three rare earths used in permanent magnet applications in direct drive wind turbines. The sustainable supply of these critical rare earths is susceptible to future supply bottlenecks as their mining is restricted to a few countries worldwide and their processing and refining occurs in even fewer. Therefore, it will be essential to factor in the criticality of such critical and strategic minerals when evaluating the feasibility of establishing specialized dedicated end-of-life wind recycling facilities – as these facilities would ensure critical rare earths are recouped and their value maximized.

Within Canada, Ontario is emerging as a possible regional recycling hub due to the current 94% market share for installed Canadian solar PV capacity as well as its proximity to Quebec – combined, these two provinces have 70% of Canada's current installed wind capacity. Finally, by exploring new uses and applications for recycled materials, Canada could consider not only developing closed material loops that recirculate these materials back into the production of products they emerged from, but build new markets for these to further stimulate demand for secondary materials.

In closing, it must however be underscored that more evidence is needed to inform policy making. Significant data gaps limit the modelling of future end-of-life scenarios, and more information on recycling options and capacity is needed.

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