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SOLAR AND WIND ENERGY IN CANADA

VALUE RECOVERY AND END-OF-LIFE CONSIDERATIONS

IMPLICATIONS FOR POLICY-MAKERS

Wind and solar energy will play an ever-growing role, globally and nationally, in meeting future energy needs under mid-century net-zero greenhouse gas emission goals. This transition, enabled by the rapidly declining costs of these technologies, is being accelerated as a mainstay of climate policy. Fittingly, the policy lens on these renewable energy technologies has focused on their promise in a net-zero future. Only lately has it broadened to include equally critical considerations of the material needs and end-of-life management implications of this transition.

Wind turbines and solar photovoltaic (PV) modules require more material per unit of energy generation (t/MW) relative to fossil-fuel-based counterparts, including critical and strategic minerals and metals subject to potential near-term economic or geopolitical supply constraints. This includes 13 of the 31 minerals designated as critical by Canada based on their necessity for economic growth and national security, plus four rare-earth elements. As early wind and solar installations advance in age and reach end-of-life, rapidly growing volumes of material are being decommissioned and valuable resources are finding their way into waste streams, while policy frameworks have yet to catch up.

To get ahead of this challenge, policies are needed to both encourage the adoption of low carbon renewable energy sources, while also accounting for the material requirements and end-of-life considerations these technologies entail. Circular economy approaches offer the potential to reduce the material intensity of wind turbines and solar PV modules, minimize material loss along their life cycles, recover value at their end-of-life, and reduce future volumes of waste sent to landfills.

This report represents a first effort to explore these issues in the Canadian context. Building on scenarios of projected solar PV and wind turbine adoption to 2050 from the Canada Energy Regulator (CER), it models the potential scale of future end-of-life material volumes stemming from Canadian installed wind and solar energy sources. Drawing on a review of literature, leading global policies, and interviews with selected experts, it outlines pathways to reduce material consumption, extend lifespans and recover value from wind turbines and solar PV modules; lists a menu of policy options to minimize waste generation and encourage circularity of materials; and identifies further research needs.

Key findings include:

- By 2050, even conservative scenarios of renewable energy technology uptake from the CER suggest a 60-fold increase in accumulated end-of-life solar PV modules, and a 30-fold increase in accumulated end-of-life wind turbines (including hard-to-recycle blade waste) from today.

- Bulk recycling of solar PV and wind turbines can be done by existing Canadian recycling facilities for bulk materials with established markets such as glass, iron, steel, and aluminum. Specialized facilities are needed to recover other metals and semi-conductors found in solar PVs, which also have high strategic value; Canada does not yet have facilities for this high-value recycling, nor the volumes to make domestic facilities economically feasible. The rare earths used in wind turbines have established competitive recycling channels, but wind blades lack established economically viable recycling pathways due to their size and composition.

- Voluntary programs currently collect a small share of Canada's thin-film solar PVs for specialized recycling in US facilities. At present, most decommissioned solar PV modules and blade waste from end-of-life wind turbines are now directed to landfills or are being stored pending future recycling options.

- These materials represent a valuable resource, encompassing several critical and strategic minerals which could become subject to potential supply bottlenecks in the near future.

- To date, there has been little policy action in Canada anticipating the volume of end-of-life renewable energy technology material flows, or encouraging greater circularity of materials used in solar PV and wind technologies. This may change with the Government of British Columbia's recently announced intention to include solar panels in its Recycling Regulation and EPR strategy. SPI proposes five policy objectives to guide future action:

1. Divert waste from renewable energy technologies from landfill;

2. Recover critical minerals and metals used in renewable energy technologies and support the creation of markets for the secondary materials;

3. Shift the onus of end-of-life management of renewable energy technologies from the public to the producers of the products;

4. Encourage the consideration of lifecycle impacts in the procurement of renewable energy technologies; and

5. Align with emerging international policies and practices.

- Looking to emerging international policies and practices, potential policy tools include targeted end-of-life regulations such as waste classification and landfill bans; extended producer responsibility; eco-design regulations; labelling and certification; binding and measurable recovery and recycling targets from end-of-life solar PV and wind turbines; and guidelines for testing and certification of second-hand panels.

- More evidence is needed to inform policymaking. There remains a need to address crucial data gaps which limit the modelling of future end-of-life scenarios, conduct more in-depth assessments of recycling options and capacity, and consider stakeholder input on policy options.

While preliminary, these findings clearly identify that evolving strategies to increase the uptake of renewable energy technologies across Canada need to be paralleled with similar attention to policies designed to address equally critical considerations of the material needs and end-of-life management implications of this transition.

Canada must manage the flow of materials in renewable energy technologies sustainably and in an environmentally sound manner.

Our findings are presented in three working papers, as outlined below:

Material needs and end-of-life resource flow implications under Canada's climate change objectives and data gaps;

Pathways to reduce resource consumption, extend the life of products and recover value, and associated Canadian capacity; and

Policy options to minimize waste generation and encourage circularity of materials and further research needs.

Three working papers with more details on the findings in this Policy Brief are available at **institute.smartprosperity.ca/library**

BACKGROUND

The global transition to a low-carbon future is expected to have a profound effect on primary material demand. It will also change the profile of end-of-life materials (waste) produced by the energy sector. While there is a growing body of research into potential supply constraints for key minerals and metals for low carbon energy technologies,[1] only recently has attention turned to the value recovery opportunities and end-of-life considerations of the transition to a low-carbon future, including the potential role of circular economy strategies to reduce the material intensity of these technologies, minimize material loss along their life cycles, and recover value at their end-of-life.

More than 80% of Canada's current greenhouse gas emissions stem from energy generation and use in transportation, buildings, heavy industry, and extractives. For Canada to meet its commitments to exceed its 2030 Nationally Determined Contributions and achieve net-zero emissions by 2050, the country must accelerate its transition to renewable energy sources to meet projected energy demands and reduce related GHG emissions. Wind and solar energy technologies will play an important part in reducing the GHG footprint of Canada's energy profile, especially in provinces and territories with limited potential for or access to hydroelectricity. However, adopting these technologies at scale will result in other environmental footprints, including resource depletion, waste generation, and pollution.

As governments at all levels introduce policies to increase the uptake of renewable energy technologies, Canadians are increasingly concerned about how the related waste streams will be managed once these technologies reach their end-of-life. There are also concerns around the limited stock of certain critical minerals and metals used in these products, given the projected increase in demand as these technologies are adopted around the world.[2]

Therefore, in the transition to a low carbon economy, Canada must manage the flow of materials in renewable energy technologies 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 are recycled to the greatest extent possible to maximize retained value and minimize material loss; and any remaining residual waste is disposed of safely.

The objective of this project is to use the example of solar PV module and wind technologies to explore emerging opportunities for value recovery and end-of-life management considerations associated with Canada's commitment to transition to a low carbon economy more broadly. To do so, it has conducted a review of literature on wind and solar technologies, end-of-life strategies and relevant policy experiences, and interviews with selected experts. Furthermore, the project has also developed a model of Canadian renewable energy capacity to 2050 to (1) estimate potential magnitudes of future end-of-life material volumes and content stemming from Canadian installed wind and solar energy sources, and (2) to assess preliminary scenarios with factors that may affect end-of-life material generation.*

* 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. For solar PV, it estimates of end-of-life material generation for both "Regular Loss" and "Early Loss" scenarios to capture different rates of component failure for installed capacity. More details on scenario assumptions and model limitations are included in the technical note at the end of this document.

MATERIAL NEEDS AND END-OF-LIFE RESOURCE FLOW IMPLICATIONS UNDER CANADA'S CLIMATE CHANGE OBJECTIVES

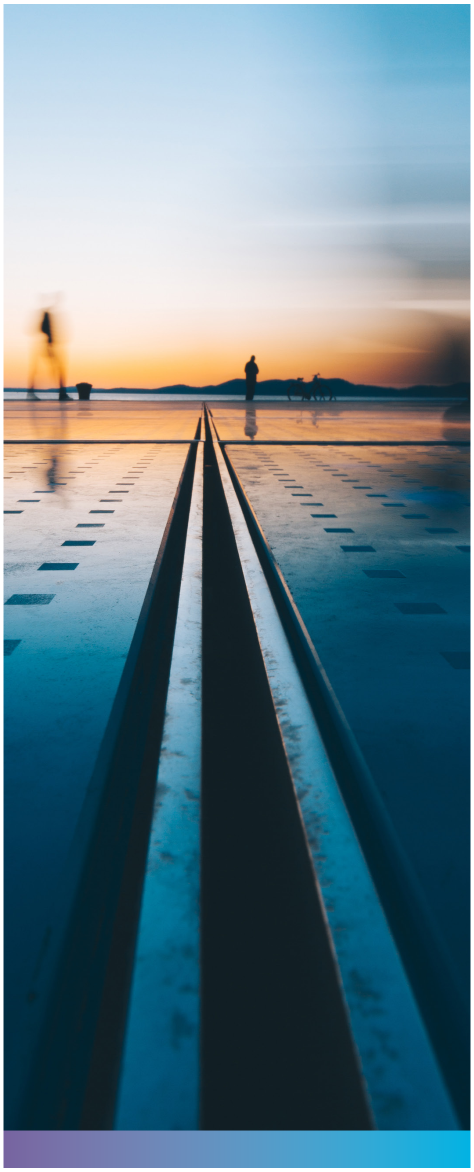
The rapid increase in renewable capacity presents novel challenges such as potential material supply bottlenecks and end-of-life material recovery and waste disposal.

