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SOLAR AND WIND ENERGY IN CANADA

VALUE RECOVERY AND END-OF-LIFE CONSIDERATIONS

PART 1.

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

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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 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.*

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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Foreward

The global transition to a low-carbon future is expected to have a profound effect on primary material demand. Low-carbon energy technologies have a larger material requirement per unit of energy generation (tonne/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]

Tis transition will also change the profile of end-of-life materials (waste) produced 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,[2] work on green industrial policy has paid less attention to managing the end-of-life implications of the large-scale transition to these new technologies. It has only begun to look into the potential role of circular economy strategies to reduce material intensity of low-carbon energy technologies, minimizing waste along technology life cycles, and recover value at end of life.

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

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

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

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

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

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

These findings from these related streams of work are presented in three parts (listed below), with part 1 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

In the Canadian context, 80% of current GHG emissions stem from energy generation and end-use.[6] In order to meet 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.

The updated federal plan *A Healthy Environment and a Healthy Economy*, unveiled in December 2020, identifies 'making clean, affordable transportation and power available in every community' as one of its five pillars. This includes "expand(ing) the supply of clean electricity through investments in renewable and next-generation clean energy and technology…" This pathway will be supported by an additional investment of $964 million over four years to advance smart renewable energy and grid modernization projects, increasing renewable power generation capacities for wind and solar, and the deployment of grid modernization technologies such as power storage.

While these renewable and next-generation clean energy technologies are essential to net-zero ambitions, they are not without environmental footprints. They require more materials per unit of energy generation, compared to fossil-fuel based energy technologies. They also produce large waste streams which need to be managed once these technologies reach their end-of-life. There are also concerns around limited stock of critical minerals and metals used in these products, given the projected increase in demand as these technologies are adopted around the world, as well as the environmental, social,and governance records of some of these stocks.

According to a recent World Bank Report, the demand for aluminum and copper used in solar panels is projected to grow by more than 350% by 2050. Similarly, the demand for zinc used in wind turbines is projected to grow by more than 80% by 2050.[7] Hence, while current material demand for these technologies may be marginal to total global demand, the proliferation of low carbon technologies could add to future resource stress and influence criticality assessments in the absence of robust end-of-life resource recovery.

The accelerated adoption of new solar PV and wind technologies will also come with novel waste disposal implications. By 2050, global solar PV waste is projected to reach 78 million metric tonnes,[8] while wind turbine blade waste is projected to reach 43 million metrics tonnes.[9] The presence of toxic chemicals in solar panels, the sheer size and number of wind turbines, and the lack of established economically viable recycling channels for end-of-life wind turbine blades have raised concerns about the end-of-life management of these technologies.[10]

2. Solar Energy

Solar energy can be converted into electricity through photovoltaic (PV) cells. This energy can be used, stored, or added to the grid. The amount of electricity generated depends on the intensity of sunlight. It is impacted by cloud cover, seasonal variation in daylight hours, and panel obstruction by snow and dust. Solar power generated also fluctuates with weather conditions and is not available during nighttime, making it a variable power source.[11] The main environmental advantage of solar energy is that it does not emit greenhouse gases. In addition, it does not emit ionizing radiation, produce radioactive waste or require the use of water, or cause noise pollution. However, some land degradation (soil compaction, potential alteration of drainage channels, and increased runoff and erosion) and habitat impacts can arise from the use of land for solar farms.[12]

The past forty years have seen a sharp decline in solar PV costs. This decline can be attributed to a range of factors, including efficiency improvements, cost reductions of non-silicon materials, a decline in silicon price, reduced wafer area and plant size, and reduction in silicon usage. Overarching mechanisms such as public and private R&D, economies of scale, and learning-by-doing have been equally crucial to the rapid cost decline.[13] According to the International Energy Agency's World Energy Outlook 2020 report, solar is now one of the cheapest sources of new electricity generation in history.[14]

In 2019, the global installed solar energy capacity was 578.5 GW, an increase of 1336% from 2010 levels.[15] Close to 70% of this installed capacity is in China, the United States, Germany, Japan, and India, with Canada accounting for only about 1%.[16]

In 2019, Canada had approximately 3300 MW of installed solar capacity (see Figure 1).[17] This capacity generated 0.6% of the country's electricity in the same year.[18] Figure 2 shows installed solar PV capacity by province and territory. Ontario had 94% of the country's installed capacity, with Alberta a very distant second at 3%, then Manitoba, Saskatchewan, and British columbia in descending order.

