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SOLAR AND WIND ENERGY IN CANADA

VALUE RECOVERY AND END-OF-LIFE CONSIDERATIONS

PART 2.

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

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

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

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

Working Paper 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.*

About Smart Prosperity Institute

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

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Foreword

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

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

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

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

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

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

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

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

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

These findings from these related streams of work are presented in three parts (listed below), with part 2 presented in the document which follows:

1. Material needs and end-of-life resource flow implications under Canada's climate change objectives, and data gaps;
2. Pathways to reduce resource consumption, extend the life of products and recover value, and associated Canadian capacity; and
3. Policy options to minimize waste generation and encourage circularity of materials, and further research needs.

1. Introduction

As the transition to a low-carbon economy scales up, so does the development and deployment of low-carbon infrastructure. However, a review of academic and industrial literature reveals that a long-term vision or plan to deal with life-cycle material extraction, usage, and recovery across these technologies lags behind this deployment.

As documented in Part 1 of this report, solar and wind technologies contain millions of tonnes of valuable materials. Under current Canadian practices and policies, much of this risks ending up as landfill waste when these technologies reach end-of-life. There is a tremendous opportunity to sustainably recover, manage and return these materials to productive use, some of which will also be in scarce supply as the transition to a low-carbon economy accelerates.

Realizing this opportunity requires a rethink of linear take-make-waste models of low-carbon technology production, a rethink now underway. The emerging alternative is the circular economy model that aims to gradually decouple economic activity from the consumption of finite resources and design waste out of the system. [6] This model is already in evidence in selected sectors, for example metal recycling in the auto sector and lead-acid battery recycling.

The circular economy model, its strategies and practices offer a pathway to a Canadian renewable energy transition that also incorporates broader concerns about overall environmental sustainability. This report gives an overview of these strategies. It describes potential industry practices along the life-cycle of renewable energy technologies that can close or extend material loops, create value and minimize waste. These were identified by analyzing existing best practices being implemented or considered in Canada and other jurisdictions. In addition, this report presents potential barriers or challenges to the broader deployment and scaling of these practices in Canada, which were largely drawn from interviews with sectoral experts. (See Annex 1 for interviewee list). Given the presence of these barriers to adoption, many of these practices require the support of related public policies and institutional/system infrastructures to achieve their full potential. For instance, ecodesign for recycling may only result in more recycling if systems to collect and recycle materials are in place, and there exist policy incentives to use recycled materials. These policies are noted and described in Part 3 of this series.

2. The Circular Economy

The circular economy is a conceptual model that has begun to emerge in business, policy, and civil society discussions as a potential response to emerging global challenges of unsustainable resource use, and the environmental impacts (including carbon emissions and other environmental degradation) that this causes. The CE model promotes three main principles: (i) design out waste and pollution, (ii) keep products and materials in use, and (iii) regenerate natural systems. Importantly, CE also represents a potentially powerful economic strategy to capture value from current waste products and processes.

This emerging model draws inspiration from the natural world, where materials cycle infinitely in one form or another in the ecosystem, and there is no waste. In its ideal, a circular economy is a sustainable, productive economic model that is financially, environmentally, and socially sustainable. It is characterized by the highly efficient use of primary and secondary resources, designing waste and pollution out of the system, and a continuous recirculation of post-consumer materials while using renewable energy.[7] These materials can be either biological or technical. Biological materials that are at least non-toxic and possibly even beneficial, and can be safely returned to the biosphere, directly or in a cascade of consecutive uses. Technical materials like metals and plastics on the other hand cannot be retuned to the biosphere and instead should be designed for continuous re-circulation in the economy.[8]

(Note- Given the technical material composition of solar and wind technologies, this report will focus on the latter).

The circular economy goes far beyond the traditional 3R's (Reduce, Reuse, Recycle) thinking 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 and manufacturers.[9]

As businesses and governments globally recognize the opportunities offered by a circular economy, many circular practices are growing in prominence and achieving scale. Key applied strategies across the extraction, manufacturing, distribution, and use system can be clustered according to four broad objectives, identified by the Quebec-based Institut EDDEC (Figure 1):[10]

- **Reduce resource consumption** through strategies like ecodesign; responsible consumption and procurement; and process optimization (lean manufacturing)
- **Intensify product use** through strategies like sharing economy, and short-term renting
- **Extend the life of products and components** through strategies like maintenance and repair; donating and reselling; refurbishing; and performance economy (product as a service)
- **Give resources as new life** through strategies like industrial ecology (or symbiosis); material recovery, recycling and composting; and energy recovery.

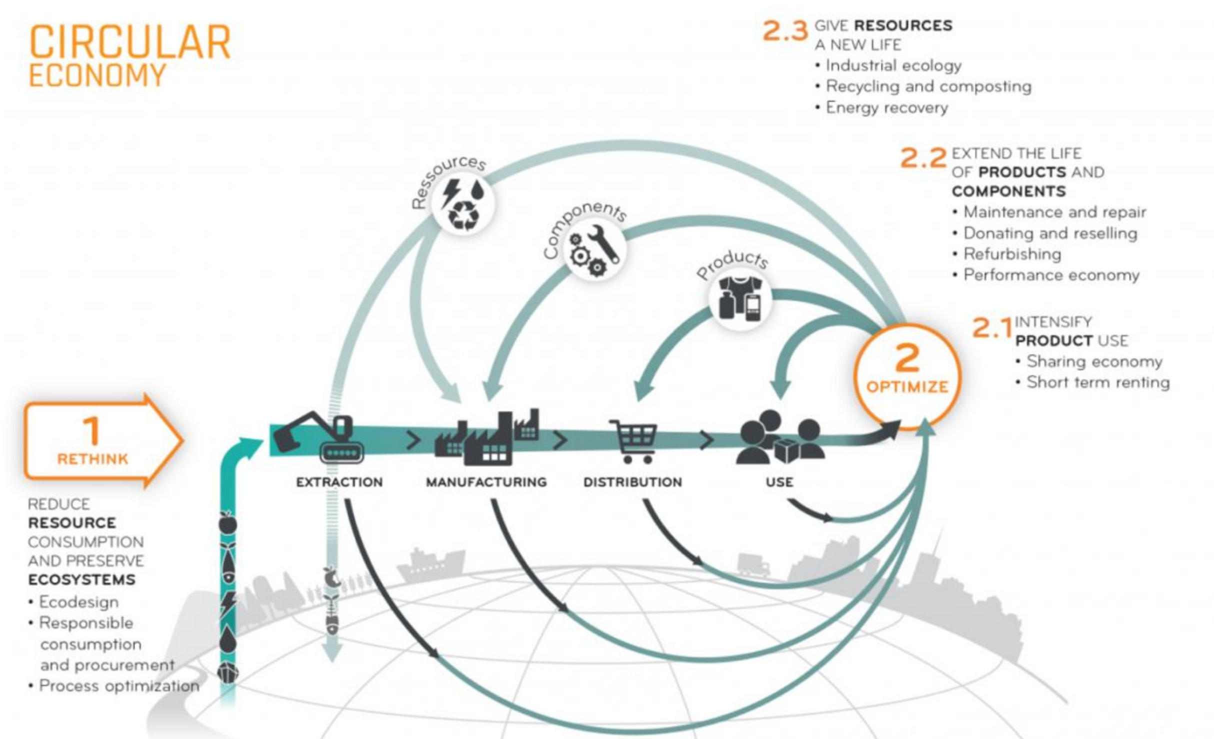

Figure 1: A Circular Economy.
Source: Institut de l'environnement, du développement durable et de l'économie circulaire (I-EDDEC). (2018).