As mentioned above, 80% of Canada's current GHG emissions stem from energy generation and end-use.[3] The rapid decline in the Levelized Cost of Energy production coupled with low carbon footprints makes solar and wind energy critical to Canada's goal of net-zero emissions by 2050. This criticality is reflected in several Canadian-specific projections for installed solar PV and wind capacity under varying GHG reduction targets.[4, 5, 6] One such recently released set of projections are the Canada Energy Regulator scenarios, which project cumulative installed Canadian solar and wind capacity to scale to a combined 60 GW by 2050, under a carbon price reaching $125/tonne CO_2 eq. by 2050 ('Evolving Scenario').[7] The 'Evolving Scenario' serves as the reference scenario for the modelling in this study. *To note, this scenario represents a conservative uptake of projected solar PV and wind technologies, unlikely to be sufficient to meet the net-zero target. Therefore, end-of-life resource flows modelled for our study could be underestimated, but most of the difference occurs post 2050.*

While this rapid increase in renewable capacity will lead to substantial GHG emission reductions, it will, in turn, present novel challenges such as potential material supply bottlenecks and end-of-life material recovery and waste disposal issues.

Material and resource implications

Global production of certain minerals will need to grow twelvefold to 2050, relative to today's output, to support the renewable energy technologies needed to achieve the Paris Agreement's goals.[8] While the cumulative material demand for renewable energy technologies represents a small share compared to overall material demand by other economic sectors,[9] for some critical minerals, the production of wind turbines and solar PV is already using a significant share of the global output.[10] Several critical metals and minerals occur in low concentrations within the earth's crust, and not all proven reserves are economically viable; decades may be involved in scaling production rates, and geopolitical risk accompanies certain supplies.[11] The growth in demand for other advanced technology applications will further compete for these limited supplies.



The technology pathways that emerge to decarbonize electricity production will shape which minerals will experience the most significant increases in demand. Demand for individual minerals will change depending on the choice of technology and sub-technology deployed, and possible material substitution as well as expected technological improvements.[12, 13]

Notably, while recycling and re-use of minerals is expected to grow in the coming decades, research indicates that such practices will only mitigate increases in mineral demand to some extent. To meet the remaining primary demand, mining will continue to be required.[14] As a resource-rich country with reserves of many of the critical minerals that will be required to support a low-carbon future and a solid reputation on environmental, social, and governance issues, this represents a competitive opportunity for Canada.

At the other end of the technology value chain are end-of-life waste disposal issues. Currently, there is limited policy action to enforce standardized decommissioning of, and value capture from end-of-life solar PV and wind turbines. While the iron and steel used in wind turbines may get recycled, and voluntary programs collect a small stream of thin-film solar PVs for US-based recycling, most decommissioned materials from end-of-life solar PVs and wind turbines are directed to landfills, or being stored pending future recycling options.[15,16] This represents a significant lost opportunity to recover valuable materials that are being lost from the economy. Moreover, this waste is only a fraction of what is expected to follow in the coming decades as more and more solar PV and wind turbines – both currently installed and projected capacity – come to their end-of-life.

Solar PVs

The last decade has seen a dramatic geopolitical shift in the global value chain for the solar photovoltaic (PV) industry. Initially, the value chain for solar PV technologies was concentrated in a few developed economies such as the US, Japan, and Germany. Over the past decade, manufacturing has consolidated primarily in China. China, and to an extent, Taiwan are also world leaders in upstream and midstream segments of the value chain and supply more than 80% of the global market.

The CER Evolving Scenario projects Canadian installed solar PV capacity to scale from 3 GW in 2020 to 8 GW in 2030 and 20 GW in 2050.[17] As of 2019, Ontario had 94% of the country's installed capacity, with Alberta a very distant second at 3%, then Manitoba, Saskatchewan, and British Columbia at 1% or less each, in descending order.[18]

Future projections of material needs, end-of-life resource flows, and potential recycling systems need to take into account that solar technologies are evolving rapidly, as is their relative market share. The first-generation of silicon-based (c-Si) PVs are now reaching end-of-life and appearing in Canadian waste streams. Second-generation thin-film PVs – which have grown to 10% of the global market since 2014 but are not expected to take much more – are more technologically complex to manufacture and recycle, only showing up in current waste streams from early failure events. Third-generation PVs include a vast array of sub-technologies. They currently have 16% of market share but are expected to take over 44% of the global market by 2030.[19] *Due to the uncertainty around market adoption of these third-generation PV technologies, this report focusses on first- and second-generation solar PV technologies.*

The material requirements for the conductive layer for solar PVs differ across first-, second-, and third-generation technologies, giving rise to differing material waste compositions. For first-generation c-Si panels, over 90% of the mass is composed of glass, polymer, and aluminum, which can be considered as non-hazardous waste and are relatively easy to recycle. However, smaller traces of silicon, silver, tin, and lead (together accounting for around 4% of the mass) pose a more significant recovery challenge. For second-generation thin-film panels, over 98% of the mass is composed of glass, polymer, and aluminum, while 2% of the mass is copper and zinc. Thin-film panels also contain materials such as indium, gallium, selenium, cadmium, tellurium, and lead.[20] Of these, cadmium and lead have the highest negative impact on human health and the environment.[21]

In terms of material criticality, eight of the nineteen mineral products and metals used in solar PVs are designated as critical minerals by Canada (copper, indium, molybdenum, tellurium, titanium, gallium, germanium, and tin), based on their necessity for economic growth and national security.[22]

Solar PV waste is typically generated during the four primary lifecycle phases of a PV panel: i) production, ii) transportation, iii) installation and use, and iv) end-of-life disposal. In projecting end-of-life disposal, the life expectancy of a solar panel is generally assumed to be 30 years;[23, 24] however, the potential for early failure must be accounted for. Additionally, annual repowering needed to maintain commercial solar facilities at high production results in panel turnover before full lifespan.

Modelling for this study indicates that *cumulative* solar PV end-of-life waste in Canada under the CER's Evolving Scenario will reach approximately 365,000 to 470,000 tonnes by 2050, depending on assumptions on the evolution of losses over technology lifespans. An "Early Loss"and a "Regular Loss" scenario were modelled. The 'Regular Loss' scenario assumes the shape factor for solar panel losses extracted from Kuitche et al. – which is based on a group of c-Si PV modules being monitored over 8 years in Arizona.[25] The 'Early Loss' scenario introduces a corrected shape factor that accounts for statistical data on PV module failure during early life stages.[26] Figure 1 shows the evolution of cumulative solar PV end-of-life waste as installed capacity grows over time. Table 1 shows the associated cumulative waste material mass over time by material for these two scenarios.

By 2050, even conservative scenarios of renewable energy technology uptake from the CER suggest a 60-fold increase in accumulated end-of-life solar PV modules, and a 30-fold increase in accumulated end-of-life wind turbines (including hard-to-recycle blade waste) from today.

Figure 1 : Solar PV Waste Evolution - Canada

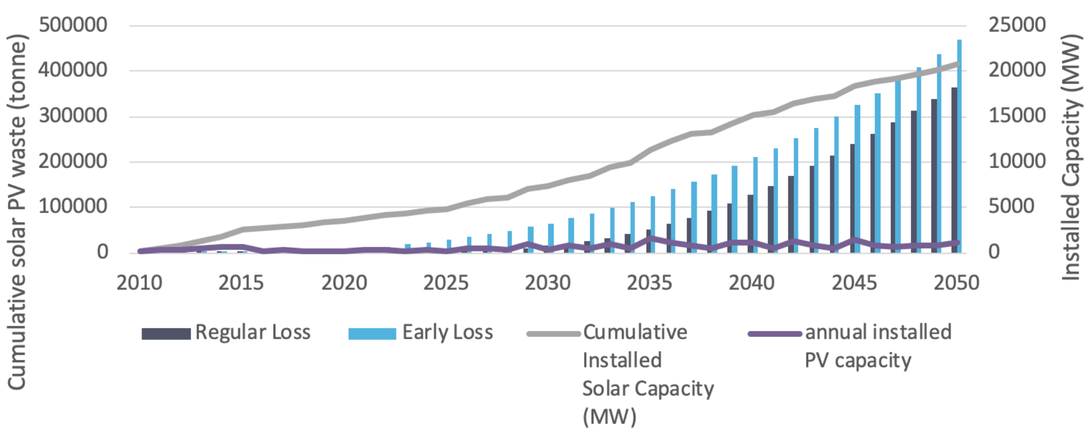
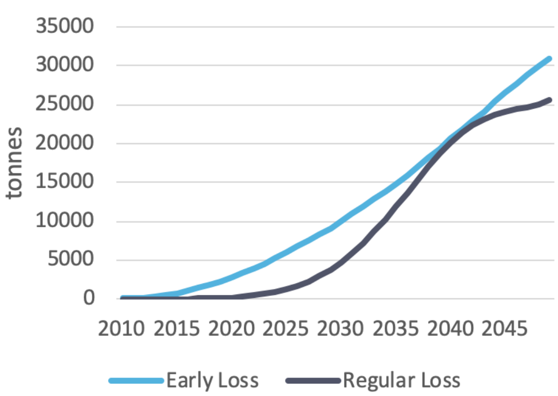


Table 1: Evolution of cumulative waste material mass in end-of-life solar PV modules for Regular Loss and Early Loss Scenarios

Waste Material	Cumulative waste material mass (tonnes)							
	2020		2030		2040		2050	
	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss
Glass	192	6,242	11,184	49,818	97,344	159,834	275,898	356,514
Polymer	25	521	1,472	6,555	12,808	21,031	36,302	46,910
Aluminium	20	657	1,117	5,244	10,247	16,825	29,042	37,528
Silicon	13	411	736	3,277	6,404	10,515	18,151	23,455
Copper	3	82	147	655	1,281	2,103	3,630	4,691
Silver	0	8	15	66	128	210	363	469

Figure 2 : Annual Solar PV Waste Evolution



The temporal evolution in annual solar PV waste mass also varies by scenario. In the 'Early Loss' scenario, the annual solar PV waste generation rate is almost linear, while under the 'Regular Loss' scenario, it grows exponentially with time, reaching a maximum at around 2040, followed by a progressive decrease. This is relevant for planning the recycling capacities needed for incoming waste flows (Figure 2).