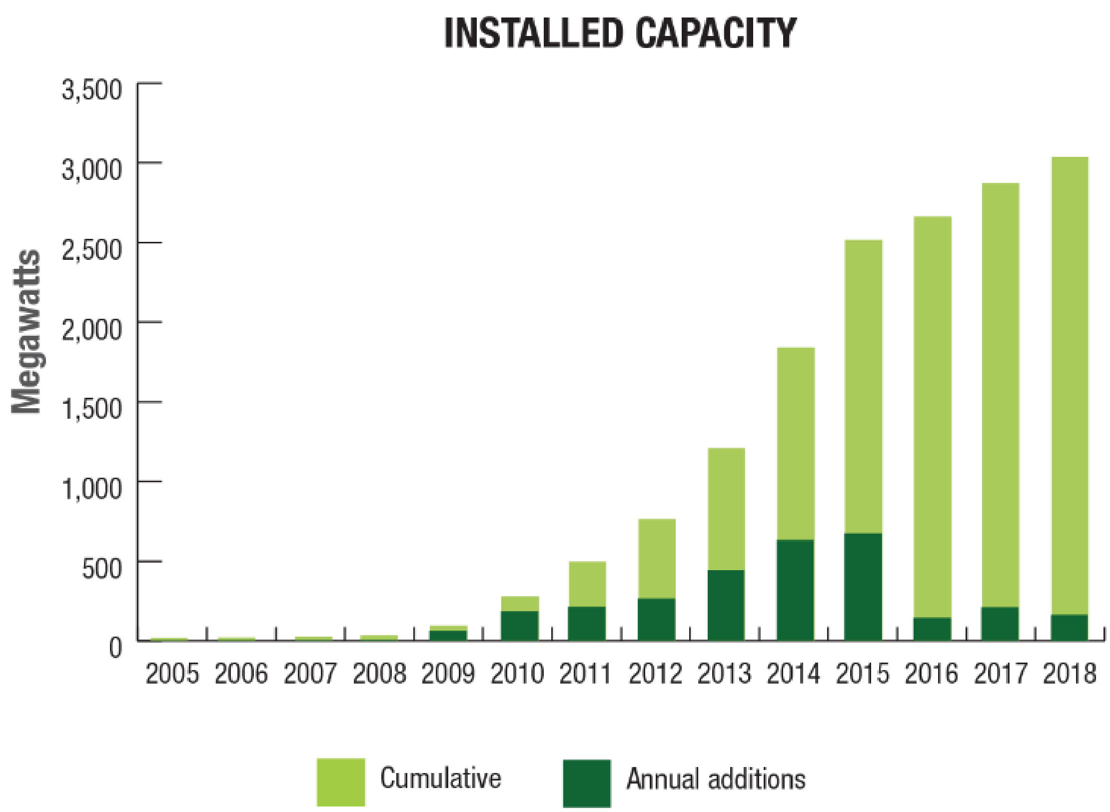


Figure 1: Installed Solar Capacity in Canada.
Source : Natural Resources Canada

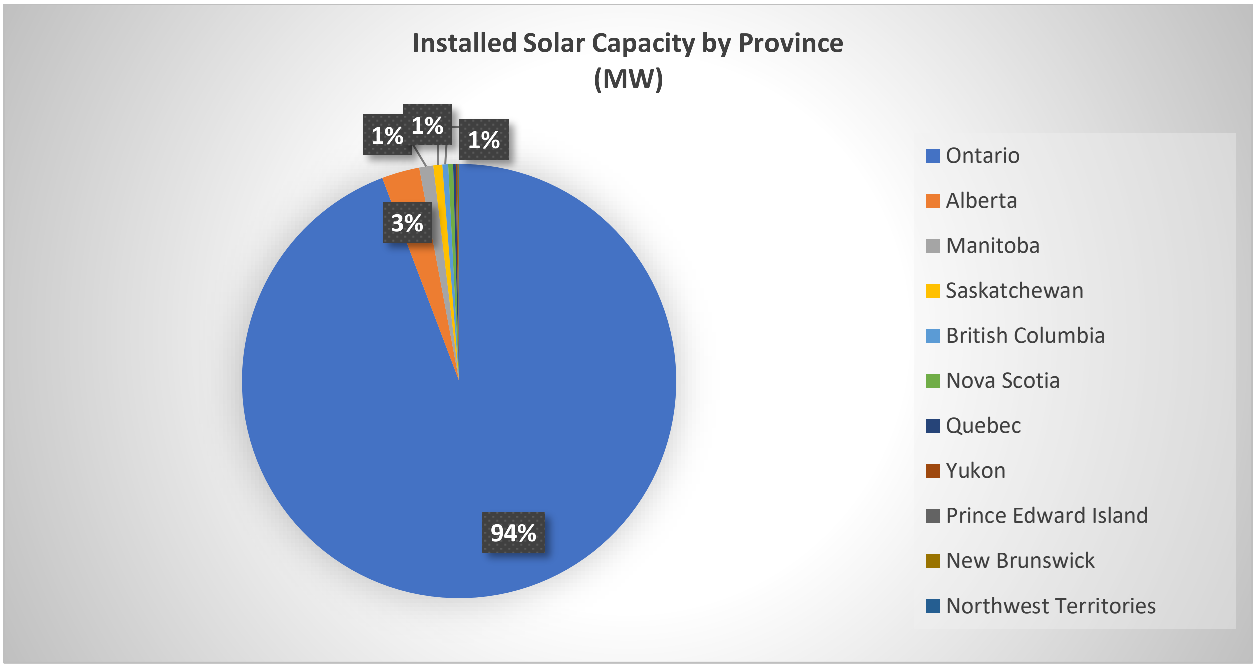


Figure 2. Installed solar PV capacity by Province
Source: International Energy Agency[19]

The primary historical impediment to broader adoption of solar energy in Canada has been cost. In 2016, the average lifetime cost of solar PV power in Canada was around 23 cents per kWh. As a result, solar relied overwhelmingly on incentive programs for development.[20] For instance, over 94% of Canada's solar power generation capacity is located in Ontario. This can be attributed in part to Ontario's feed-in tariff (FIT) program.[21] The FIT program was critical to the rapid growth in installed solar PV capacity in Ontario between 2010 and 2018. However, the recent decline in the levelized cost of energy (LCOE) production for solar PV has seen rapid growth in installed solar PV capacity even in provinces without financial support for solar PV such as Alberta. By 2026, the levelized cost of new onshore wind and solar PV is projected to drop below gas-fired and conventional generation.[22] And as Canada pursues its ambitious climate targets, solar PV deployment is expected to shift towards grid parity in most Canadian provinces and territories.

2.1. Projected Growth

As Canada pushes to meet its climate targets, installed solar PV capacity is expected to continue to grow. The Canada Energy Regulator (CER) provides an insight into how solar and other complementary renewable and low-carbon energy systems might evolve over the long term. In 2020 CER modelled an evolving energy system scenario (Evolving Scenario) that builds on the historical trend of increasing action on climate change. The assumptions that underpin this modeling exercise are detailed in Appendix 1.

Results from the Evolving Scenario indicate that total non-hydro renewable capacity in Canada doubles to approximately 40 GW by 2030 and more than triples to over 60 GW by 2050 from a 2018 baseline. This scenario also sees interconnection between several provinces to help regions integrate more considerable amounts of variable energy. See Figure 3.

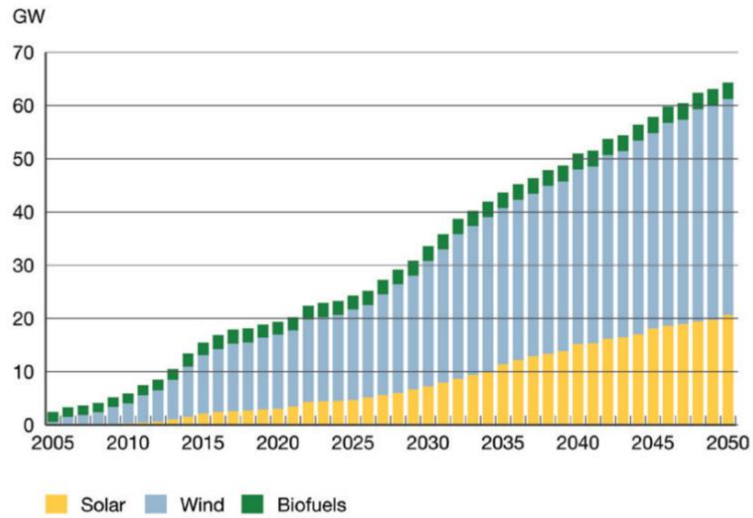


Figure 3 : Projected Capacity of Non-Hydro Renewables in the Evolving Scenario
Source : Canada Energy Regulator (2020)

Total solar PV capacity grows from 3 GW in 2020 to 8 GW by 2030 and 20 GW by 2050. Other forms of energy such as hydropower and natural gas provide back-up to help integrate increasing levels of variable resources such as wind and solar. The Evolving Scenario also included approximately 3 GW of utility-scale battery storage - critical for large solar additions.[23]

2.2. Key Technologies and Their Material Composition

The future end-of-life considerations of solar energy will be determined by the dominant solar PV sub-technologies in the market today and those that are predicted to be introduced or capture a larger market share in the future.

Photovoltaic (PV) panels can be classified into three generations as depicted in table 1, with current and future global market shares as shown in Figure 4.