Applied strategies for solar and wind technologies across the extraction, manufacturing, distribution, use and end-of-life stages were identified through a review of existing global practices, and described below, organized according to three of these objectives. Objective 2.1 (intensifying product use) is not referred to since promising and appropriate strategies for wind and solar were not identified.

3. Key Pathways to reduce resource consumption, intensify product use, extend the life of products, and recover value

3.1. Strategies to Reduce Resource Consumption

Ecodesign

More than 80% of all 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.[11] End-of-life waste of renewable energy technologies like solar panels and wind turbines can be dramatically reduced if they are designed for repair, upgrades, refurbishment, and recycling. Considering these needs at the design stage can enable higher uptake of circular strategies at later stages of the lifecycle. Further, certain sub-technologies are inherently more efficient to produce. For example, second generation thin film solar panels produced by First Solar have a carbon footprint six times smaller and a water footprint 24 times smaller relative to first-generation silicon solar panels. Consequently, these thin-film solar panels also have shorter energy payback periods.[†, 12]

Design considerations for circularity include: [13,14,15]

- **Design for sustainable and reduced material use (dematerialization)**: Solar panels and wind turbines should be designed as far as possible using materials that are recycled, recyclable and non-hazardous. Further, product designs and technologies should continuously evolve to increase resource and material efficiency, reducing the amount of material required. Over the years, considerable research has been taking place to make these technologies more energy and material-efficient (See Table 1 for an illustrative list of ongoing R&D focus for materials used in solar panels). As the market for solar and wind grows and increases the demand for rare and valuable materials, it is expected that these materials' availability and prices will further drive reduction and substitution efforts.
- **Design for easy repair and upgrades:** A solar panel and wind turbine's typical lifespan is between 20-30 years. These technologies can experience various types of failures during this lifespan, which require them to be either repaired or replaced. Identifying these failures and making design changes to reduce failure rates can extend the lifetime of these technologies. This can also potentially be achieved through more modular design. Modular designs help improve separability, reparability, and upgradability. It also makes deconstruction easier, which in turn can enable higher resource recovery and recycling rates. There is also a need for adaptability of wind turbine components to different module softwares: experience in Canada with older wind turbines has been that supporting technologies and software become increasingly difficult to locate, a barrier to extended lifespans (see under direct reuse, below).[16]
- **Design for recycling**: Solar panels and wind turbines are currently offered by multiple businesses across the globe. For example some large solar PV panel manufacturers include JinkoSolar (China), Canadian Solar (Canada) and First Solar (USA), while large wind turbine manufacturers include Vestas (Denmark), Siemens Gamesa (Spain) and Enercon (Germany). As a result, different models

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

with different designs are available on the market. These designs are not currently optimally designed for recycling, which would improve recycling rates. This can also be achieved through more design standardization across the globe to enable potential recyclers to use fewer techniques to recycle different product types, thereby increasing their recycling rates.

Box 1: Design for Recycling [17,18]

Design for Recycling

Solar panels and wind turbines are currently not optimally designed for recycling. For instance, the laminate encapsulant (often made of ethylene-vinyl acetate (EVA), a thermosetting plastic) placed on the glass of many solar panels is difficult to remove. This is a significant barrier to recycling. This can be potentially overcome by using thermoplastic films, which are easier to recycle.

In the case of wind turbines, researchers and businesses worldwide are exploring rotor blade designs that are more recyclable. For instance, ACT Blade uses technology adapted from the sailing industry to design a blade that uses a combination of carbon fiber structure and textile, making it partly recyclable.

Table 1: Illustrative list of ongoing R&D for materials used in solar panels
Source: IRENA & IEA-PVPS (2016)

Material	Research & Development Focus
Indium	Reducing the use of indium in indium-tin-oxide (used in some thin-film PV technologies as transparent conducting oxide) by developing new transparent conducting oxide layers incorporating more abundant and cheaper compounds like fluorine doped tin-oxide.
Glass	Optimization of glass composition, thickness, anti-reflective coating and surface structures to increase transmission of the front glass panes.
Polymers	Reducing or replacing the number of polymers, especially for backsheets that use a polyethylene terephthalate foil that currently cannot be dissolved or melted for recycling without decomposition.
Silicon	Transition to a thinner back-contact cell design that can reduce silicon use by half and energy consumption by 30%.
Silver	Reducing the use of silver (the most expensive component per unit of mass of a c-Si panel) through improved inkjet and screen-printing technologies and the use of rear-contact or bifacial cells.

3.2. Strategies to Extend the Life of Products and Components

Repair and Maintenance

Regular maintenance and repair involve preventative, planned, or ad hoc inspection/servicing tasks to restore a component to a good working condition. This can prolong the use of low-carbon technologies, thereby extending their useful lifespan. More recently, new technology powered by Artificial Intelligence is fueling an evolution from reactive to predictive maintenance. Coupled with data and analytics, this can help prevent costly downtime and avoid hazardous emergency repair work. For instance, automated drones can be flown over offshore wind farms to reduce inspection time. Such remote sensing powered by the Industrial Internet of Things (IIoT) can 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.[19] However, smart technology does not replace the need for traditional maintenance programs at wind and solar installations.

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 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.[20] 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 are common. Repair of minor defects may occur a few times during the blade lifetime. Usually, major repairs only occur for specific blade batches and are typically caused by manufacturing defects or design defects. Major repairs may also be required to fix damages due to extreme weather.[21]

Product as a service

Offering a product as a service involves delivering performance rather than products, with ownership of the product retained by the service provider. Due to economies of scale, service providers can typically better manage and maintain assets than their customers. Since the service provider is responsible for maintenance, repairs, and recovery in this business model, it creates an incentive to ensure a longer lifespan of assets and high-quality repairs and maintenance.[22]

Offering renewable energy technologies as a service has the potential to provide more flexible and efficient ways to use renewable energy. There are two ways in which this can be done:[23]

- **Leasing**: Through leasing of renewable energy technology, customers commit to pay a certain amount of money for the use of technology assets. This can increase utilization rates but reducing initial acquisition costs, while making renewable energy more accessible. Leasing models currently exist for both residential and commercial solar PV systems in many markets including Canada. Leasing agreements can include repairs and maintenance and a warranty for the life of the panels.