Also germane to policy development is a distinction between legacy stock (defined here as stock in place as of 2020), operating under grandfathered policies, and future stock which could be subject to new policy frameworks. 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 (Early Loss) or in 2042 at 17,347 tonnes (Regular Loss).

Wind Turbines

Wind turbine production is dominated by ten original equipment manufacturers (OEMs). Over the past decade, these OEMs have vertically integrated their value chains to bypass supply chain bottlenecks and to squeeze costs.[27,28] However, beyond turbine production, the global wind value chain offers opportunities for new players at many stages of the value chain, such as raw material supply, design and development services, component suppliers, construction and installation services and wind farm development. As wind turbines get more powerful, longer blades and taller towers create logistic challenges that favour on-site/closer-to-site manufacturing.[29] For instance, one-third of Alberta's total installed wind capacity was developed by Alberta-based companies,[30] and major wind turbine manufacturers Siemens, Repower, Enercon, and Vestas all have Canadian factories. Large and heavy turbine components may present the most promising opportunities for domestic production, as these are the costliest to ship over long distances. This presents an opportunity for increased domestic demand for secondary material in manufacturing of new turbine components such as rotor blades, casting and forgings, assemblies and covers, and the tower sections.[31]

The CER Evolving Scenario projects Canadian installed wind capacity to scale from 13.7 GW in 2020 to 23 GW in 2030 and 40 GW in 2050.[32] As of 2019, Ontario had 41% of the country's installed capacity, Quebec was second with 29%, and Alberta third with 13%, with B.C. and Nova Scotia tied with 5% each.[33]

Solar PVs and wind turbines contain critical and strategic minerals which could become subject to potential supply bottlenecks in the near future.

Modern utility-scale wind turbines are of two types, geared or direct drive. Geared turbines account for about 80% of global installed wind capacity, and also dominate the market share of onshore wind installations where maintenance is relatively straightforward. Direct drive turbines require lower maintenance during the turbine's operation, and hence are the preferred technology for offshore wind.

A wind turbine consists of four basic parts. The foundation, tower, and nacelle use concrete, iron, and steel; the nacelle also uses aluminum, copper, fibre glass and resin.[34] The rotor blades can be made of various materials, including reinforced fibres (e.g. glass, carbon, aramid, basalt), polymer matrices (e.g. thermosets such as epoxies, polyesters, vinyl esters, polyurethane, or thermoplastics), sandwich core (e.g. balsa wood or foams such as polyvinyl chloride (PVC), polyethylene terephthalate (PET)), and metals such as copper wiring and steel bolts.[35] Direct drive turbines use a generator with permanent magnets consisting of rare earth minerals such as neodymium and dysprosium or electrically excited rotors using significant amounts of copper, and require greater material inputs for their foundations (mainly steel) and cabling to transmit the electricity onshore (for example, copper).[36]

Critical minerals found in wind turbines include copper, aluminum, chromium, molybdenum, manganese and nickel.[37] Moreover, neodymium, praseodymium and dysprosium—rare-earth elements used in direct drive turbines—are produced only in a few countries, making them relatively scarce and at risk of experiencing future supply constraints, unless efforts are made to expand production capacity, material recycling, technology efficiency or find substitutes.[38]

Similar to solar PV, wind turbine waste is typically generated during the four primary lifecycle phases of a turbine: i) production, ii) transportation, iii) installation and use, and iv) end-of-life disposal. The standard lifetime of a wind turbine is approximately 20-25 years.

Figure 3 : Cumulative Wind Waste Evolution

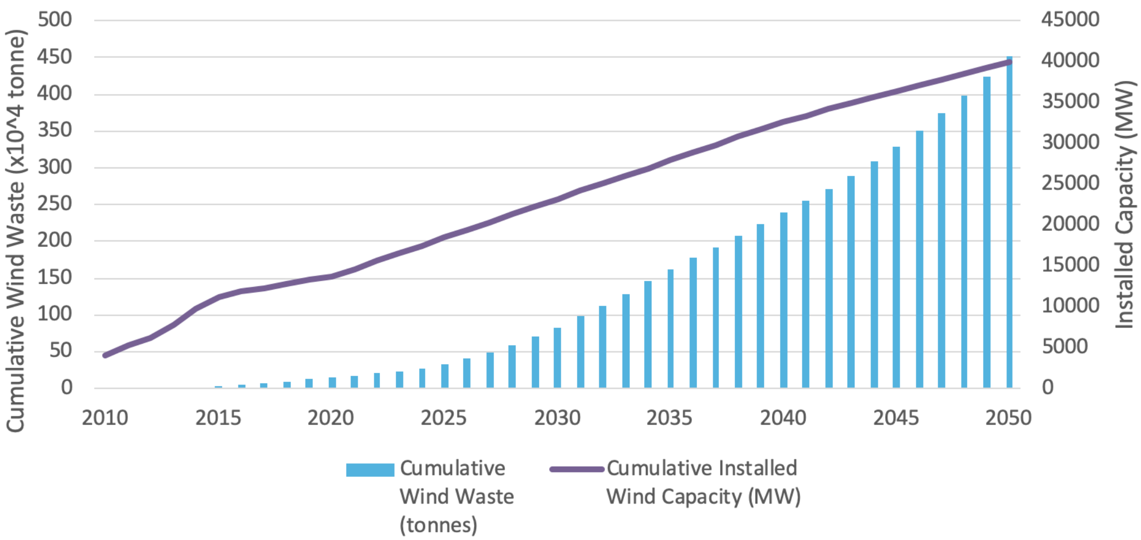


Table 2 : Evolution of cumulative waste material mass in end-of-life wind turbines

Waste Material	Cumulative waste material mass (tonnes)			
	2020	2030	2040	2050
Steel	136,885	755,050	2,168,060	4,100,885
Composite Material	10,785	59,492	170,828	323,121
Copper	2,160	11,918	34,221	64,729
Aluminum	738	4,073	11,696	22,124
Plastic	193	1,065	3,059	5,786

Addressing uncertainties and data gaps will be essential to establish recycling targets and better understand socio-economic opportunities.

Unlike solar PV waste, there is a gap in studies on total wind turbine waste and insights into Canada's wind turbine waste evolution. Adopting the methodology used to project solar PV waste, projections of wind turbine waste to 2050 developed for this study indicate that cumulative wind turbine end-of-life waste under the CER's Evolving Scenario rises to approximately 831,000 tonnes by 2030 and 4,500,000 tonnes by 2050. Figure 3 shows the evolution of cumulative wind waste as installed capacity grows over time. Table 2 shows the evolution of cumulative waste material mass for end-of-life wind waste over time.

End-of-life blade materials represent a small fraction of cumulative end-of-life wind turbine materials but lack established economically viable recycling pathways due to low prices of virgin materials, with most blades being landfilled. Blades, comprised of composite material, PVC, balsa, and small traces of metal, paint, and putty, are retired after a life span of about 20 years. Modelling for this study projected that cumulative end-of-life blade waste would rise from 4,500 tonnes in 2020 to 25,000 tonnes by 2030 and 135,000 tonnes by 2050.

For wind turbines, annual end-of-life volumes from Canadian legacy stock (defined here as stock in place as of 2020) peak in 2034 at 125,000 tonnes.

Limitations: data gaps and uncertainties

The methodology used to projecting future solar PV and wind turbine end-of-life material streams presented above relied on several assumptions for key parameter values due to the lack of publicly available data. These included (1) lack of data on current end-of-life solar PV and wind turbine materials and volumes; and (2) uncertainties on the projections for the installed capacity of solar PV and wind; the mass-to-power ratio; degradation scenarios; and the definition of solar PV waste (for further detail, see technical note at end of this document). Addressing these uncertainties and data gaps will be essential to accurately estimate the magnitude of the challenge that lies ahead in terms of end-of-life material management, and also to establish recycling targets and better understand the socio-economic opportunities that accompany the circular economy transition.

PATHWAYS TO REDUCE RESOURCE CONSUMPTION, EXTEND THE LIFE OF PRODUCTS AND RECOVER VALUE, AND ASSOCIATED CANADIAN CAPACITY

The circular economy (CE) is a conceptual model that has begun to emerge in business, policy, and civil society discussions as a potential response to global challenges of unsustainable resource use and associated environmental impacts (including carbon emissions and other environmental degradation). The circular economy model promotes three main principles: (i) design out waste and pollution, (ii) keep products and materials in use, and (iii) regenerate natural systems. Importantly, the circular economy also represents a potentially powerful economic strategy to capture value from current "waste" products and processes. The circular economy model, its strategies, and practices offer a pathway to a Canadian renewable energy transition that has a lower carbon footprint and also incorporates broader concerns about overall environmental sustainability.

The circular economy goes far beyond the traditional 3R's (Reduce, Reuse, Recycle) model of waste management. It focuses on managing resources to keep materials and products recirculating in the economy at their highest utility and value by rethinking, redesigning, reducing, and reusing. It also proposes new business models such as platforms for sharing and exchanging products and services, selling products as a service rather than the product itself, and shifting responsibility for the post-consumer stage of a product's life cycle to producers (Extended Producer Responsibility).[39]

Pathways to reduce resource consumption, extend product life, and recover value

Applied strategies for solar and wind technologies across the extraction, manufacturing, distribution, use and end-of-life stages were identified by reviewing existing best practices worldwide. These are described below, organized according to three broad circular economy objectives: i) reduce resource consumption, ii) extend the life of products and components, and iii) recover value by giving resources new life.[†, 40]

† A 4th standard broad circular economy objective, intensify product use, is not covered since promising and appropriate strategies for wind and solar were not identified.