Table 1: Solar PV Generations and Technologies

Technology Generations	Solar PV Sub-technologies
First generation- Crystalline Silicon (c-Si)	Monocrystalline
	Poly or Multi-crystalline
Second Generation- Thin-film based	amorphous silicon
	Copper indium gallium (di) selenide (CIGS)
	Cadmium telluride (CdTe)
Third Generation- concentrator photovoltaics and emerging technologies	Concentrator photovoltaics
	Dye-sensitised solar panels (OPV)
	Organic panels
	Hybrid panels

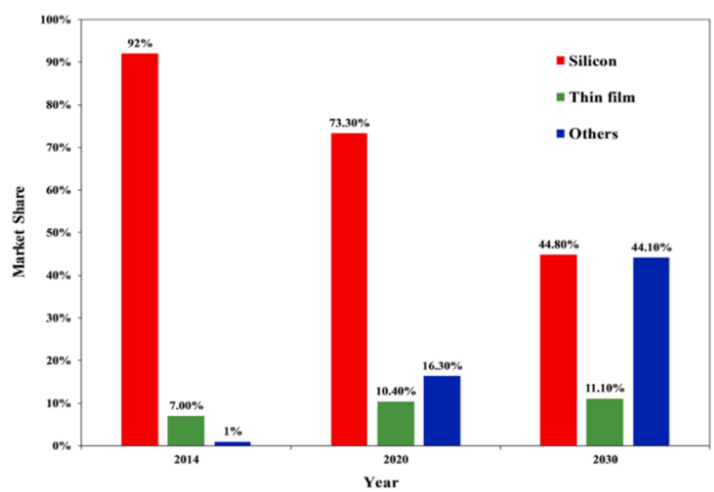


Figure 4: Global Solar PV Technology Market Share
Source : Chowdhury et al. (2020)

2.2.1 Silicon-based (c-Si)

C-Si is the oldest PV technology. C-Si technology consists of slices of solar-grade silicon, also known as wafers, made into cells and then assembled into panels and electrically connected (Figure 5). The majority of silicon-based PV panels are Multicrystalline silicon panels and Monocrystalline silicon panels. Silicon-based panels currently dominate the market. In 2014, these panels accounted for 92% of the global solar PV market share. By 2030, their market share is projected to decrease to 44.8% with the emergence of newer, third generation technologies.[24] This can be attributed to their long lifespan, low deterioration rate, and high conversion efficiency.[25]

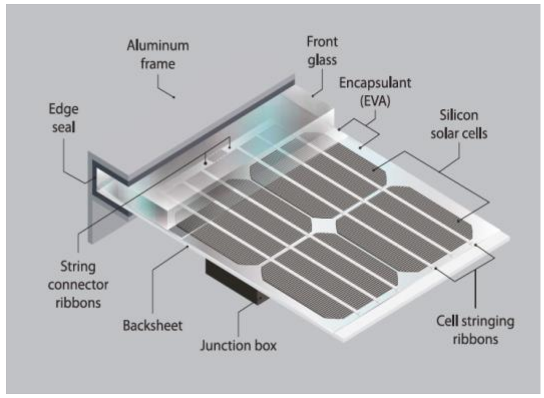


Figure 5:Illustration of a typical c-Si panel
Source :National Renewable Energy Laboratory (2016)

A typical c-Si PV panel with an aluminum frame and 60 cells has a capacity of 270 watt-peak (Wp) and weighs 18.6 kilogrammes (kg) (e.g. TrinaSolar TSM-DC05A.08).[26] Currently c-Si panels contains 76% glass (panel surface), 10% polymer (encapsulant and back sheet foil), 8% aluminum (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (mostly tin and lead). As technical advancements continue to result in thinner and more flexible wafers and more complex manifold cell structures, this composition is expected to change in the future. By 2030, the glass content of c-Si panels is predicted to increase by 4%. The share of silicon and aluminum is expected to fall by 2% and 1%, respectively. Specific silver consumption is expected to further decrease by better metallisation processes and replacements with copper or nickel/copper layers.[27] See Figure 6.

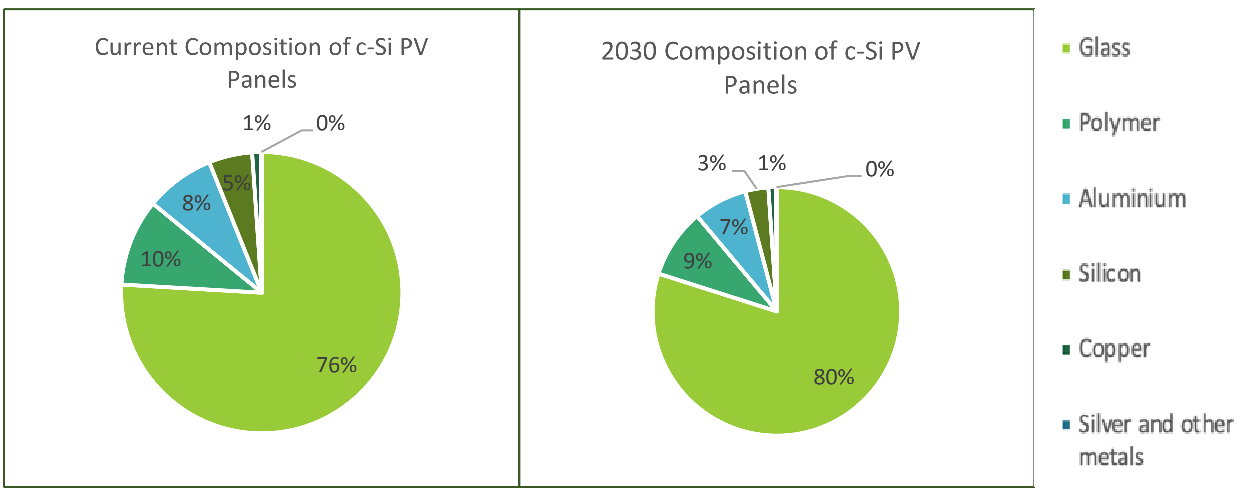


Figure 6: Current and expected 2030 Composition of c-Si Panels
Data Source: IRENA & IEA-PVPS (2016)

2.2.2 Thin Film based

Thin-film panels are the second generation of solar panels. They are generally cheaper than silicon-based panels, however are more technologically complex. They consist of thin layers of semiconducting material deposited onto large substrates such as glass, polymer, or metal (Figure 7). Thin-film PV panel technologies can be broken down into three sub-categories: Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe), and amorphous sillicon panels (a-Si). Due to low-efficiency ratios, a-Si products have been discontinued in recent years, and their market share is negligible.[28] CIGS and CdTe panels have a lower conversion efficiency relative to silicon panels at about 15%. However, while CIGS has great potential for better efficiencies and may gain market share, CdTe is not expected to grow.[29] In 2014, thin-film panels accounted for only 7% of the global market share and are expected to capture around 11% by 2030.[30]

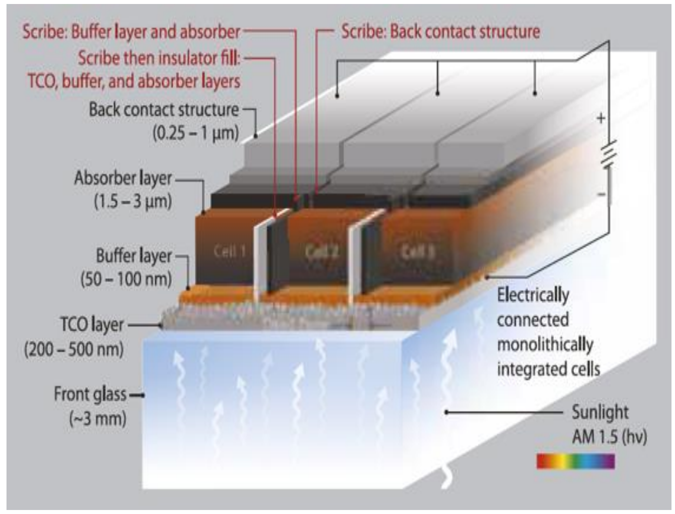


Figure 7 : Illustration of a Typical Thin Film panel
Source : National Renewable Energy Laboratory (2016)

A typical CIGS panel usually holds a capacity of 160 Wp and 20 kg (e.g. Solar Frontier SF160-S). These are composed 89% of glass, 7% aluminum, 4% polymer, and small quantities of other metals like copper, indium, gallium, and selenium. By 2030, the share of glass is expected to fall by 1%, while the share of aluminum is expected to rise by 1%. A slight reduction of 0.2% is also expected in other metals and a 0.2% increase in semiconductors.[31] See Figure 8.