- **Power Purchase Agreements (PPA):** PPA's are an alternative to leasing and ownership whereby a customer commits to buy a certain number of kWh of energy from a provider. This power could either be generated at the consumer site or be transmitted from another location.

Circular Economy Strategy Definitions

Box 2: Circular Economy Strategy Definitions

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

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

Refurbish: extending a products service life by replacing some or all components.

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.

Recycle: the collection and preparation of wastes into materials that can re-enter production, and the reprocessing of

Box 3: Solar PV Leasing[24, 25]

Solar PV Leasing

Solar PV leasing is an emerging means of financing the acquisition of solar PV equipment that reduces the financial barrier to accessing solar electricity by reducing the upfront payment required. However, the overall cost of solar lease financing tends to be higher than an outright purchase. Solar leasing can be offered by an original equipment manufacturer (OEM) or a third-party service provider. In a solar PV lease, either of these businesses enters into a long-term agreement with a customer whereby the customer pays periodic rents for use of the system. It can be structured such that only periodic rent is paid with no requirement for a deposit, or to require a deposit with low and affordable lease payments thereafter.

There are two forms of a solar PV lease: finance lease and operating lease. In a finance lease customers are given an option to purchase the solar PV equipment at the end of the lease term, and the cost of maintenance and repair is borne by the customer. In an operating lease the solar PV equipment is returned at the end of the term and the cost of maintenance and repair is borne by the business offering the service.

In both cases, the solar equipment is owned by the business offering the lease. Where this business is a third-party service provider, they are incentivized to purchase higher quality equipment with longer lifespans and lower maintenance costs. This increases the demand for higher quality products and

Direct Reuse

Direct reuse can give low-carbon technologies a new life extension, thereby extending useful lifespan.

It is estimated that the degradation rate of a solar panel is less than 1% per year. This implies that even after a few years of use, solar panels operate at high-efficiency rates. As a result, there is a thriving international second-hand market for solar panels that have been repaired or decommissioned, as well as those that have been uninstalled. Panels are usually decommissioned when solar systems are repowered due to aging components or to upgrade technology. Falling prices for bifacial and high-efficiency modules along with next-generation microinverters and batteries are accelerating repowering. Sometimes panels are resold even before being commissioned for various reasons, such as equipment from canceled projects, leftovers from bulk purchases, and older stock sitting in warehouses.

The second-hand market for solar panels is concentrated in Asia, the Middle East, Africa, Latin America, and the Caribbean, where customers look for energy security at affordable prices. Typically, a used panel sells for between 50- 70% of the price of an original.[26] This makes them attractive even though they come without the original manufacturer's warranty. Some resellers do test used panels to guarantee product safety and verify performance levels, and may offer a limited-term service warranty or a money-back guarantee.[27] However, there are no commonly accepted standards or regulations for second-hand panels, a particular concern in relation to product safety.

Box 4: Solar X's Reuse Program[28]

Solar X's Reuse Program

In 2020 Solar X, a local Canadian residential and commercial solar contractor, became the first solar company in Canada to launch a solar panel reuse + recycle program.

Recognizing the need for inexpensive off-grid installations in developing countries, Solar X collects end-of-life panels in Canada and ships them to industry partners in developing countries for use in local installations.

The structural heterogeneity of wind turbine components and the nature of the North American market makes the reuse of wind turbines challenging. The rapid pace of technology innovation is moving the demand in North America towards high-power turbines with the lowest possible price and this is mainly materialized by using new modules (see Part 1, Section 4).[29]

The difficulty in sourcing compatible replacement parts further diminishes the case for reuse. To illustrate, in Canada, the Crawley Ridge wind farm in Alberta had four wind turbines down for a couple of years, preventing their reuse, because they were unable to find matching blades of the right vintage. Even when decommissioned blades were located in California, they could not find appropriate circuit boards. The turbines also ran on older software and even older laptops, thus posing a serious risk of failure if the software crashed.[30] Therefore, it is extremely challenging to continue using older wind turbines as parts, supporting technologies and software become increasingly difficult to locate, maintain and operate.

Refurbishment

In the case of solar panels, most manufacturers guarantee at least 80%[31] performance output after 20 to 30 years of life indicating that they retain significant value and output capacity even at the end of their warranty. Depending on the decommissioned solar panels' performance outlook, they can either be reused directly or first refurbished and then reused. There is however, some reported pushback towards refurbishment from solar manufacturers, similar to other sectors[32], as they are uncomfortable with having their brand on a refurbished product. This is due to reputational risks associated with having a product on the market for which they cannot guarantee performance. [33]

Wind turbine refurbishment is a popular practice. It can involve changing a major component if it fails for any reason or as a result of adverse weather or dismantling and replacing the complete wind turbine. Refurbished turbines are a cost-effective alternative to new turbines, delivering a shorter payback period. Further, reconditioned turbines have a shorter lead time: between 2-3 months versus over two years for a new turbine.[34] However, they come with a shorter warranty. In 2018, Europe's wind turbine gearbox repair and refurbishment market was valued at over USD $3,800 million and is expected to grow at a compound annual growth rate of 8.17% between 2020-2027.[35]

Repurposing

Similar to reusing, repurposing can also give low-carbon technologies a new life extension, thereby extending useful lifespan. While reuse refers to re-using an asset for the same purpose as it was originally used for, repurposing refers to re-using it for a different application, usually of a lower value than the original.

In the case of wind turbine blades, there are some creative examples of repurposing. For instance, they have been used to build structures like bicycle shelters and walkways. They have also been re-used to build 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 components.[36]

Box 5: Netherlands's Wind Turbine Blade Waste Repurposing

3.3. Strategies to Recover Value by Giving Resources a New Life

Recycling

Recycling is the most popular and commonly used circular economy strategy, although it is not the most favoured waste management hierarchy option. Recycling involves collecting and preparing end-of-life products and then reprocessing them into secondary material. Boradly there are two types of recycling:

- bulk recycling where only the bulk materials are recovered
- high-value recycling: where both bulk materials and specialty materials (metals and semi-conductors) are recovered

Netherlands's Wind Turbine Blade Waste Repurposing

In 2007, the Rotterdam municipality unveiled a playground for Kinderparadijs Meidoorn built out of rotor blades that were originally destined for landfills. The city also has public seating at the Willemsplein square where nine intact rotor blades were placed at various angles to create ergonomic public seating with a diversity of seating options.

Source: Denis Guzzo/Flickr

In 2014, the city of Almere created a durable bus shelter from end-of-life turbine blades.