The circular economy model offers a pathway to a Canadian renewable energy transition that has a lower carbon footprint and also incorporates broader concerns about overall environmental sustainability.

Reduce resource consumption

Ecodesign : *an approach to designing product with special consideration for the environmental impacts of the product during its whole lifecycle.*

Over 80% of product-related environmental impacts are determined at the design phase of a product. Ecodesign aims at reducing the environmental impact of products throughout their entire life cycle through use of low impact materials (e.g. secondary, non-toxic), reduction of material usage, optimization of end-of-life system, etc.[41,42]

End-of-life waste of renewable energy technologies like solar panels and wind turbines can be dramatically reduced if they are designed for dematerialization, repair, upgrades, refurbishment, and recycling. Considering these needs at the design stage can also enable higher uptake of circular strategies at later stages of the lifecycle. For this reason, the EU recently studied the feasibility of proposing ecodesign regulations among other policy instruments for solar photovoltaic modules, inverters, and systems. New regulations based on this study's recommendations are expected soon. Research and development is also underway globally to reduce the use of indium, glass, polymers, silicon, and silver in solar panels, driven by considerations of performance, cost reduction and eco-design.[43] In the case of wind turbines, various institutions are researching more recyclable designs and material compositions of rotor blades.

Certain sub-technologies are also inherently more eco-efficient to produce. For example, second-generation thin-film solar panels produced by the company First Solar have a carbon footprint six times less and a water footprint 24 times less relative to first-generation silicon solar panels. Consequently, these thin-film solar panels also have shorter energy payback‡ periods.[44]

Extend the life of products and components

Repair and Maintainance: *preventative, planned or ad hoc inspection/ servicing tasks, which may involve repairs to restore a component to a good working condition*

Regular maintenance and repair can extend the useful lifespan of wind and solar technologies. Artificial Intelligence is fueling an evolution from reactive to predictive maintenance, preventing costly downtime and hazardous emergency repair work. For instance, automated drones can be flown over offshore wind farms to reduce inspection time and trigger predictive maintenance activities to extend the life expectancy of gearboxes, bearings, and other equipment. It is estimated that the market for digital services in renewable energy will grow to nearly $90 billion by 2030.[45]

In the case of solar panels, defective panels can typically be returned to the contract partner, a producer service partner, or the producer itself for inspection and repair. If defects are discovered in the early phases of a panel's life, customers can claim

‡ The period in which the PV system can produce the same amount of energy that the PV system will consume over its lifecycle..

warranties or guarantees for repair. When repairs are both required and feasible, they typically involve applying a new frame, new junction box, diode replacement, new plugs and sockets, and more.[46] However, given rapid improvements in the performance efficiencies of new solar panels, replacement is often considered a better financial decision than repair.

In the case of wind turbine blades, minor repairs of flaws or stone damage may occur a few times during the 20-year blade lifetime. Usually, major repairs only occur for specific blade batches and are typically caused by manufacturing defects or design defects or to fix damages due to extreme weather.[47]

Product as a service: *a business model delivering performance rather than products, with ownership of the asset, and often its repair and maintenance, retained by the service provider*

In the product as a service business model, the service provider is responsible for maintenance, repairs, and recovery of assets, theoretically creating an incentive to ensure a longer lifespan of assets, high-quality repairs and maintenance, and increased end-of-life recovery.[48] Leasing models for both residential and commercial solar PV systems currently exist in many markets, including Canada, and can include repairs and maintenance and a warranty for the life of the panels. Power Purchase Agreements for green power are an alternative to leasing and ownership whereby a customer commits to buying a certain number of kWh of energy from a provider, generated either at the consumer site or be transmitted from another location.[49] Bullfrog Power is an example in Canada.[50]

Direct Reuse: *the re-use of a product for the same purpose as it was originally used*

The degradation rate of a solar panel is less than 1% per year. There is a thriving international second-hand market for solar panels that have never been installed, been repaired or decommissioned for repowering, or those that have been uninstalled. The second-hand market for solar panels is concentrated in Asia, the Middle East, Africa, Latin America, and the Caribbean, where a used panel sells for 50- 70% of the original price.[51] This makes them attractive even though they come without the original manufacturer's warranty. Some resellers do test used panels to guarantee product safety, verify performance levels, and offer a limited-term service warranty or a money-back guarantee.[52] However, there are no commonly accepted standards or regulations for second-hand panels.

The reuse of wind turbines is challenging due to the difficulty in sourcing compatible replacement parts for older wind turbines as components, supporting technologies, and software become increasingly difficult to locate, maintain and operate.[53]

Refurbish: *extending a product's service life by replacing some or all components.*

Solar panels retain significant value and output capacity even at the end of their warranty, with most manufacturers guaranteeing at least 80% performance output after 20 to 30 years of life.[54] At this stage, they can either be reused directly or first refurbished and then reused. However, some solar manufacturers are uncomfortable with having their brand on a refurbished product due to reputational risks associated with having a product on the market for which they can no longer guarantee performance.

Wind turbine refurbishment is standard and can involve changing a major component or dismantling and replacing the complete wind turbine. Refurbished turbines are a cost-effective alternative to new turbines, delivering a shorter payback period and with a 2-3 months lead time compared to 2 years for a new turbine.[55] However, they also come with a shorter warranty. In 2018, the European market for wind turbine gearbox repair and refurbishment was valued at over USD $3.8 billion and expected to grow at a compound annual growth rate of 8.17% between 2020-2027.[56]Circular economy strategies require training and availability of a skilled task force to undertake the necessary services.

Repurpose: *the re-use of a product for a different application than what is was originally used for usually of a lower value than the original*.

In absence of viable options, there are some creative examples of repurposing of wind turbine blades to build structures like bicycle shelters, walkways, playgrounds and street furniture. However, most of these applications are one-off examples and are unlikely to be a large-scale solution for end-of-life blades.[57]

Recover value by giving resources new life

Recycle: *the collection and preparation of wastes into materials that can re-enter production, and the reprocessing of recyclates into new components.*

Bulk recycling of solar PV and wind turbines can be done by existing recycling facilities and markets for materials such as glass, iron, steel, and aluminum but not for specialty materials like other metals and semi-conductors which have higher strategic value. In high-value recycling, both bulk materials and specialty materials (metals and semi-conductors) are recovered.[§] Canada does not yet have specialized facilities for this high-value recycling, nor the volumes to make domestic facilities economic (see p.11).

The materials in solar PVs have significant value, estimated at US$450 million globally for projected installed capacity by 2030 and US$15 bilion by 2050.[58] The recycling potential for panels varies by sub-technology and depending on recycling infrastructure. Silicon-based and thin-film solar PV use distinct industrial high-value recycling processes. In the European context, as much as 90% of the materials for silicon-based and up to 97% for non-silicon-based PV modules are reported to be recyclable.[59] With silicon-based panels, 95% of the glass parts and the aluminum frame can be recycled after disassembly, and the remaining materials can be separated and captured for reuse through thermal processing.[60] Thin-film panels can be recycled using a combination of mechanical and chemical treatments, a process that can achieve about 90% recovery of the glass and about 95% of the semiconductor material by mass.[61,62] Silver is the most valuable material in PVs; however, silver recovery is still technically challenging. New recycling processes for solar panels are continuously being developed as the solar market grows and more waste is anticipated from these technologies.

§ High-value recycling ensures 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).

For wind turbines, 85%-90% of total mass can be recycled. Concrete, iron, and steel used in the foundation, tower, and parts of the nacelle have enough value for secondary markets.[63] However, due to size and composition, recycling of the rotor blades is a major challenge. While typically designed to be lightweight and only constitute 2-3% of the wind turbine's mass,[64] rotor blades can be 80m in length or longer and still weigh up to 30-35 tons each, making them difficult to transport.[65] They are typically made of glass, or carbon fibre reinforced composites and built to withstand extreme weather, making them very difficult to remelt and remold. Older glass fiber blades can be recycled as a component of cement mix (cement clinker). This process reduces the carbon footprint of cement production by burning the polymer matrix as fuel, but the glass's fiber shape disappears and therefore cannot be used in other composites applications.[66] Recycling processes for more recently used carbon fibre composites have not yet reached commercialization. A key factor stalling their uptake is that in many cases, the recycled material cannot compete with virgin materials' price.[67]

A gap between possible circular economy practices and their current implementation is not unique to solar and wind technologies.

Energy Recovery: *recovery of the energetic input invested into the preparation of materials and components*.

For material components that cannot be reused, refurbished, or recycled, energy recovery is a preferable waste handling process to sending waste to landfills. A portion of manufacturing waste from solar panels, and components from end-of-life that cannot be reused or recycled, are directed towards energy recovery. In the case of wind turbines, if rotor blades made of carbon fibre can be cut down to a reasonable size, the composite material can be mixed with municipal waste and burned to produce useful heat. During this high-temperature process, organic substances are combusted and converted into non-combustible material (ash), flue gas and energy. The resulting ash can be used as a substitute for aggregate in other applications or failing that must be landfilled.[68] This practice is not possible for glass fibre blades, which are not combustible.

Barriers to broader deployment and scaling of these practices

A considerable gap between possible circular economy practices and their current implementation is widely observed in circular economy literature,[69] and therefore not unique to solar and wind technologies.