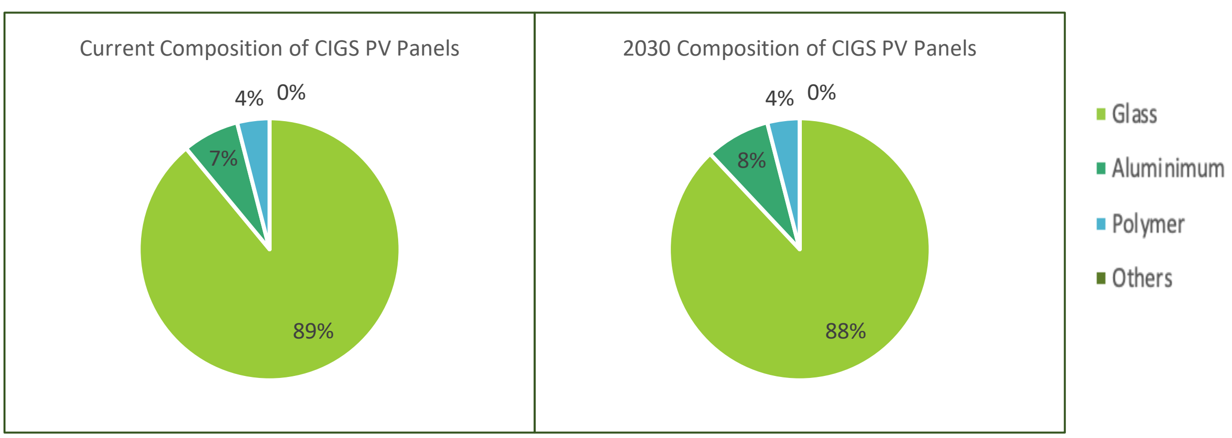


Figure 8: Current and Estimated 2030 Composition of CIGS Panels
Data Source: IRENA & IEA-PVPS (2016)

A standard CdTe panel usually holds a capacity of 110 Wp and 12 kg weight (e.g. First Solar FS-4100).[32] These are composed 97% of glass and 3% polymer. By 2030, the share of glass is expected to fall by 1%, while the share of polymer is expected to rise by 1%. Compared to CIGS panels, semiconductors' material usage as a proportion of panel usage is expected to decline from 0.13% to 0.07%. The share of other metals (e.g. nickel, zinc and tin) is expected to grow from 0.26% to 0.41%. See Figure 9.

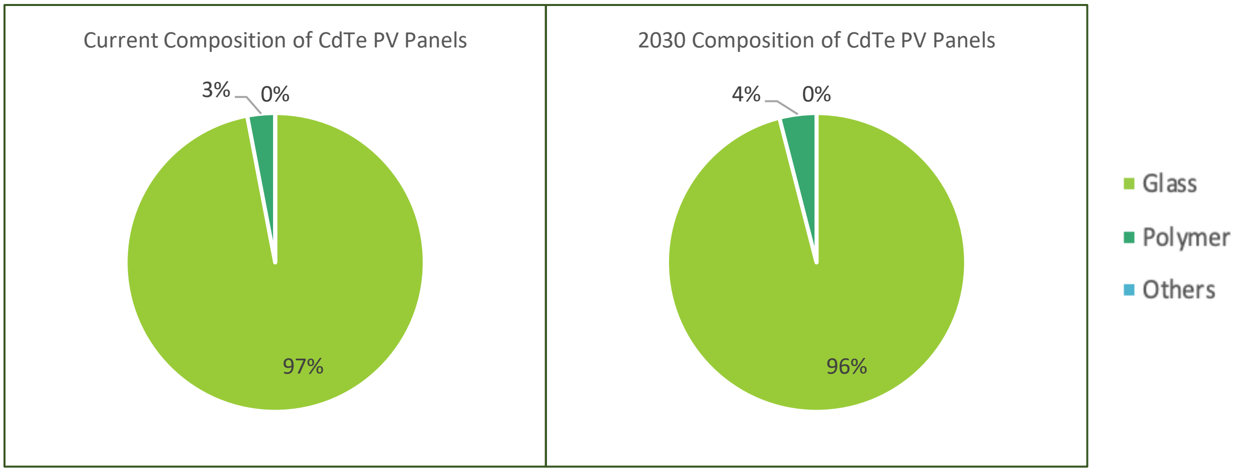


Figure 9: Current and Estimated 2030 Composition of CdTe Panels
Data Source: IRENA & IEA-PVPS (2016)

A summary of how the material composition of different PV panel technologies as a percentage of total panel mass is expected to change is depicted in Figure 10.

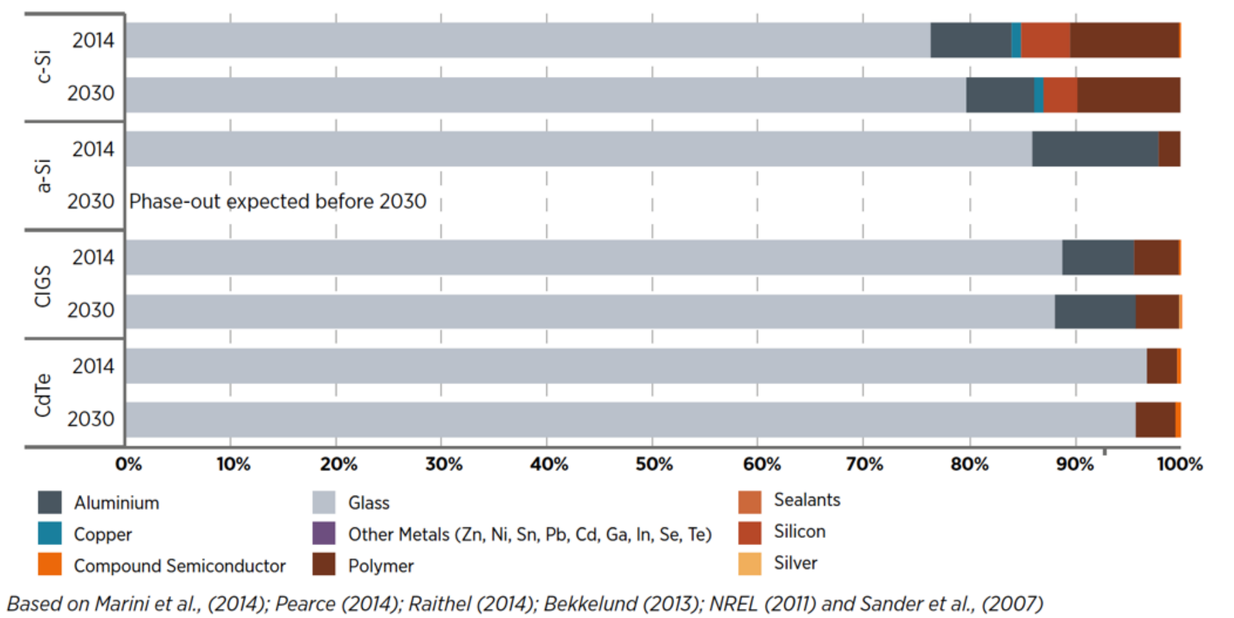


Figure 10: Evolution to 2030 of Materials used for Different PV Panel Technologies as a Percentage of Total Panel Mass
Source: IRENA & IEA-PVPS (2016)