It is estimated that if only 5% of the Netherlands' yearly production of urban furniture such as

Typically bulk recycling of solar PV and wind turbines can be done by existing recycling facilities. However, high-value recycling requires the establishment of dedicated and specialized facilities.

In the case of solar panels, both silicon-based and thin-film panels can be recycled using distinct industrial processes. See Figure 2. While the recycling potential for panels varies by technology and depending on recycling infrastructure, 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.[37]

For silicon-based panels, the recycling process starts with disassembling the actual product to separate aluminium and glass parts. Almost all (95%) of the glass can be reused, while all external metal parts are used for re-molding cell frames. The remainder materials are treated at 500°C in a thermal processing unit to ease the binding between the cell elements. Due to the extreme heat, the encapsulating plastic evaporates, leaving the silicon cells ready to be further processed. Supporting technologies can direct the plastic for use as a heat source for further thermal processing. After the thermal treatment, the remaining hardware is physically separated. Eighty percent of these can readily be reused, while the remainder can be further refined. Silicon particles—called wafers—are etched away using acid. Broken wafers are melted to be used again for manufacturing new silicon modules, resulting in 85% recycling rate of the silicon material.[38] The literature on the potential emissions associated with the evaporation of the encapsulant plastic is unclear. However, non-thermal pathways such as mechanical and chemical processes provide an alternative route to ease the binding between cell elements.[39] The suitability of any particular method will require a trade-off between cost and associated emission profile.

Box 6: Europe's first solar panel recycling plant[40,41]

Europe's first solar panel recycling plant

In 2018, Veolia (a France-based waste management group) and PV CYCLE joined forces to open the first European plant for recycling waste solar panels in Rousset, a small town in France.

This site, dedicated to the treatment of crystalline silicon PV panels, separates and isolates all the materials, from the special photovoltaic panel glass to the aluminium frame, connection box, and connection cables. Once recovered, the materials are redirected to various industrial sectors: the glass, 2/3 recovered as clean cullet is used in the glass-making sector, the framework in an aluminium refinery, plastic as recycled fuel in cement works, and silicon in precious metal sectors. The cables and connectors are crushed and sold in the form of copper shot.

In 2018, the plant managed to process 1,800 metric tons of materials. It aims to gradually increase this capacity by 40% in recycled tonnages annually to exceed 4,000 tonnes at the end of 2021 and

Thin-film panels can be recycled using a combination of mechanical and chemical treatments. One method involves first putting panels in a shredder and then crushing them in a hammer mill. This is done to break down particles to a size of about 5mm at which point the lamination keeping the inside materials together breaks and can be removed. Once removed, the remaining substance consists of both solid and liquid material. A rotating screw is utilized to separate these, which keeps the solid parts rotating inside a tube, while the liquid drips into a container. For the solid parts, semiconductor layer etching is carried out. Solid matters which are contaminated with interlayer materials can be removed through a vibrating surface. Finally, the glass is rinsed with water and dried on a belt filter unit. For the liquid part, a precipitation and dewatering process is used. The resulting substance goes through metal processing to completely separate the different semiconductor materials. This process can achieve about 90% recovery of the glass and about 95% of the semiconductor material by mass.[42,43]

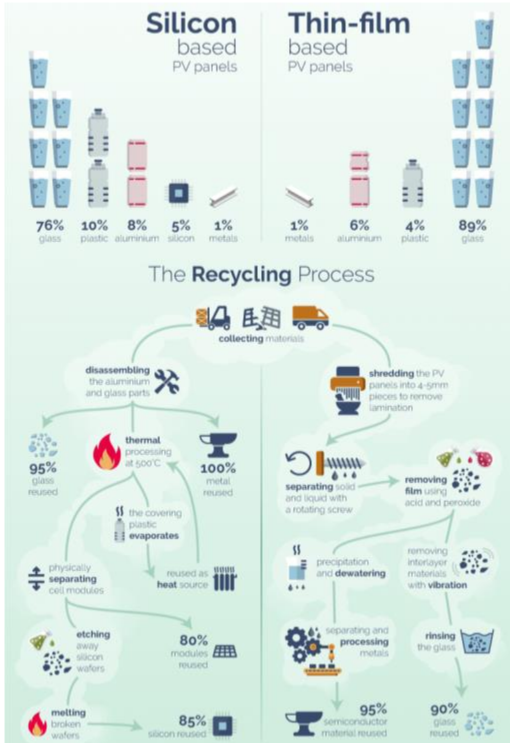

Figure 2: Recycling Process of silicon-based and thin film solar panels.
Source: Green Match (2017)

These are just illustrative recycling processes. New recycling processes for solar panels are continuously being researched and developed as the solar market grows and more waste is anticipated from end-of-life solar panels. This waste has significant value and can play a role in recirculating materials into the solar market to help it grow further. Figure 3 describes the global end-of-life material recovery potential under IRENA's regular-loss scenario[‡] through 2030.

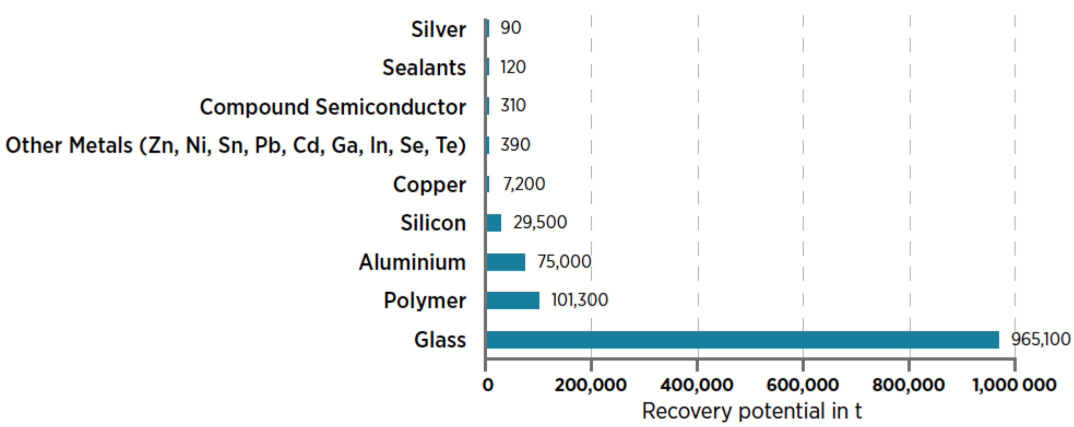

Figure 3: End-of-life recovery potential under regular-loss scenario to 2030 (t).
Source: IRENA & IEA-PVPS (2016)

The value of these materials recovered through PV panel treatment and recycling could amount to USD $450 million by 2030. This is equivalent to the raw material value needed to produce 60 million new panels or 18 GW. By comparison 180 million new panels were produced in 2015. By 2050, this value is expected

‡ See Part 1 of this report series.

to surge to over USD $15 billion. This equates to the raw materials needed to produce two billion new panels or a capacity of 630 GW.[44]

Of all the materials used in Solar PV panels, silver is by far the most valuable one. However, silver recovey is still technically challenging. R&D to make silver recovery from solar PV panels technically and economically feasible is currently underway and could the business case for solar PV panel recycling in the years to come.