One of the main technical obstacles to the efficient and safe recycling of end-of-life solar PV is treatment of its composite components, specifically the separation of ethylene-vinyl acetate (EVA) from the glass of many c-Si panels.[70] For wind turbines, the main technical obstacle is the absence of economically viable and mature recycling channels for composite material in blades,[71] which is leading to landfilling at their end-of-life. Composites represent the second largest material stream for a wind turbines end-of-life (see Table 2) and will require novel solutions for recycling. Currently, research is focussing on a range of alternatives, including material and design choices for greater recyclability or reuse; methods to extend blade life; mechanical recycling; and cement co-processing.[72] Standardization and modularization in solar PV and wind turbine design would also increase the potential for disassembly and recycling.[73] Refurbishment and recycling of wind blades also face a reverse logistics transportation barrier due to their length. Finally, because Canada imports the majority of its solar PV and wind turbine components, there is a barrier to the dialogue between product designers or OEMs and Canadian-based

Currently, Canada has no regulations for the recycling of solar PVs and wind turbines, nor any dedicated solar panel or wind turbine recycling facilities.

recyclers which could enable adaptable recycling processes and increase potential for returning valuable material components that face potential supply bottlenecks in the near future to manufacturers. Potential EU ecodesign regulations for solar panels (see p.12) are of interest in this regard.

Financial barriers to recycling are created when the cost of virgin materials is lower than secondary materials (dampening demand for cycled materials). In the absence of established systems, low costs for landfilling may also be more attractive than investing in circular strategies such as reuse, resale, or recycling. High collection costs due to geography pose a uniquely Canadian barrier to domestic recycling of solar PV and wind materials, as disaggregated distribution of installed solar PV and wind turbines will make it challenging to pinpoint a central location to establish recycling facilities, and to reach volume thresholds for more specialized recycling systems. Financial barriers for circular economy strategies other than recycling include the high cost for performance and reliability testing for reuse and lack of purchase incentives, which make refurbished solar PVs not as attractive financially as new panels.[74] Finally, changing business models comes with upfront investment and transition cost,[75] a barrier to product as a service models.

Reuse and recycling of solar PV and wind technologies can be boosted through regulations to extend and close material loops, and internalize the environmental impacts associated with their production and end-of-life. Conversely, the absence of such regulations can be an obstacle to uptake of circular strategies in the free market. The absence of certification for second-hand solar panels creates uncertainties over their performance and hence a barrier to their sale and reuse. Unlike some other jurisdictions, Canadian provinces and territories currently have no restrictions on landfilling of solar PVs and wind turbine blades, have not designated solar PVs as hazardous waste, and have not developed Extended Producer Responsibility (EPR) regulations to mandate recycling of these technologies.[¶] With British Columbia currently consulting on the potential inclusion of solar PV panels under its Extended Producer Responsibility regulations, consideration should be given to a co-ordinated Pan-Canadian policy approach to reduce inconsistent inter-jurisdictional regulatory requirements and create economies of scale for domestic recycling capacity.

Canadian industrial capacity assessment

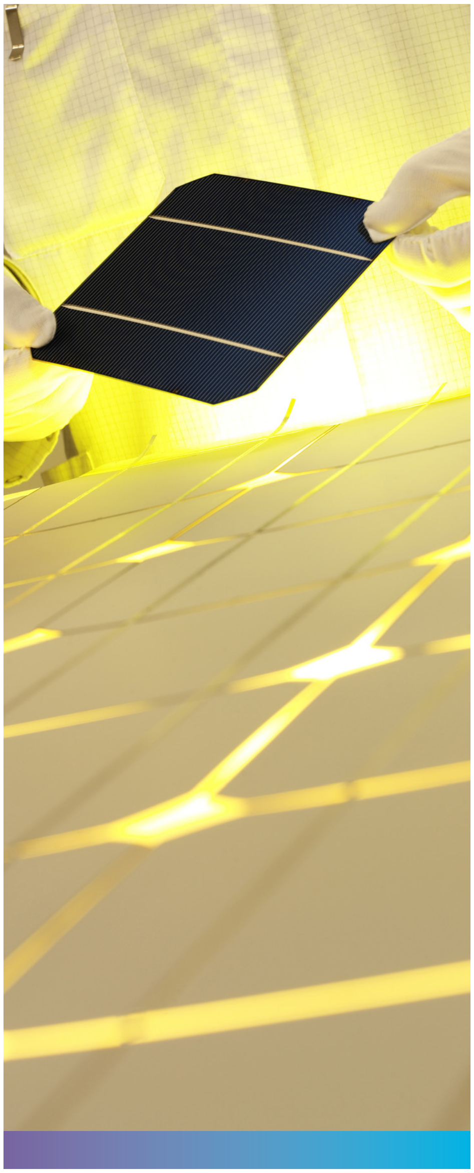
End-of-life solar PVs and wind turbines represent a valuable resource, containing substantial amounts of critical and strategic minerals essential for the transition towards a low carbon future and subject to potential supply bottlenecks in the near future. Yet currently, Canada has no dedicated solar panel or wind turbine recycling facilities.

Solar PVs

End-of-life solar PVs in Canada are currently either being landfilled, stockpiled awaiting recycling systems, or voluntarily collected and shipped by two companies to specialized solar panel recycling facilities in the U.S..[76] An Alberta pilot project

¶ However, some municipalities in Ontario have been refusing to accept decommissioned wind blades and turbines due to concerns about limited landfill capacity, and BC is currently consulting on the potential inclusion of solar PV under their EPR regulations.

to accept solar panels as part of an expansion of electronic recycling is exploring existing bulk recycling avenues(see p.13).[77] For reuse, a Canadian company recently began collecting end-of-life solar panels to ship to partners in developing nations for use in local installations.[78] High collection costs due to Canada's geography, including the growing use of these technologies in remote communities, and a lack of supporting regulations such as EPR currently pose a bottleneck in establishing dedicated domestic solar panel recycling facilities. However, municipal push for having more products being added to EPR regulations, increasing end-of-life waste volumes, and research into mobile recycling units' potential may change the outlook for solar PV recycling in Canada.[79]

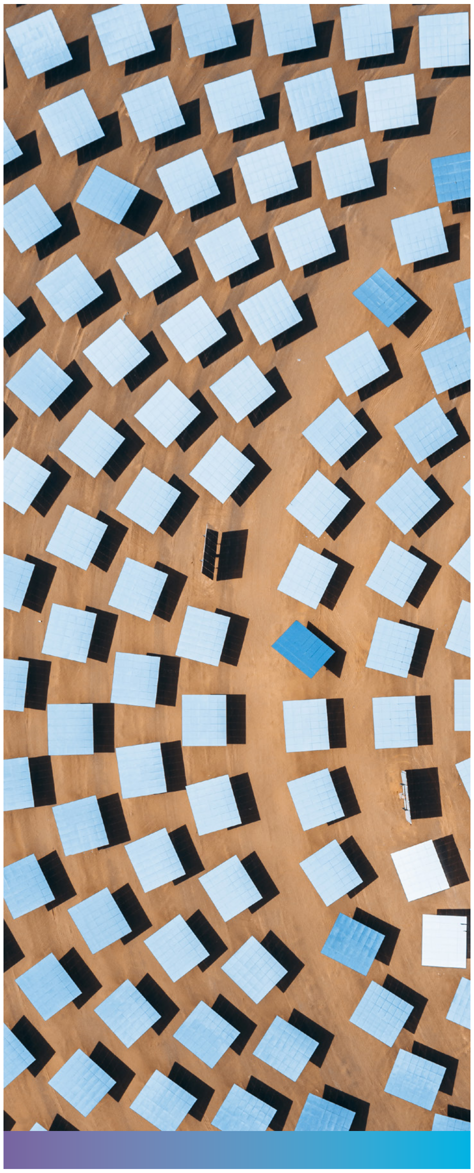


Currently, the waste streams for end-of-life solar PV are small, and as such, there is very little investment directed towards specialized PV recycling plants.[80] One expert identified an annual end-of-life waste volume of 10,000 tonnes for solar PVs as the baseline to establish a dedicated solar recycling facility.[**] The modeling for this study suggests that Canada as a whole may not generate this kind of flow rate until somewhere between 2030 and 2035,[††] and given the current distribution of installed capacity, this is likely to be clustered in Ontario. Thus, regionally oriented north-south Canada – US specialized recycling clusters will be more attractive for most regions of Canada for the foreseeable future and for Ontario in the near future. In the interim or as an alternative, existing steel, glass, and e-waste recycling facilities could be adapted to recycle the end-of-life solar PV panel and wind turbines, however potentially with lower or inefficient recovery rate for specialty metals. Metal and glass recyclers have begun to show interest in PV waste and see it as a future business opportunity.[81]

Wind Turbines

For wind, 85% to 90% of a wind turbine's total mass can currently be recycled.[82] The decommissioning of TransAlta's commercial wind farm at Cowley Ridge in Alberta, Canada's oldest commercial wind facility, successfully recycled 90% of the turbines – approximately 1,252,000 kilograms of metal. The sale of the recovered metal allowed TransAlta to cover 50% of the wind farm's decommissioning costs.[83] Significant quantities of lubricants and dielectric fluids (used in transformers) were also recovered; this could be managed under used oil EPR schemes already in place in several provinces and with established industrial recycling capacity. However, the lack of economically viable recycling for blades remains a significant bottleneck, resulting in landfilling or warehousing of end-of-life blades.

** Expert interview conducted by authors, March 2021.
†† Based on panel degradation rate of "Early Loss" scenarios



POLICY OPTIONS TO MINIMIZE WASTE GENERATION AND ENCOURAGE CIRCULARITY OF MATERIALS, AND FURTHER RESEARCH NEEDS.

Non-hydro renewable energy sources are relatively new in the Canadian energy landscape, proliferating only in 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. While 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 will grow exponentially post 2025, from 2,700 tonnes today to 9,000 tonnes/year by 2030 and 13,500 tonnes/year by 2035, a 400% increase.[‡‡] 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.