2.2.3 Others

In addition to the commercial technologies, a vast array of third-generation solar PV sub-technologies are currently being developed. These technologies currently have a relatively small market share, but are expected to take over 44.1% of the global PV market by 2030.[33] The past five years have already seen rapid technological advancements with organic and perovskite solar cells believed to be on the verge of possible large-scale deployment.

The critical difference between traditional (First and Second-generation) solar cells and organic/ perovskite solar cells lies in the mechanism of charge generation. The active layer material is an organic semiconductor and hybrid organic-inorganic perovskite for organic and perovskite solar cells, respectively.

The photoactive layer comprises a semiconducting polymer and a fullerene or non-fullerene acceptor (NFA) derivative for organic solar cells. Recent improvements in cell efficiency from approximately 2.5% in 2013 to 18% in 2020 in organic solar PV cells can be attributed to these novel NFA.[34]

For perovskite solar cells, organic-inorganic lead halide perovskite is an ideal material for solar PV applications. While there are alternative perovskite-type compounds, their certified power conversion efficiency (PCE) is extremely low. In 2019, organic-inorganic lead halide perovskite demonstrated a PCE of 25.2%, surpassing the PCEs of legacy thin-film solar cells such as CIGS and CdTe.[35]

Issues such as long-term stability pose a bottleneck for further commercialization of organic and perovskite solar cells. However, recent advancements in efficiency improvements and material substitution provide optimism.[36]

Due to the uncertainty around these new technologies' market adoption, this report currently focusses on first and second-generation solar PV panel technologies.

2.3. Global Value Chain

The last decade has seen a dramatic spatial shift in the global value chain for the solar PV industry. Initially, the value chain for solar PV technologies was concentrated in a few developed economies such as the US, Japan, and Germany. However, the past decade has seen the consolidation of manufacturing in China, accompanied by drastic price decreases of approximately 85% from a 2009 baseline. China also leads in terms of demand for PV systems and now is the largest global market.

Today, crystalline photovoltaics dominate the supply chain of solar PV technologies, accounting for over 90% of the solar PV market.[37] The crystalline PV production process involves five main stages as illustrated in Figure 11.[38] These are :

1. Silicon purification – heavy and energy-consuming chemical processes transform silica found in quartz sand into the ultra-high purity form required for PV applications;
2. Ingot and wafer manufacturing – pure silicon is used to grow an ingot (cylinder of silicon). Ingots are subsequently sawed into thin layers forming wafers;
3. Cell production – two differently doped wafers are connected along with top and rear metal contacts to form the cell. This assembly comprises the p-n junction responsible for the photovoltaic effect;
4. Module assembling – multiple cells are soldered together, and the subsequent cell structure is encapsulated in glass sheets to form a module; and
5. Systems – modules are assembled with supplementary equipment including support structures, wiring and inverters (as well as batteries in selected cases) to deliver electricity to the loads

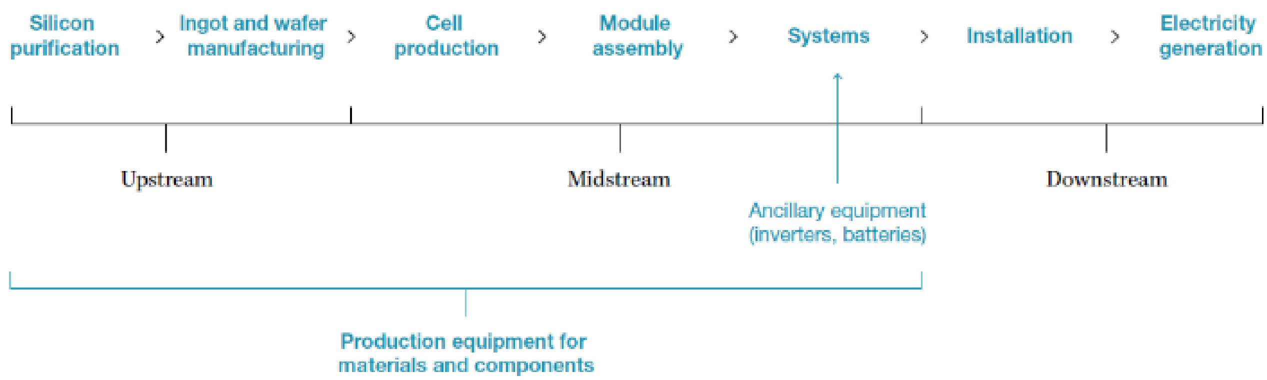


Figure 11: Crystalline PV supply chain

Source : Maria Carvalho et al. (2017)

China, and to an extent, Taiwan are now world leaders in upstream and midstream segments and supply more than 80% of the global market. However, in contrast to the remainder of upstream and midstream segments, silicon purification remains the one market where Chinese firms remain slightly less successful. Despite a continual overcapacity level, data from the IEA[39] indicates new manufacturing plants for polysilicon production came online in South Korea and the USA. This trend can be attributed, in part, to technological advancements and adopting cost-efficient production equipment that can help companies maintain profitability against other polysilicon competitors.

Solar PV manufacturing associations in the USA and Europe have petitioned against importing Chinese solar PV products. They argued that Chinese solar PV firms unfairly benefit from the Chinese government's subsidized loans to sustain production even under unfavourable market conditions. This argument has led to both US and EU imposing duties against Chinese solar PV products. Moreover, certain countries have implemented market support mechanisms for solar PV, such as local content requirements.

However, Chinese firms have worked to bypass these barriers partially. They have set up manufacturing plants in countries worldwide, including Thailand, India, Germany, and Brazil. Chinese solar PV associations use these manufacturing plants to serve domestic markets and as an export base to supply markets that currently have duties against them.[40]

Non-Chinese solar developers are highly dependent on China to supply essential materials that are critical for solar panel production. Several emerging concerns pose the threat of costly disruptions to the global solar PV supply chain. The importance of addressing these concerns is accentuated when the importance of solar PV and wind energy towards achieving ambitious climate targets is considered.