In the case of wind turbines, about 85%-90% of a wind turbine's total mass can be recycled. Components such as the foundation, tower, and parts of the nacelle already have established recycling practices since these components' raw materials have enough value for secondary markets. For example, the steel used for the tower is 100% recyclable. There is a well-established market for steel scrap since it is regarded as a valuable raw material for steel production. The foundation of wind turbines can also be recycled into aggregate for building materials or road construction. However, in some cases where removal may lead to higher environmental impacts, it is left in-situ.[45]

A major recycling challenge for wind turbines is the rotor blades, although these are typically only 2-3% of the windmill's mass.[46] This is due to their size and composition. Rotor blades can be over 80m long or longer and weigh up to 30-35 tons each, making them difficult to transport.[47] They are typically made of glass, or carbon fiber reinforced composites and built to withstand extreme weather, making them very difficult to remelt and remold. While research is underway on material innovation to improve the recyclability of blades, these innovations will not significantly change the end-of-life materials in the period prior to 2050 given the 20 year lifespan of blades.

The more recently used carbon fiber composites' recycling processes are still being researched and haven't yet reached commercialization. However, some solutions have emerged for the older blades made of glass fiber. A popular process for recycling the composite waste in Europe is through cement co-processing, also known as the cement kiln route; GE, the largest supplier of turbines in the U.S., recently announced it will be adopting this process.[48] In cement co-processing, the glass fiber is recycled as a cement mix component (cement clinker). This process reduces the carbon footprint of cement production by burning the polymer matrix as fuel. However, in this process, the glass's fiber shape disappears and therefore cannot be used in other composites applications.[49] Recently, the University of Sherbrook in Québec concluded research into the recycling of wind turbine rotor blades for use in concrete production in Canada. It found that adding fiberglass from blade waste can increase the flexural strength of concrete by 15%. The next stage of the research will study the commercial potential of this process. [50]

In addition to the cement kiln route, composite materials can also be recycled or recovered through mechanical grinding, thermal (pyrolysis, fluidised bed), thermo-chemical (solvolysis), or electro-mechanical (high voltage pulse fragmentation) processes or combinations of these. These alternative technologies are available at different levels of maturity, some of which are available at industrial scale. They also vary in their effects on the fiber quality (length, strength, stiffness properties), thereby influencing how the recycled fibers can be applied. A key factor stalling their uptake is that in many cases, the recycled material cannot compete with virgin materials' price.[51] Figure 4 describes the estimated relative costs and values of composite recycling technologies in Europe.

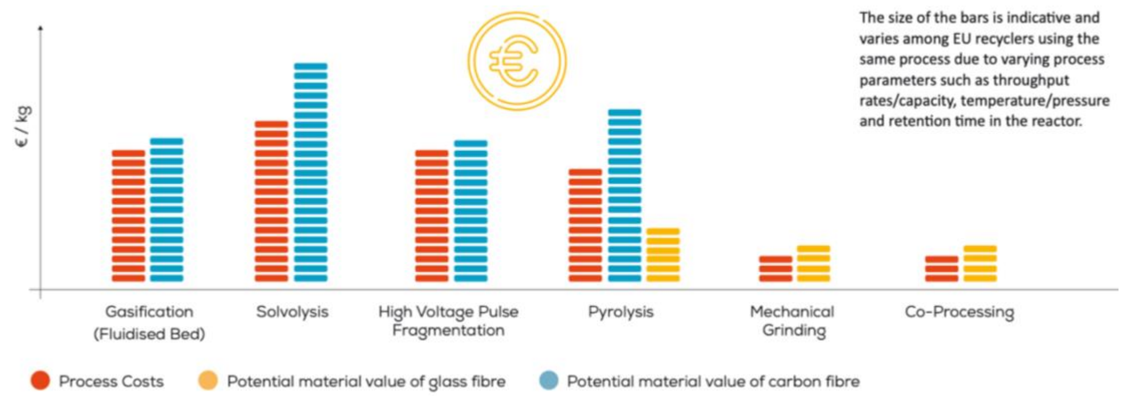

Figure 4: Estimated relative costs and values of composite recycling technologies.
Source: ETIP Wind (2020)

Energy Recovery

Energy recovery involves recovering 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 landfill .

For solar panels, an interviewee noted that components from end-of-life solar panels that cannot be reused or recycled, as well as a portion of manufacturing waste, are directed towards energy recovery. In the case of wind turbines, if rotor blades made of carbon fiber can be cut down to a reasonable size, the composite material can be mixed with municipal waste and burned to produce useful heat. This is not possible for glass fiber blades since glass fiber is incombustible. During this process which requires very high combustion temperature - over 800 °C, organic substances are combusted and converted into non-combustible material (ash), flue gas and energy. The resulting ash could theoretically be used as a substitute for aggregate in other applications, if technical specifications allow, or must be landfilled.[52] To date, no economically viable use for the ash has been found except its use as an input for cement production.

4. Barriers

A considerable gap between possible circular economy practices and current implementation is widely observed in circular economy literature,[53] and therefore not unique to solar and wind technologies. This literature identifies that implementation of effective circular economy strategies depends on a network of information and feedback loops. Knowledge and transparency of non-financial information, data on resource location and availability, and information and clarity on the availability and eligibility of funds to support circularity are key to ensuring businesses and end-users can detect avenues to create value under the circular economy paradigm. Recent research has identified the need for governments to provide the financial sector with incentives and an enabling policy and legislative framework to de-risk the circular economy transition and to accelerate the integration of circularity into products and services.[54]

Achieving a more circular economy is also identified as depending on collaborative action among stakeholders who are interdependent yet independent, making collaboration, coordination, and communication complex.[55] Availability, transparency, and exchange of information on resource condition, location, availability, etc., allows for broader adoption of circular economy practices amongst companies and consumers, and also allows for circular business models to perform better and more flexibly.[56]

With climate change and the development and deployment of low carbon infrastructure, there is a need to integrate circular economy practices and business models throughout the low carbon infrastructure value chain. The global growth in this infrastructure will increase demand for an array of environmentally impactful rare earths and other precious and highly processed materials (for example see Part 1, section 3.4). As components of a low carbon economy, it is essential that these in-demand materials not only be sustainably extracted and deployed, but also managed and retained in the economy at their end-of-life.[57] Downstream, end-of-life materials from retiring solar PVs and wind turbines could therefore present either another critical global problem, or a significant opportunity.