In a Canadian context, there is therefore a modest lead time to develop and implement strategies, capacity and infrastructure, and the required policies and regulatory frameworks to minimize waste generation and encourage circularity of materials for these two renewables. Experiences of other jurisdictions with a lead in introducing policies to reduce and manage the end-of-life materials generated from renewable energy technologies may be drawn from to inform future approaches In Canada. New research to fill knowledge gaps, data collection, and planning for future infrastructure requirements will also be needed.

Global Policy Review

Solar PV

Specific solar PV panel waste regulations are present in only a few jurisdictions, with most countries classifying it as general or industrial waste. However, many jurisdictions are now beginning to consider, research, and propose regulations in this area.

The European Union (EU) is currently the only jurisdiction with national waste regulations specific to solar PV, which came into force in 2014 under their Waste Electrical and Electronic Equipment (WEEE) Directive.[84] All producers (regardless of location of manufacturing) selling solar PV in the EU are liable for the costs

‡‡ See Part 1 for assumptions and scenarios

of collecting, treating and monitoring of the ensuing waste. These include responsibilities for the cost of collecting and recycling of products; reporting on panels sold, taken back, and forwarded for treatment; reporting on tonnes treated, recovered, recycled, and disposed of by material; and providing information to buyers and waste treatment companies about appropriate end-of-life procedures. The WEEE Directive currently sets an annual collection target of 65% (by weight) of equipment put on the market or 85% of waste generated, an annual recovery target of 85% and an annual recycling target of 80%.[85] This, along with supplementary standard and technical specification for PV panel collection and treatment released in 2017,[86] has resulted in the implementation of high-value recycling processes in the EU. The 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.[87] The EU also included solar panels in the Ecodesign Working Plan 2016-2019 and are expected to introduce ecodesign legislation based on the findings of a preparatory study published in 2019.[88]

Alberta is piloting an expanded electronics recycling project that includes solar PVs, and BC has announced plans to include solar panels in its EPR strategy.

The United States has no federal laws or regulations specifically on the end-of-life management of solar PV. Solar waste modules are governed by the federal Resource Conservation and Recovery Act (RCRA) and evaluated using the characteristic hazardous waste method to determine if they exceed the regulatory levels of hazardous waste. In most cases, they are deemed hazardous and, as a result, cannot be disposed of in landfills.[89] At the sub-national level, Washington State is the leader, with a 2017 bill creating the Photovoltaic Module Stewardship and Takeback Program, under which manufacturers must finance the takeback and recycling system for all modules purchased after July 1, 2017 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.[90,91] In other states, Illinois started a Solar Module Recycling Initiative in 2017, Minnesota established Solar Module Recycling Strategy Working Group in 2019, while California and New York are in the process of developing regulations.[92] In addition, the United States has several industry-led collection and recycling initiatives, and the first dedicated solar panel recycling facility in the US was opened in 2018.[93]

In Japan, 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.[94]

There are no specific end-of-life solar PV regulations in place in Canada; PV modules are regulated by common waste management legislation. Solar PVs are neither classified as hazardous waste nor as recyclable waste (e-waste) in Canada. In provinces like British Columbia and Quebec, where solar PV are largely used in the residential sector, they are considered construction waste. Solar PV is also not currently included in any provincial and territorial EPR programs, nor in the 2009 Canada-wide Action Plan for Extended Producer Responsibility by the Canadian Council of Ministers of the Environment.[95] There are however signs of change. In 2020, the Alberta Recycling Management Authority, which implements the Province's stewardship programs, began a two-year pilot project to accept new categories of electronic products, including solar panels. Under this pilot, municipalities will receive funding for collecting the additional electronics included in the recycling expansion. Options are being explored to recycle these through existing bulk recycling sectors.[96] In 2021, the Government of British Columbia however, announced its intention to include solar panels in its Recycling Regulation and EPR

strategy.[97] This was largely prompted by the Ministry's focus on reducing local government costs and shifting the burden of waste management away from taxpayers and Indigenous communities.[98]

Wind turbines

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 markets and 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.

Unlike solar PV, wind turbine waste does not come under the ambit of the revised EU WEEE Directive, which explicitly excluded 'large-scale fixed installations', such as wind turbine stations (including their cabin, wings, equipment in tower, cranes). However, some European nations have introduced regulations that have a bearing on wind turbine blade waste. In the Netherlands, landfilling of composite waste is banned, with exemptions where the cost of alternative treatment is higher than 200 EUR/t. In practice, most wind farm operators can get this exemption and landfill their wind turbine blades.[99] Germany bans direct landfilling of waste with an organic content higher than 5%, and 10,000 tons/year of wind turbine blades are consequently sent for cement co-processing.[100] A 2019 study for the German Government made numerous recommendations for wind turbine decommissioning and waste management, including many elements of producer responsibility. That same year, a study on wind turbine circularity commissioned by the French Government recommended introducing EPR for wind turbine blades. However, this was not implemented as it was deemed that joint efforts between authorities and the industry would be more likely to be successful in increasing blade recycling.[101]

Canada currently has no specific end-of-life management regulations for decommissioned wind turbines. Off-shore wind farms such as those in Ontario however, would be subject to the United Nations Convention on the Law of the Sea (UNCLoS),[102] which states that "*Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation…*". In light of decommissioning costs to $30,000 to $80,000 per turbine, some authorities in Ontario and Alberta have begun requesting letters of credit or decommissioning bonds to be furnished by wind project developers.[103] 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.[104] This does not, however, specify recovery nor how the decommissioning should be done.

Proposed Policy Objectives and Menu of Potential Policy Instruments

Five policy objectives are proposed to support the circularity of materials used in solar PV and wind technologies by reducing resource consumption, intensifying the use of renewable energy products, extending their lifespan, and giving these materials a new life post-consumption:

1. Divert waste from renewable energy technologies from landfill;

2. Recover critical minerals and metals used in renewable energy technologies and support the creation of markets for the secondary materials;

3. Shift the onus of end-of-life management of renewable energy technologies from the public to the producers of the products;

4. Encourage the consideration of lifecycle impacts in the procurement of renewable energy technologies; and

5. Align with emerging international policies and practices.

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 or policy packages for Canada, as this seems premature in light of crucial data gaps, the need for further technical assessment, and stakeholder input. The list is also agnostic to the level of Government having jurisdiction to employ the policy tool. Some thoughts on temporal and volume threshold considerations to policy timing follow.

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

The following policy instruments help to create strong market signals for better value recovery and end-of-life materials management:

Encouraging ecodesign, repair and reuse

- **Ecodesign regulations:** 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, repairability, dismantlability, recyclability, etc. More standardization of these technologies across the industry will facilitate easier value recovery and better end-of-life management.

Policy instruments can be deployed along the lifecycle of wind and solar energy technologies to minimize waste generation and support circularity of materials used.

- **Tax incentives:** encourage more repair, reuse, and recycling activities, and incentivize use of secondary raw material. This should be accompanied by reviews of related regulations to ensure barriers to adoption/use of secondary material are removed or adjusted appropriately. Tax incentives to increase uptake of new technologies should also be assessed for inadvertent incentives to accelerate capital stock turnover of otherwise still productive existing installations.

- **Labeling and certification**: There are two aspect to this. The first would inform purchasers of the lifecycle impacts of renewable energy technologies by disclosing the energy intensity, material composition, hazardous substance use, degradation rates, durability, repairability, recyclability etc. The second would set guidelines for testing and certification for second-hand panels to stimulate domestic and international second-hand markets.

Managing end-of-life through EPR and regulations

- **Extended Producer Responsibility:** assign to producers[§§] full financial and physical responsibility for managing their products at their end-of-life, which could incentivize improvements along the whole value chain from design to manufacturing to post-consumer waste management. Consideration should also be given to waste definitions in EPR development to allow for product life-extension opportunities, where units reach their OEM-defined optimal performance levels.

- **Legally binding end-of-life standards/guidelines/regulations:** set specific collection and recycling regulations for renewable energy technologies at end-of-life, such as recycling and treatment standards; and requirements for project developers to detail how they will manage their waste on decommissioning, and/or to post bonds to ensure funds to implement these plans should the company goes bankrupt.

- **Waste classification :** appropriate waste classification can protect human health and the environment by ensuring proper management of these materials at end-of-life. Classification could be based on the hazardous material composition of solar PV and wind turbines and should be considered as part of recycling regulation development.

- **Landfill bans**: restrict landfilling of select products or materials. But note, this should only occur after alternative end-of-life material management pathways are created.

Supporting businesses that develop and provide circular practices

- **Financial support:** enable the development of new businesses in related energy and waste sectors, including those providing repair and recycling services, as well as for capital-intensive dedicated recycling infrastructure.

- **Public Procurement guidelines/criteria:** can minimize lifecycle cost and environmental impacts of renewable energy procurement commitments, allowing governments to lead by example and provide a test bed for market innovation.

§§ Producers may be defined to include domestic and/or international manufacturers, resellers, and importers of technology products.

- **Non- financial support:** encourage the growth of domestic solar PV and wind turbine repair and recycling services by offering technical support, advisory, training, demonstration of best practices, etc.

Supporting 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 (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-centry net zero target.

- **Targets:** mobilize private sector initiatives by establishing binding and measurable recovery and recycling targets from end-of-life solar PV and wind turbines in future renewable energy policies, strategies, plans, and programs.

- **End-of-Life policy coherence across provinces/territories and alignment with international standards and best practices:** supports efficient and cost-effective recovery and recycling of materials and takes into consideration the global nature of solar PV and wind turbine supply chains.

- **Partnerships:** engage and enable the cooperation of a wide array of stakeholders across the lifecycle and value chain of these technologies (project developers, manufacturers, consumers, recyclers etc.)

- **Skills, Training & Workforce Development:** trains the workforce needed to develop the technical, regulatory, logistics, and management systems necessary to maximize value extracted from growing renewable energy technology end-of-life material streams, including specific education and training on repairs, maintenance, and refurbishment to extend the lifetime of these technologies

- **Data Collection and Monitoring:** collects 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 renewable energy technologies.