First, a shortage of glass is causing price hikes and delaying the production of new solar panels in China. Chinese glass manufacturers are unable to meet rising demands, and recent proposals for new production facilities have been rejected by the Chinese government due to the industry's energy-intensive nature and fears of over-capacity.[41] Moreover, there are growing concerns surrounding the sustainable supply of sand - a key component in glass production. Fifty billion tonnes of sand and gravel are used annually worldwide, and If not managed correctly, sand extraction from places with fragile ecosystems can have significant environmental impacts. Rising demands also present an ethical issue with "sand mafias" threatening vulnerable local communities.[42]

Second, there are also growing technical and ethical concerns with the supply of polysilicon - another key material required in the production of solar panels. Currently, China controls 80 percent of global polysilicon supply, with approximately one-third coming from the Xinjian region - the region in which China is reportedly abusing Uighurs and other minorities.[43] The U.S. House of Representatives recently passed a bill that bans goods made "wholly or in part" in this region. Moreover, the Solar Energy Industries Association is publicly encouraging companies to relocate their supply chains outside these regions. The lack of diversity in the supply chain further accentuates import bans' adverse impact to the solar panel industry.[44]

2.4. Material Criticality

Solar panels require various mineral products and metals.[45] Many of these are designated as critical minerals in Canada, based on their necessity for economic growth and national security. These include copper, indium, molybdenum, tellurium, titanium, gallium, germanium and tin. [46]

Of all the minerals used in the production of solar PV panels, aluminum, copper, and silver have the highest proportions. According to a World Bank study, aluminum accounts for more than 85 percent of the mineral demand from solar photovoltaic through 2050 (under an IEA modeled scenario with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100). Copper follows this at 11%, while silver accounts for less than 0.05%.[47] See Figure 12.

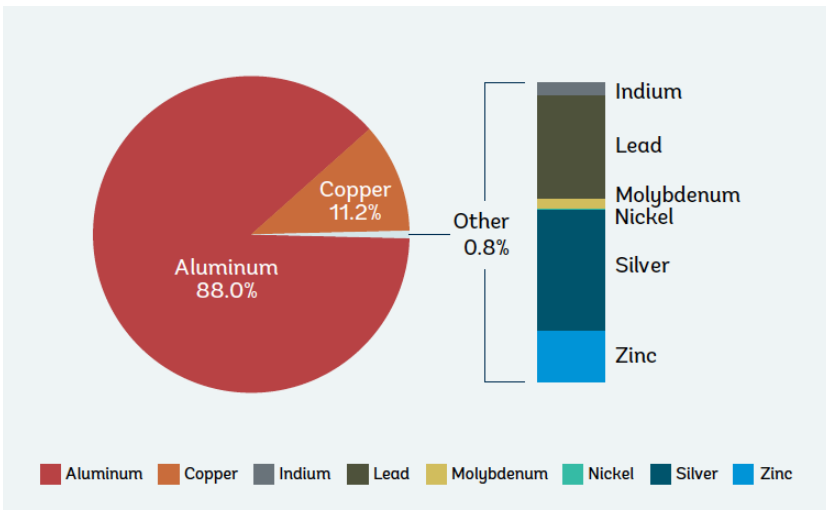


Figure 12: Share of Mineral Demand from Solar Photovoltaic through 2050
Source: World Bank (2020)

The same study also found that under all technology-based mitigation scenarios modelled by the IEA and IRENA, aluminum and copper demand will grow through 2050. Under IRENA's Remap ambitious scenario that limits the rise in global temperature to "well below" 2°C above preindustrial levels by 2100, demand for both minerals is projected to grow by more than 350 % to 160 million tonnes of aluminum and 20 million tonnes of copper.[48] See Figure 13.

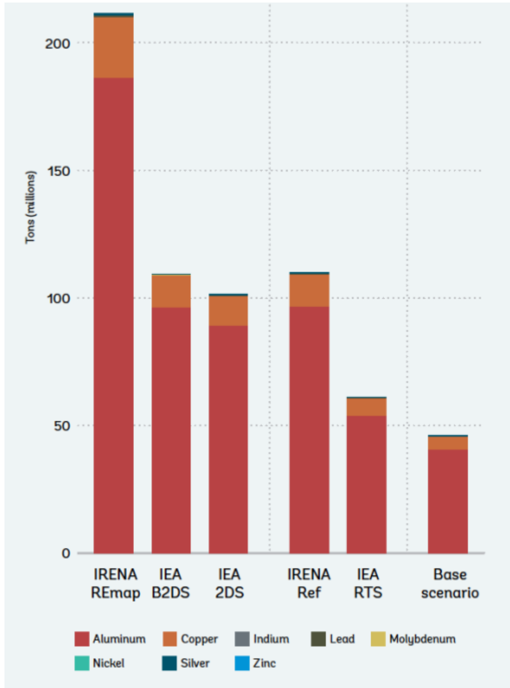


Figure 13: Cumulative Demand for Minerals Needed for Solar through 2050.
Source : World Bank (2020)

Further, while aluminum and copper demand will undoubtedly grow, this demand is expected to be relatively stable. Aluminum and copper are used in various clean energy generation and storage technologies and have a cross-cutting demand. On the other hand, minerals that are used only in a few clean technologies possess higher demand uncertainty as they have a concentrated demand. For instance, indium is predominantly used in CIGS solar cells and could see between a -61% and +172% change in demand through 2050 compared to a base share of about 30 thousand tonnes in 2017, under the IEA's 2 degree scenario (with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100). The uncertainty in demand can be attributed to uncertainty in the market evolution of solar PV sub-technologies.[49] See Figure 14.

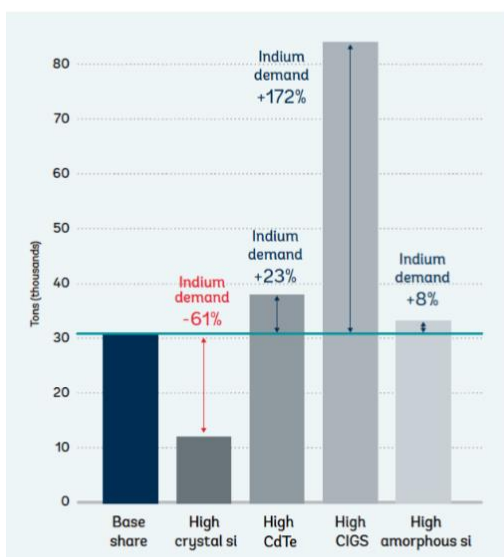


Figure 14: Cumulative Demand for Indium from Solar PV Subtechnologies Through 2050
Source : World Bank (2020)

Further, while Indium's abundance in the earth's crust is estimated to be approximately 0.1 ppm, its deposits in nature are highly dispersed. It is challenging to find enriched indium deposits of economic interest. Currently, indium is only recovered as a co-product from zinc-sulfide ore mineral sphalerite. Despite being found in trace amounts in other base metals deposits, it is often not economically viable to process and extract it.[50]

Like indium, gallium- another criticial mineral used in CIGS panels is only found in low concentrations in metal ores. It rarely occurs in mineable concentrations and seems to be concentrated in certain oxide minerals such as bauxite, corundum, and magnetite. Global gallium resources are estimated to be approximately 2 million tonnes in bauxite deposits and 6,500 tonnes in zinc deposits.[51]

For CdTe solar panels, the supply of tellurium is often highlighted as a bottleneck for growth. Tellurium is extremely rare, making up approximately 0.0000001% of the earth's crust. Most of the tellurium produced today is recovered as a byproduct from the electrorefining of copper. However, as copper grades continue to decline, copper miners are turning to different recovery methods to exploit lower-grade ore which largely bypass any recovery of tellurium.[52]

2.5. Waste Streams

Solar PV waste is typically generated during the four primary lifecycle phases of a solar PV panel. These are:

- panel production
- panel transportation
- panel installation and use
- panel end-of-life disposal

Further, waste is also generated when panels fail before their estimated lifespan. The three main panel failure phases are:

- Infant failures, defined as occurring up to four years after installation (average two years);
- Midlife failures, defined as occurring about five to eleven years after installation;
- Wear-out failures, defined as occurring about 12 years after installation until the assumed end-of-life at 30 years.