A 'systems thinking' approach to developing circular business models instead of a model that only focuses on recycling enables an array of benefits to be realized, including reduced waste and landfill volumes, greater utilization rates, resource efficiencies, economic stimulation, new markets, and better social outcomes.[58]

However, changing business models away from business-as-usual pathways is always challenging. There are barriers to widescale circular business model adoption, which can be broadly classified into three categories: (1) technical, (2) financial, and (3) regulatory. The section below lists select barriers.

Technical Barriers

A lack of technical viability can be an obstacle to the adoption of circular economy practices. However, recent research indicates that while essential to address, technical barriers are not the main barriers to circular economy generally.[59]

In the case of solar PV recycling, this occurs with the separating of film and glass. The film is often made of ethylene-vinyl acetate (EVA) and is placed on the glass of many c-Si panels. Its removal is considered a major technical obstacle in the efficient and safe recycling of end-of-life solar PV panels.[60]

For wind turbines, while the foundation, tower, and nacelle have high recyclability potential, there are currently no mature recycling channels for blades.[61] Wind turbine blades are composed of composite materials, and the lack of economically viable recycling technologies is causing end-of-life blades to be landfilled. 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.[62]

Moreover, the size of the wind turbine blades creates a reverse logistic barrier to refurbishment and recycling. Wind turbine blades can be between 80m long or more and need to be cut up on-site before they can be transported.[63] Similarly, software updates and accessibility of reliable and compatible spare parts pose a challenge to product life extension in wind turbines.[64]

The development and adoption of 'intelligent assets' – such as next-gen solar PV and wind turbines that can signal the need for maintenance before breaking down will unlock tremendous opportunities for businesses and individuals.[65]

Broader technical barriers for circular economy adoption in solar PV and wind technologies include current design practices following a model based on disposing at end-of-life instead of reuse, disassembly, recycling, driven in part by the rapid evolution and related obsolescence of these technologies.66 Standardization and modularization in solar PV panels and wind turbine design would also allow for the creation of adaptable processes for disassembly and recycling.[67] Currently, Canada imports the majority of its solar PV panels and wind turbine components, creating a barrier to dialogue between product designers and potential Canadian recyclers to enable adaptable recycling processes. There is an inherent lack of motivation for non-domestic manufacturers to standardize solar PV and wind turbine design.[68] Potential EU ecodesign regulations for solar panels are of interest in this regard.

A final technical barrier is a lack of labeling to help with tracking of materials. Material passports that track and disclose material origin and composition, recyclability and repair process of the solar PV panel and are accompanied by a global database on solar panel contents are seen as future enablers of circular economy adoption.

Financial Barriers

Costs can undermine the economic benefit for investing in circular practices. Currently, the cost of some virgin materials is lower than secondary materials because they have established supply channels and certainty of supply, and (particularly in the absence of established systems) low costs of landfilling may be more attractive than the investment in finding channels for reuse, resale, or recycling. Secondary materials are also taxed higher relative to virgin materials and research has called for the taxation system to remove any systemic biases against recycling and to provide recycled materials a level of taxation that is lower than that for virgin materials.[69]

Finally, high collection costs due to geography pose a uniquely Canadian barrier to solar PV and wind recycling, particularly for installations in remote communities. Disaggregated distribution of installed solar PV and wind turbines makes it challenging to pinpoint a central location to establish recycling facilities, and to reach thresholds for more specialized recycling systems.

Other financial barriers are the high cost of performance and reliability testing, which hamper product reusability. Second-hand panels are also typically not eligible for purchase incentives and, as such, are not as attractive financially as new panels.[70] Research from the IRENA suggests that the cost of a typical second-hand solar panel is approximately 70% of the original price.[71]However, high costs associated with comprehensive testing of panels shrinks this price advantage. Research suggests that the cost of comprehensive testing can be in the order of the cost of a new panel itself.[72] Statistical sampling of large batches could reduce the number of tests required and bring costs down and provide a pathway to overcome this financial barrier.[73]

Finally, changing business models comes with upfront investment and transition cost.[74] Businesses are less likely to take this on if competing companies and entities along the product value chain do not share this burden. With the product as a service model, there is a significant upfront cost as this model requires upfront investment in sufficient products, while payback times are relatively longer since user fees is spread out over time.[75] This presents a financial barrier to the product as a service and sharing economy models. Overcoming this barrier could yield significant benefits to both users and original equipment manufacturers that focus on designing and producing higher quality products that extend component and material lifetimes.[76]

Regulatory Barriers

Regulations requiring product design standardization, modularization, minimum secondary material requirements, and extended producer responsibility can boost these technologies' reuse and recycling. Conversely, the absence of such regulations can be an obstacle to widescale circular economy adoption.

Quasi-regulatory barriers to the sale and reuse of second-hand solar PV panels are uncertainties over performance and a lack of certification. While second-hand markets for solar PV panels exist globally, second-hand panels are not as attractive to domestic consumers and tend to be exported. Panel testing and certification could provide quality assurance for second-hand panels, albeit the cost of comprehensive testing of panels can be in the order of a new panel's cost.

There are two types of regulations relevant for end of life management of materials:

1. Hazardous material regs (for example for used oil) which lay out an end of life requirement for recovery and handling in an environmentally sound manner; and
2. Recycling regulations, including through extended producer responsibility or stewardship programs, to recycle certain materials or products (for example electronic waste).

Unlike some other jurisdictions, no province or territory has classified photovoltaics as designated hazardous waste requiring special end of life recovery or treatment, nor are there any policies in Canada restricting landfilling of solar PVs and wind turbine blades. However, some municipalities in Ontario have been refusing to accept decommissioned wind blades and turbines due to concerns about limited landfill capacity.

Similarly, solar panels and wind turbines are not currently included in any provincial or territorial electronic waste recycling programs. Extended producer responsibility (EPR) or stewardship programs aim to keep electronic waste out of landfills.[77] The Government of British Columbia however, has recently announced its intention to include solar panels in its Recycling Regulation and EPR strategy.[78] Recycling regulation in Canada is a provincial jurisdiction, and has in the past often been implemented inconsistently across provinces and territories.[79] A co-ordinated Pan-Canadian policy approach could reduce inconsistent inter-jurisdictional regulatory requirements and create economies of scale for recycling capacity.