Canada is more than a decade away from seeing the volume threshold necessary to establish dedicated domestic end-of-life solar PV recycling facilities.

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. Municipalities and regional waste authorities may continue to bear much of the onus for end-of-life management for legacy stock. Some policies, such as tax incentives for repair and reuse, testing and certification for used panels, end-of-life standards, or landfill bans, can apply to both legacy and future stock. Other policies may only be applied to future stock, but put in place now to establish the design expectations, create 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, establish material passports that are accompanied with global databases on panel and turbine contents, establish 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. Modelling for this study indicates that this annual end-of-life solar PV waste flow rate may only be achieved between 2030 and 2035 in Canada,[¶¶] 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.

Potential research areas to improve evidence for policy making

Policies for value recovery opportunities and end-of-life management for solar PV and wind turbines require improved evidence of the scale of the opportunity/challenge as well as the technical and policy options. Potential areas for future research are presented in Table 3.

¶¶ Based on differing rates of panel degradation under the two modelled scenarios

Table 3: Areas for potential future research

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 the evolution of losses in solar PV and wind turbines.	To account for regional variations and to improve the 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.
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.

CONCLUSIONS

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. Doing so can make climate change and circular economy objectives mutually supportive. 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. Circular economy strategies and policies can extend the life of solar PVs and wind turbines and make it easier to recover value and close material loops, while diverting waste from landfills.

Despite these synergies, the climate change and circular economy agendas in Canada are currently progressing in silos.

Installed capacity of solar PV and wind renewables in Canada's energy landscape has accelerated during the past two decades; solar capacity is projected to expand a further seven-fold, and wind capacity a further three-fold in the coming three decades, even under the conservative CER "Evolving Scenario" used in our modelling. Due to their long lifespans, these technologies are only now reaching end-of-life at sufficient scale to bring attention to their emerging waste streams. Fortunately, the vast majority of past installations are still a decade away from end-of-life, allowing time for policy deployment.

Policies need to differentiate between management of end-of-life material streams from existing installed capacity, forward-looking policy intervention now to influence the opportunities for value-recovery and assignment of the onus for end-of-life management of future installed capacity, and preparation for the escalation of end-of-life material flows within this decade.

Modelling done for this study projects that annual end-of-life material streams from solar PV will increase 400% by 2030, and 1,000% by 2050.[***] In 2019, 94% of Canada's installed solar capacity was in Ontario, suggesting that Province will initially be at the forefront of managing these end-of-life material streams.

Currently, Canada has no dedicated solar panel recycling facilities or targeted policies. End-of-life solar PV in Canada are either being landfilled, stockpiled to await recycling systems, or voluntarily collected and shipped to specialized solar panel recycling facilities in the U.S. These panels are predominantly glass, polymers, and aluminum: components which can be recycled in existing Canadian bulk recycling industries. However, high-value recycling facilities would capture the smaller volumes of metals and semi-conductor materials which have higher economic and strategic value. The annual end-of-life volume of 10,000 tonnes, identified to authors as the threshold for a dedicated high-value solar recycling facility, is far above Canadian volumes--*cumulative* end-of-life material streams are calculated to range between only 253-7,921 tonnes to date in Canada.[†††] This volume flow rate might be reached between 2030 and 2035,[‡‡‡] although the geographic distribution of the materials would likely make north-south Canada-US specialized regional recycling clusters more logical even at that time, except in Ontario.

*** Under the CER Evolving Scenario, with 2050 carbon price at $125 (2019$).
††† Based on differing rates of panel degradation under the two modelled scenarios.
‡‡‡ Based on differing rates of panel degradation under the two modelled scenarios.

For wind installations, the annual end-of-life material streams will be five-to-six-fold larger by 2030, and eleven-fold larger by 2050.[§§§] In 2019, Ontario had 40% of Canada's installed wind capacity, followed by Quebec at 29% and Alberta at 12.5 %, suggesting that these three provinces will initially be at the forefront of managing these material streams.

Although Canada also has no dedicated wind turbine recycling facilities, 85% to 90% of a wind turbine's total mass can readily be recycled, since the concrete, iron, and steel used in the foundation, tower, and parts of the nacelle have well-established and economically viable domestic secondary markets. However, the lack of economically viable recycling for rotor blades, as well as their size and weight, remains a significant bottleneck, and is resulting in landfilling or warehousing of blades at end-of-life. Anecdotally, some municipalities in Ontario are refusing to accept decommissioned wind blades due to concerns about limited landfill capacity. In Europe, older glass fiber blades are being recycled as a component of cement clinker, but recycling processes for newer carbon fibre composites have not yet reached commercialization.

Under current Canadian policies, these solar PV panel and wind blades end-of-life materials risk continuing to be landfilled, imposing high new costs on local governments, including under-resourced rural, remote, and Indigenous communities, and putting the burden of waste management on taxpayers. These material streams also 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.

Circular economy policies, strategies, and practices offer a pathway to a renewable energy transition that incorporates the sustainability of materials alongside reducing carbon emissions while providing a potentially powerful economic strategy to capture value from current waste products and processes. These go far beyond the traditional 3R's (Reduce, Reuse, Recycle) thinking of waste management to focus on keeping materials and products recirculating in the economy at their highest utility and value by rethinking, redesigning, reducing, and reusing. In keeping with emerging international policy directions, policies to support this shift should seek to divert waste from renewable energy technologies from landfill; recover critical minerals and metals used in renewable energy technologies and support the creation of markets for the secondary materials; while encouraging the consideration of life cycle impacts in the procurement of renewable energy technologies. Policies and regulatory approaches can incentivize improvements in material use and waste recovery along the whole value chain, from design to manufacturing to post-consumer resource management – including approaches to extend financial or physical responsibility for managing solar PV and wind energy technologies at end-of-life to producers.

This first effort to explore the eco-efficiency, value recovery opportunities and end-of-life considerations of Canada's transition to a more wind and solar-powered energy system, and modelling related future end-of-life material flows, should be considered preliminary. More evidence is needed to inform policymaking. There remains a need to address crucial data gaps which limit the modelling of future end-of-life scenarios, conduct more in-depth assessments of recycling options and capacity, and consider stakeholder input on policy options. However, even though preliminary, these findings clearly identify the need for parallel policy attention to the integration of critical resource, waste management, and end-of-life considerations into evolving strategies to increase the uptake of renewable energy technologies across Canada.

Evolving strategies to increase the uptake of renewable energy technologies across Canada need to be paralleled with similar attention to policies designed to address equally critical considerations of the material needs and end-of-life management implications of this transition.

§§§ Under the same CER Evolving Scenario as above.

TECHNICAL NOTE ON MODELLING

A methodology was developed to model the waste generation profiles and volumes for future Canadian wind and solar energy sources. Due to data limitations and uncertainties, the objective of this modelling is to be illustrative of potential future scale, not precise.

The methodology draws on installed capacity projections from the 'Evolving Scenario' of Canada Energy Regulator (CER)'s Canada's Energy Future 2020 report.[105] It must be underscored that the policy stringencies under this scenario are not sufficient to reach net-zero emissions in 2050; it is considered mid-way between the old reference scenario and a net-zero scenario. A sensitivity analysis using a more ambitious ('High Hydro") scenario from Canada's Energy Outlook revealed that end-of-life materials from solar PV and wind technologies' real development potential in Canada could be underestimated, but most of this end-of-life material flow will be post 2050.

This installed capacity scenario was combined with methodologies to project solar PV end-of-life materials developed by IRENA & IEA-PVPS [106] and Santos et.al.[107] For solar PV, two scenarios were modelled due to uncertainties on rates of panel degradation. The 'Regular Loss' scenario assumes the shape factor for solar panel losses extracted from Kuitche et al. – which is based on a group of c-Si PV modules being monitored over 8 years in Arizona.[108] The 'Early Loss' scenario introduces a corrected shape factor that accounts for statistical data on PV module failure during early life stages.[109] This methodology was also adapted to project wind turbine end-of-life resources.

The projections presented have some other limitations and uncertainties. These include uncertainties regarding the mass-to-power ratio used to convert installed capacity into mass since this profile may change over time, and a third, the degradation scenarios. Finally, the lack of a national inventory for end-of-life solar PV and wind waste makes it impossible to validate the projections, and indeed a final uncertainty lies in the definition of when a solar PV module and a wind turbine becomes 'waste' itself.

Due to these limitations, data gaps, and uncertainties, this first effort at a Canadian forecast should be interpreted as illustrative in scope, not in detail.