A study published by the International Renewable Energy Agency (IRENA) and the International Energy Agency Photovoltaic Power Systems (IEA-PVPS) in 2016 estimated that global PV panel waste was between 43,500 tonne -250,000 tonne in 2016. See Figure 15. Further, it was projected that this waste would increase to between 1.7 million tonne and 8 million tonne in 2030 and between 60 million tonne and 78 million tonne in 2050. This study covers all life cycle stages except production. The study assumes that production waste is easily managed, collected, and treated by waste treatment contractors. The range in estimates of solar PV waste projections can be attributed to the assumptions employed in the two modelled scenarios:[53]

- a regular-loss scenario that assumed a 30-year lifetime for solar panels, with no early attrition
- an early-loss scenario that took account of infant, mid-life and wear-out failures before the 30-year lifespan.

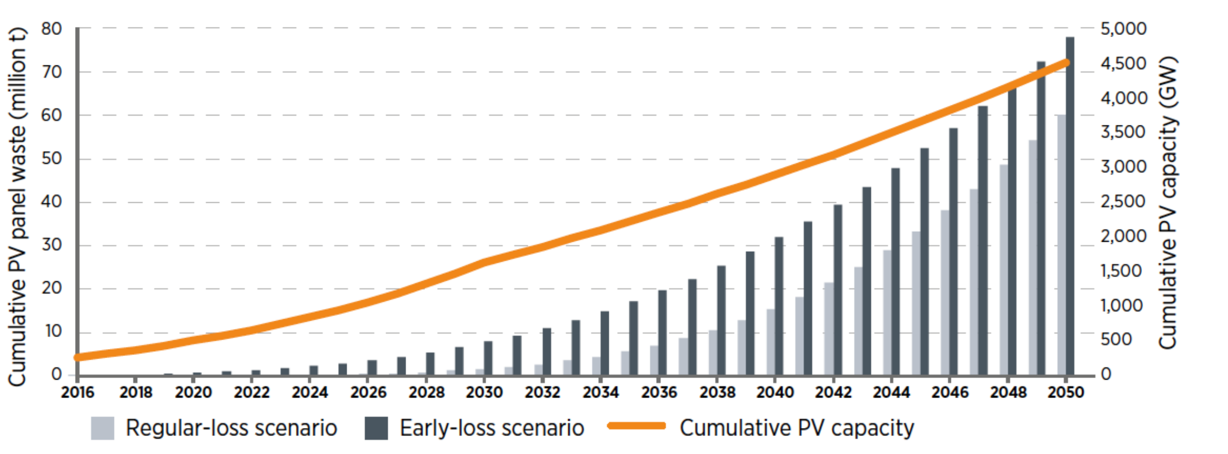


Figure 15: Estimated Cumalative Global Waste Volumes (million tonnes) of End-of-Life PV Panels.
Source: IRENA & IEA-PVPS (2016)

The study also estimates Canadian waste volumes for end-of-life solar PV panels (See Figure 16). The study estimates that solar PV panel waste will rise significantly in Canada from between 350 tonne - 1600 tonne in 2016 to between 650,000 tonnes to 800,000 tonnes in 2050. Waste volumes are expected to increase more rapidly after 2030, given the surge in solar PV deployment since 2010 and average lifetime and failure rates for panels.[54] See Figure 16.

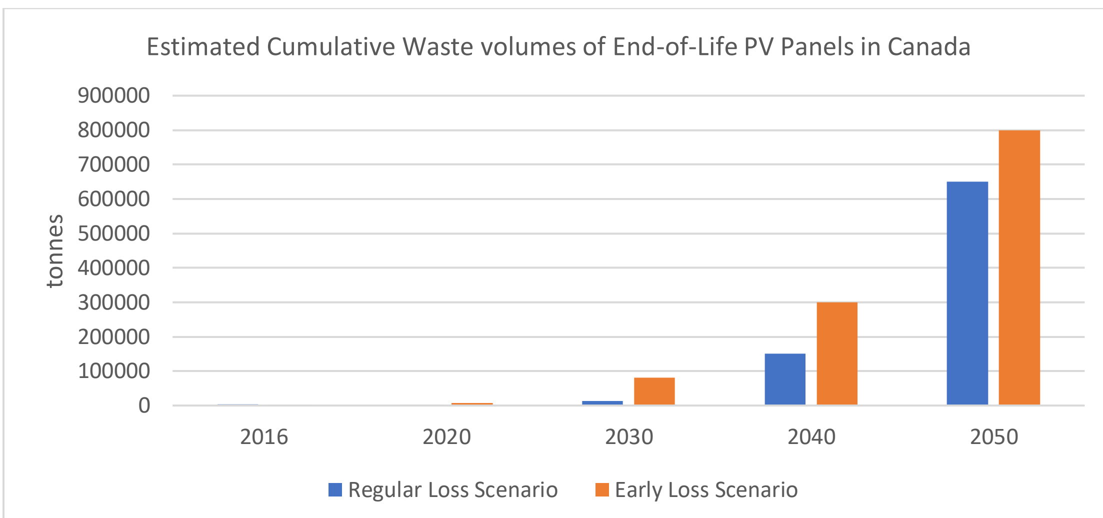


Figure 16: Estimated Cumulative Waste Volumes of End-of-Life PV Panels in Canada
Data Source: IRENA & IEA-PVPS (2016)

The IRENA report provides an insight into how solar PV waste streams will increase as cumulative installed solar PV capacity increases. However, IRENA's model uses an ambitious global average annual solar PV growth rate of 8.92% between 2015-2030 and a conservative growth rate of about 2.5% between 2030-2050. This growth rate varies by country and is affected by political and economic uncertainties and the IRENA report subsequently adjusts it for each country. However, the IRENA report fails to outline what this corresponding adjusted growth rate is for Canada. The growth rate affects future solar power installed capacity, and the installed capacity is the most significant factor determining waste evolution.

A study by Santos et al. provides an updated methodology to calculate solar PV waste projections. The authors highlight the importance of accounting for annual repowering needs when projecting future waste streams. Solar PV plants are subject to progressive annual power losses (annual re-powering needs), and these losses need to be taken into account when estimating annual installed solar PV power. Thus, a failure to account for annual re-powering needs runs the risk of misrepresenting future solar PV waste flows as annual installed solar PV capacity is the key driver to estimate future waste streams.[55]

To account for these disparities, this project's modelling used data from Canada Energy Regulator's "Canada's Energy Future 2020" report for projected increasing solar capacity in the 'Evolving Scenario. Table 2 shows projections for installed capacity in Canada:

Table 2: Installed Solar PV Capacity Projections up to 2050 for Canada Source Canada Energy Regulator (2020)

Year	2015	2020	2025	2030	2035	2040	2045	2050
Installed Solar Capacity(MW)	2517	3500	4879	7300	11387	15236	18367	20782

Additionally, this project's modelling used the updated methodology from Santos et al. and factors in similar initial and early loss assumptions as the IRENA report to project solar PV waste evolution in Canada.