5. Industrial Capacity Assessment

As Canada continues to pursue its ambitious climate targets, installed solar PV and wind capacities are expected to continue their rapid growth. And as first-generation solar PV and wind turbines approach their end-of-life, Canada faces a need to institute policies supporting responsible solar PV and wind turbine end-of-life management, including whether (and if so when) to establish dedicated local solar PV and wind turbine recycling facilities. The end-of-life solar PV and wind turbine material streams should be seen as a resource rather than waste: they contain 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, and end-of-life assets are often being storehoused until opportunities become available. [80]

The only solar PV recycling option available to Canadians lies presently in the U.S., offered by First Solar, a U.S.-based photovoltaics company with a large presence in Canada, and Dynamic Lifecycle Innovations, a full-service electronics and materials lifecycle management corporation. Both companies collect end-of-life solar PVs and ship them to U.S. recycling facilities.[81] More recently, Solar X, a local Canadian residential and commercial solar contractor, established a new program collecting end-of-life solar PVs in Canada and shipping them to industry partners in developing nations for use in local installations.[82]

High collection costs due to Canada's geography, a lack of supporting regulations such as extended producer responsibility currently pose apotential bottleneck in establishing dedicated domestic solar panel recycling facilities. However, reported municipal push for more products being added to EPR regulations, increasing end-of-life waste volumes, and research into investigating mobile recycling units' potential may change the outlook for solar PV recycling in Canada.[83]

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.[84] For solar PV, an interviewee suggested an annual end-of-life waste volume of 10,000 tonnes 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 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

However, an alternative to establishing dedicated solar PV and wind turbine recycling facilities could be to adapt existing steel, glass, and e-waste recycling facilities for bulk recycling of the end-of-life solar PV panel and wind turbines. Metal and glass recyclers have begun to show interest in PV waste and see it as a future business opportunity.[85]

For wind, currently, it is estimated that approximately 85 to 90% of a wind turbine's total mass can be technically and economically recycled.[86] This includes the foundation, tower, and parts of the nacelle. The wind industry in Canada is relatively young compared to typical wind turbine service life, and as such, decommissioning experience is limited in Canada.[87]

However, the decommissioning of TransAlta's commercial wind farm at Cowley Ridge in Alberta, Canada's first and oldest commercial wind facility, provides insight into the possibilities of recycling end-of-life wind turbines. TransAlta successfully recycled 90% of the Cowley Ridge 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.[88] Decommissioning experience from Cowley Ridge also suggests that significant quantities of lubricants and dielectric fluids (used in transformers) can be recovered from end-of-life wind turbines. While TransAlta contracted out special disposal of this oil, it may be possible to include used oil from future decommissioned wind turbines into used oil hazardous waste or recycling regulations. Since these are already in place for used oil from the automotive sector in many provinces and territories (Alberta, Manitoba, New Brunswick, Prince Edward Island, Quebec, Saskatchewan and British Columbia), it is likely that the industrial capacity to recycle this material exists in Canada.

While this success provides a positive outlook to future recycling of end-of-life wind turbines, recycling of the wind turbine blades remains a crucial issue. The lack of economically viable blade recycling pathways poses a significant bottleneck to achieving 100% end-of-life wind turbine recycling, causing end-of-life blades to pile up in landfills.

7. Summary

The circular economy model provides a foundation to address issues surrounding critical material supply as well as providing a framework to maximize material flow in the system and reduce resource consumption. This chapter identifies key strategies to reduce resource consumption, intensify product use, extend the life of products, and recover value that can be applied across the extraction, manufacturing, distribution, use and end-of-life stages of renewable energy technologies. These circular economy strategies go beyond the traditional 3R's (Reduce, Reuse, Recycle), and are equally relevant as enablers of circularity for the broader clean technology sector.

Technical, financial, and regulatory barriers create a considerable gap between possible circular strategy practices and their implementation. These barriers need to be addressed to enable the circular transition and realize its full potential.

Currently, Canada has no dedicated solar panel or wind turbine recycling facilities. For solar PV, the only advanced recycling options available to Canadians lie outside the country, and Canada as a whole may not generate sufficient volume of end of-life PVs to make a dedicated facility financially viable for another

[§] Based on differing rates of panel degradation under the two modelled scenarios decade. Given the current distribution of installed capacity, this threshold is likely to first be reached in Ontario. Thus, regionally oriented north-south Canada – US specialized recycling clusters will be more attractive for most regions of Canada in the mid-term and for Ontario in the near term. 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. Supporting regulations such as etendedproducer responsibility (see part 3) will be important to shift the onus for this end-of-life management from consumers to producers.

For wind, 85% to 90% of a wind turbine's total mass can currently be technically and economically recycled, amd this has been demonstrated in Canada’s one experience with the decommissioning of a wind turbine farm. However, recycling of the wind turbine blades remains a crucial issue in Canada as elsewhere. The lack of economically viable blade recycling pathways poses a significant bottleneck to achieving 100% end-of-life wind turbine recycling, causing end-of-life blades to pile up in landfills.

As Canada moves forward with its transition to net zero, accelerating volumes of end-of-life solar PV and wind turbines will necessitate the establishment of appropriate recycling options as they contain 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.

Appendix A: List of Sectoral Experts Interviewed

The following experts were interviewed for this project under Chatham House Rules.

Name	Designation	Organization
Andreas Wade	Global Sustainability Director	First Solar
Edward Gugenheimer	Chief Executive Officer	Alberta Recycling Management Authority
Étienne Angers	Agent de développement industriel	RECYC-QUÉBEC
Leonard Surges	Special Advisor to the Director General	Natural Resources Canada
Phil McKay	Senior Director, Operations, CanREA	Canada Renewable Energy Association (group interview with industry members)
Nick Gall	Director, CanREA	
Alauddin Ahmed	Managing Consultant, ValueInfinity Inc	
Desirée Squires	CEO, Sunset Renewables	
Janie Docouto	SCM Manager Renewable Energy, Suncor	
Hugo Giffard	Director, LM Wind Power	
Elizabeth Mason	Project Manager, Mason Composite Service	
Lyle Goldberg	Business Development Representative, HES PV	
Jen Aitchison	Senior Vice President Hugh Wood	
Kristi MacMillan	Senior Policy Analyst	Government of British Columbia
Michael Schwalb	Senior Policy Specialist, Hazardous Waste	Government of British Columbia