REFERENCES

1 Hund, K., Porta,D., Fabregas,T., Laing,T., Drexhage, J. (2020). Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank Group
2 Hund et.al. (2020).Op.cit.
3 Environment and Climate Change Canada (2020). National Inventory Report 1990–2018: Greenhouse Gas Sources and Sinks in Canada. Government of Canada.
4 J. David Hughes (2018). Canada's Energy Outlook - Current Realities And Implications For A Carbon-Constrained Future.
5 David Suzuki Foundation and partners (2016). Canada's Challenge and Opportunity: Transformations for Major Reductions in GHG Emissions.
6 CMC Research Institutes Inc. (2015). Pathways to deep decarbonization in Canada.
7 Canada Energy Regulator (2020). Canada's Energy Future 2020. Government of Canada.
8 Exter.P., Bosch.S., Schipper.B., Sprecher.B., Kleijn.R. (2018). Metal Demand for Renewable Electricity Generation in the Netherlands.
9 Ugranath Chakarvarty (2018). Renewable Energy Materials Supply Implications. IAEE Energy Forum
10 Exter et.al. (2018). Op.cit.
11 Exter et.al. (2018). Op.cit
12 World Bank Group (2020). Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.
13 World Bank Group (2017). The Growing Role of Minerals and Metals for a Low Carbon Future.
14 Hund et.al. (2020).Op.cit.
15 Chris Martin (2020). Wind Turbine Blades Can't Be Recycled, So They're Piling Up in Landfills. Bloomburg.
16 Michael Shellenberger (2018). If Solar Panels Are So Clean, Why Do They Produce So Much Toxic Waste?. Forbes
17 Canada Energy Regulator (2020). Op.cit.
18 International Energy Agency (2019). National Survey Report of PV Power Applications in Canada. IEA Photovoltaic Power Systems Programme
19 Chowdhury. Md., Rahman. K., Chowdhury. T., Nuthammachot.N., Techato. K., Akhtaruzzaman. Md., Tiong. Sopian.K., & Amin. N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews. 27. 100431. 10.1016/j.esr.2019.100431
20 IRENA & IEA-PVPS (2016). End-Of-Life Management: Solar Photovoltaic Panels.
21 Xu, Y., et al. (2018). Global status of recycling waste solar panels: A review. Waste Management.
22 Government of Canada (2021). Critical minerals.
23 IRENA & IEA-PVPS (2016). Op.cit.
24 Santos,J.D. and Alonso-Garcia, M.C. (2018). Projection of the photovoltaic waste in Spain until 2050. Journal of Cleaner Production, Volume 196, Pages 1613-1628
25 Kuitche, Joseph M. (2010). Staistical Lifetime Prediction for Photovoltaic Modules [Online]. Available. http://www1.eere.energy.gov/solar/pdfs/pvrw2010_kuitche.pdf [Accessed January 2018].
26 International Energy Agency (2014). Technology Roadmap. Solar Photovoltaic Energy, 2014 edition.
27 Energy Alternatives India (2010). An Analysis of Opportunities in the Wind Power Value Chain. Exhibitions India Group.
28 Wood Mackenzie Power & Renewables. (2018). Global wind turbine technology market report 2018. Wood Mackenzie.
29 Kraemer, Susan (2014). Early bird will catch the worm in Canadian wind supply chain.
30 Delphi Group (2017). Alberta Wind Energy Supply Chain Study. Delphi Group.
31 Kraemer (2014). Op.Cit.
32 Canada Energy Regulator (2020). Op.cit.
33 CanWEA (2019). Installed Capacity.
34 Maharaj,K. & McMahon, A. (2020). Resource and waste quantification scenarios for wind turbine decommissioning in the United Kingdom. Waste Disposal & Sustainable Energy.
35 Wind Europe (2017). Discussion Paper on managing composite blade waste.
36 Hund et.al. (2020).Op.cit.
37 Government of Canada (2021). Op.cit.
38 Li.K., Peng.K, Wang.P., Zhang.N., Feng.K., Guan.D., Meng.J., Wei.W., Yang.Q. (2020) Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions. One Earth, Volume 3, Issue 1,2020, Pages 116-125
39 Lacy, P. and Rutqvist, J. (2015). Waste to Wealth: The Circular Economy Advantage. Accenture Strategy
40 Institut de l'environnement, du développement durable et de l'économie circulaire (I-EDDEC) (2018). Circular Economy in Quebec.
41 EU Science Hub. Sustainable Product Policy. European Commission.
42 Brezet, H., & Hemel, C.V. (1997). Ecodesign : a promising approach to sustainable production and consumption.

43 IRENA & IEA-PVPS (2016). Op.cit.
44 First Solar (2020). Sustainability Report 2020.
45 Dvorak.P., Totaro.P. (2017). Renewable energy IoT to hit $5.3 billion annually by 2030. Wind Power
46 IRENA & IEA-PVPS (2016). Op.cit.
47 Lui, P. & Barlow,C. (2017). Wind turbine blade waste in 2050. Waste Management, Volume 62, 2017, Pages 229-240, ISSN 0956-053X.
48 Gentilini, Emily & Michael Salt (2020). Circular Photovoltaics: Circular business models for Australia's solar photovoltaic industry. ARUP.
49 Ibid.
50 Bullfrog Power (n.d.) Power Purchase Agreements.
51 IRENA & IEA-PVPS (2016). Op.cit.
52 Schmid, Mellisa Ann (2021). Think before trashing: The second-hand solar market is booming. Solar Power World.
53 Froese, Michelle (2017). Decommissioning Canada's oldest wind farm.
54 Vazquez and Rey-Stolle (2008). Photovoltaic Module Reliability Model Based on Field Degradation Studies.
55 Solvento (n.d).Wind Turbine Refurbishing.
56 Research and Markers (2020). Europe Wind Turbine Gearbox Repair & Refurbishment Market Outlook & Projections, 2019-2027.
57 Schmid. M., Ramon.N., Dierckx.A., Wegman.T. (2020). Accelerating Wind Turbine Blade Circularity. Wind Europe.
58 IRENA & IEA-PVPS (2016). Op.cit.
59 PV Cycle (2016). Breakthrough in PV Module Recycling.
60 Vekony, Attila Tamas (2020). The Opportunities of Solar Panel Recycling. Green Match
61 IRENA & IEA-PVPS (2016). Op.cit.
62 Vekony (2020). Op.cit.
63 WindEurope, Cefic and EuCIA (2020). Accelerating Wind Turbine Blade Circularity.
64 Veolia (2018). How can wind turbine blades be recycled?.
65 Jensen.P., Velenturf.A., Purnell.P. (2020). Highlighting the Need to Embed Circular Economy in Low Carbon Infrastructure Decommissioning: The Case of Offshore Wind. Sustainable Production and Consumption 24:266-280.
66 WindEurope et.al. (2020). Op.cit.
67 Ibid.
68 Miceli.F. (2019). Circular economy: use of wind turbines blades as combustible and mix material for cement production.
69 Augusto Bianchini, Jessica Rossi and Marco Pellegrini (2019). Overcoming the Main Barriers of Circular Economy Implementation through a New Visualization Tool for Circular Business Models. Sustainability.
70 Arup (2020). Circular photovoltaics: Circular business models for Australia's solar photovoltaics industry. Arup, Australia.
71 Siqi Hao, Adrian Kuah, Christopher Douglas Rudd and Jianan Mao (2019). A circular economy approach to green energy: Wind turbine, waste, and material recovery. Science of The Total Environment.
72 NREL (2021). NREL Research Identifies Motivations, Methods for Achieving a Circular Economy for Wind Energy
73 Arup (2020. Op.cit.
74 Ibid.
75 Joanne Houston, Elisa Casazza, Marie Briguglio and Jonathan Spiteri (2020). Stakeholder Views Report: Enablers and Barriers to a Circular Economy. R2Pi.
76 Matthews , Leigh(2020). The glaring problem with Canada's solar sector and how to fix it. National Observer.
77 Expert interview conducted by authors, March 2021
78 pvbuzz (2020). Canada's Solar X revolutionizes the solar industry in Canada with the launch of its new solar panel reuse + recycle program.
79 Matthews (2020). Op.cit.
80 Wambach.K., Baumann.K., Seitz.M., Mertvoy.B., Reinelt.B., (2020). Photovoltaic (PV) Recycling, Reusing, and Decommissioning: Current Landscape and Opportunities for Standardization. CSA Group.
81 Wambach et.al. (2020). Op.cit.
82 Canadian Wind Energy Association (2020). Wind Turbine Blade & Other Composite Components Recycling Initiative. CanWEA.
83 Froese (2017). Op.cit.
84 IRENA & IEA-PVPS (2016). Op.cit.
85 Eurostat (n.d). Summary document of the Waste electrical and electronic equipment rates and targets. European Commission.
86 ITEH STANDARDS. (2017). Collection, logistics & treatment requirements for WEEE - Part 2-4: Treatment requirements for photovoltaic panels.
87 IRENA & IEA-PVPS (2016). Op.cit.
88 Nicholas, D., Nieves.E. (2019). Preparatory study for solar photovoltaic modules, inverters and systems. European Comission
89 IRENA & IEA-PVPS (2016). Op.cit.
90 Department of Ecology (n.d.) Reducing & recycling waste: Solar panels. State of Washington

91 Department of Ecology (2019). Manufacturer Plan Guidance for the Photovoltaic Module Stewardship Program. State of Washington
92 Wambach et.al. (2020). Op.cit.
93 Recycle PV Solar (n.d). Services Offered.
94 IRENA & IEA-PVPS (2016). Op.cit.
95 Matthews (2020). Op.cit.
96 Government of Alberta (2020). Province approves expanded electronics recycling pilot.
97 Government of British Columbia (2021. Province taking action to recycle more products.
98 Expert interview conducted for this study.
99 WindEurope et.al. (2020). Op.cit..
100 Ibid.
101 Ibid.
102 Ontario Ministry of the Environment and Climate Change (2016). Assessment of Offshore Wind Farm Decommissioning Requirements.
103 Gallant. C. (2019). Pair of wind farms clear regulatory governmental hurdles. Medicine Hat News.
104 Alberta Utilities Commission (2020). Draft Revision of Rule 007: Applications for Power Plants, Substations, Transmission Lines, Industrial System Designations and Hydro Developments.
105 Canada Energy Regulator (2020). Op.cit.
106 IRENA & IEA-PVPS (2016). Op.cit.
107 Santos et.al. (2018). Op.cit.
108 Kuitche, Joseph M. (2010). Staistical Lifetime Prediction for Photovoltaic Modules.
109 International Energy Agency (2014). Technology Roadmap. Solar Photovoltaic Energy, 2014 edition.

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Three working papers with more details on the findings in this Policy Brief are available at **institute.smartprosperity.ca/library**:

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

Working Paper 3: Solar and Wind Energy in Canada – Value Recovery and End-of life Considerations: Policy options to minimize waste generation and encourage value recovery and circularity in materials.

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