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] Ibid.
[3] Canada Energy Regulator (2020). Canada's Energy Future 2020. Government of Canada.
[4] IRENA & IEA-PVPS (2016). End-Of-Life Manangement: Solar Photovoltaic Panels.
[5] 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
[6] Ellen McArthur Foundation (n.d). What is a circular economy?
[7] Cairns, S. and Patel, S. (2020). Innovation for a Circular Economy: Learning from the Clean Growth Journey. Smart Prosperity Institute
[8] Ellen MacArthur Foundation (2013). Towards the Circular Economy Volume 1: Economics and business rationale for an accelerated transition.
[9] Lacy, P. and Rutqvist, J. (2015). Waste to Wealth: The Circular Economy Advantage. Accenture Strategy
[10] Institut de l'environnement, du développement durable et de l'économie circulaire (I-EDDEC) (2018). Circular Economy in Quebec.
[11] EU Science Hub. Sustainable Product Policy. European Commission.
[12] First Solar (2020). Sustainability Report 2020.
[13] Emily Gentilini & Michael Salt (2020). Circular Photovoltaics: Circular business models for Australia's solar photovoltaic industry. ARUP.
[14] IRENA & IEA-PVPS (2016). Op.cit.
[15] Schmid.M., Ramon.N., Dierckx.A., Wegman.T. (2020). Accelerating Wind Turbine Blade Circularity. Wind Europe.
[16] Michelle Froese (2017). Decommissioning Canada's oldest wind farm. Windpower Engineering & Development.
[17] Arup (2020). Op.cit.
[18] Scottish Reneables (2020). The Circular Economy and Onshore Wind.
[19] Dvorak.P., Totaro.P. (2017). Renewable energy IoT to hit $5.3 billion annually by 2030. Wind Power
[20] IRENA & IEA-PVPS (2016). Op.cit.
[21] Lui, P. & Barlow,C. (2017). Wind turbine blade waste in 2050. Waste Management, Volume 62, 2017, Pages 229-240, ISSN 0956-053X.
[22] Emily Gentilini & Michael Salt (2020). Op.cit.
[23] Ibid
[24] Rodl & Partner (2019). Leasing of solar photovoltaic systems (PV leasing).
[25] Lindros,K. (2019). Is Leasing Solar Panels a Greener Option?
[26] IRENA & IEA-PVPS (2016). Op.cit.
[27] Melissa Ann Schmid (2021). Think before trashing: The second-hand solar market is booming. Solar Power World.
[28] Solar X (n.d). Announcing the launch of our new solar panel reuse + recycle program.
[29] 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.
[30] Michelle Froese (2017). Decommissioning Canada's oldest wind farm.
[31] Vazquez and Rey-Stolle (2008). Photovoltaic Module Reliability Model Based on Field Degradation Studies.
[32] Stakeholder interview conducted for this project
[33] Stakeholder interview conducted for this project
[34] Solvento (n.d).Wind Turbine Refurbishing.
[35] Research and Markers (2020). Europe Wind Turbine Gearbox Repair & Refurbishment Market Outlook & Projections, 2019-2027.
[36] Schmid.M., Ramon.N., Dierckx.A., Wegman.T. (2020). Op.cit.
[37] PV Cycle (2016). Breakthrough in PV Module Recycling.
[38] Attila Tamas Vekony (2020). The Opportunities of Solar Panel Recycling. Green Match
[39] Chowdhury et al. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews.

[40] Veolia (2018). Veolia opens the first European plant entirely dedicated to recycling photovoltaic panels.
[41] Taiyang News (2018). Waste Management Firm Veolia Opens First PV Module Recycling Plant In Europe To Recycle 1,300 Tons In 2018.
[42] IRENA & IEA-PVPS (2016). Op.cit.
[43] Attila Tamas Vekony (2020). The Opportunities of Solar Panel Recycling. Green Match.
[44] IRENA & IEA-PVPS (2016). Op.cit.
[45] Schmid.M., Ramon.N., Dierckx.A., Wegman.T. (2020). Op.cit.
[46] Veolia (2018). How can wind turbine blades be recycled?.
[47] 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.
[48] NREL (2021). NREL Research Identifies Motivations, Methods for Achieving a Circular Economy for Wind Energy.
[49] WindEurope, Cefic and EuCIA (2020). Op.cit.
[50] Radio Canada (2020). Projet de recherche pour recycler les vieilles pales d'éoliennes en composants de béton.
[51] WindEurope, Cefic and EuCIA (2020). Op.cit
[52] Miceli.F. (2019). Circular economy: use of wind turbines blades as combustible and mix material for cement production.
[53] 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.
[54] United Nations Environment Programme (2020). Financing Circularity: Demystifying Finance For The Circular Economy.
[55] Ibid.
[56] Julian Kirchherr, Marko Hekkert, Ruben Bour, Anne Huijbrechtse-Truijens, Erica Kostense-Smit and Jennifer Muller (2017). Breaking the Barriers to the Circular Economy. Deloitte.
[57] Paul D. Jensen, Phil Purnell and Anne P.M. Velenturf (2020). Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind. Sustainable Production and Consumption, pp. 266-280.
[58] Arup (2020). Op.cit.
[59] Julian Kirchherr, Marko Hekkert, Ruben Bour, Anne Huijbrechtse-Truijens, Erica Kostense-Smit and Jennifer Muller (2017). Op.cit.
[60] Ibid.
[61] 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.
[62] NREL (2021). NREL Research Identifies Motivations, Methods for Achieving a Circular Economy for Wind Energy
[63] Chris Martin (2020). Wind Turbine Blades Can't Be Recycled, So They're Piling Up in Landfills. Bloomberg News.
[64] Michelle Froese (2017). Op.cit.
[65] Ellen Macarthur Foundation (2016). Intelligent Assets: Unlocking the Circular Economy Potential.
[66] Peter Kelly-Detwiler (2019). Solar Technology Wll Just Keep Gettingg Better: Here's Why. Forbes.
[67] Arup (2020). Op.cit.
[68] Ibid.
[69] Jay Fothergill (2004). Scrap Mining: An Overview of Metal Recycling in Canada. Canary Institute.
[70] Arup (2020). Op.cit.
[71] IRENA & IEA-PVPS (2016). Op.cit.
[72] Arup (2020). Op.cit.
[73] Ibid.
[74] Joanne Houston, Elisa Casazza, Marie Briguglio and Jonathan Spiteri (2020). Stakeholder Views Report: Enablers and Barriers to a Circular Economy. R2Pi.
[75] Jeroen Gillabel et al. (2021). Business Models in a Circular Economy. European Environment Agency
[76] Tomohiko Sakao and Ken Webster (2020). In a circular economy, product-as-a-service has social and environmental benefits. GreenBiz.
[77] Leigh Matthews (2020). The glaring problem with Canada's solar sector and how to fix it.

[78] Government of British Columbia (2021. Province taking action to recycle more products.
[79] Canadian Council of Ministers of the Environment (2019). Discussion paper: Guidance to facilitate consistent extended producer responsibility policies for plastics.
[80] Stakeholder interview conducted for this project
[81] Leigh Matthews (2020). Op.cit.
[82] pvbuzz (2020). Canada's Solar X revolutionizes the solar industry in Canada with the launch of its new solar panel reuse + recycle program.
[83] Leigh Matthews (2020). Op.cit.
[84] Wambach.K., Baumann.K., Seitz.M., Mertvoy.B., Reinelt.B., (2020). Op.cit.
[85] Ibid.
[86] Canadian Wind Energy Association (2020). Wind Turbine Blade & Other Composite Components Recycling Initiative. CanWEA.
[87] Canadian Wind Energy Association (2020). Decommissioning/Repowering a Wind Farm.
[88] Michelle Froese (2017). Op.cit.