While these findings give a sense of cumulative solar PV waste evolution, differences in solar PV sub-technology types subsequently give rise to differing material waste compositions. For c-Si panels, over 90% of the mass is composed of glass, polymer, and aluminum which can be classified as non-hazardous waste and 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 thin-film panels, over 98% of the mass is composed of glass, polymer, and aluminum, while 2% of the mass is copper and zinc, which are environmentally hazardous. Thin-film panels also contain hazardous materials such as indium, gallium, selenium, cadmium tellurium, and lead.[56] Of these, cadmium and lead have the highest negative impact on humans' health and the environment.[57] However, thin-film modules are projected to represent only a tenth of the market into the future (Figure 4, above), and the incentive to recycle these modules to re-source their materials is high, which is why the main manufacturer of the CdTe modules, First Solar, has its own collection and recycling program.

2.5.1 Modelled Solar Waste Projections

Figure 17 illustrates the temporal evolution of cumulative solar PV waste in Canada. It can be observed that in the 'Early Loss' scenario, cumulative solar PV waste mass increases faster than in the 'Regular Loss' Scenario. This can be attributed to the 'Early Loss' scenario accounting for certain probabilities of failure in the early life stage of solar PV modules. As an illustrative example, in the 'Early Loss' scenario, a cumulative solar PV waste mass of approximately 100,000 tonnes is reached in 2033. For the 'Regular Loss' scenario, this equivalent solar PV waste mass is expected by 2039.

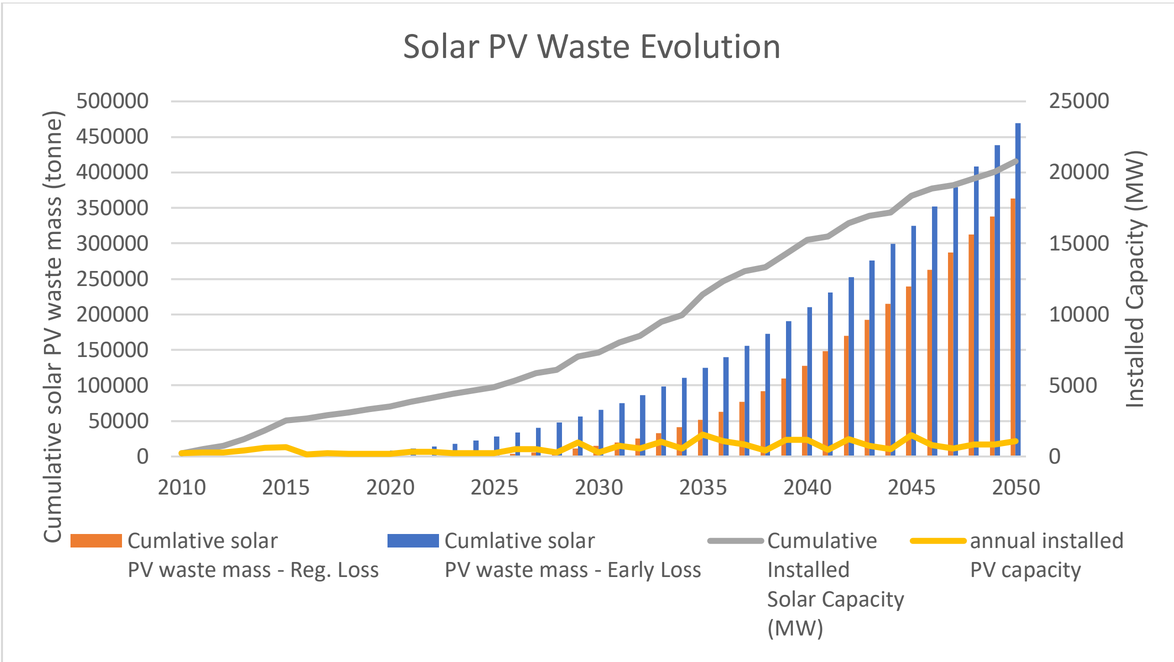


Figure 17. Cumulative Solar PV Waste Evolution

In 2050, the cumulative solar PV waste mass is approximately 470,000 tonnes for the 'Early Loss' scenario and 365,000 for the 'Regular Loss' scenario. The 'Early Loss' scenario understandably presents a greater cumulative solar PV waste mass relative to the 'Regular Loss scenario' over the time period analyzed. Early losses require larger re-powering needs relative to the 'Regular Loss' scenario, which subsequently increase the annual installed capacity of solar PV in Canada – and installed capacity is the key driver to estimate future waste streams.

Figure 18 illustrates annual solar PV waste mass for the 'Regular Loss' and 'Early Loss' scenario. The annual solar PV waste mass's temporal evolution is important to analyze the balance between incoming waste flows and recycling capacities.

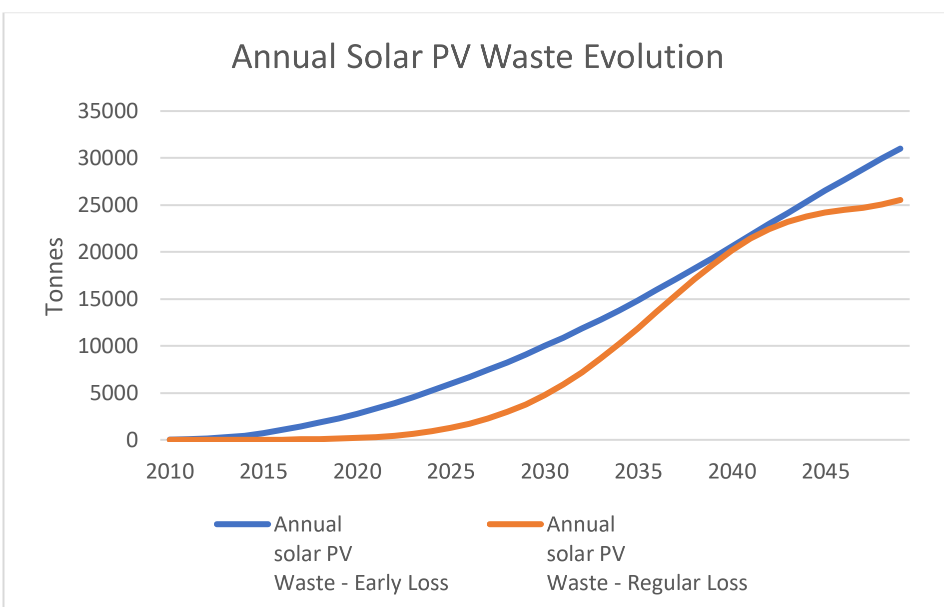


Figure 18. Annual Solar PV Waste Evolution

Understandably, annual solar PV waste mass increases faster in the 'Early Loss' scenario relative to the 'Regular Loss' scenario. The 'Early Loss' scenario sees an almost linear growth in the annual solar PV waste generation rate. For the 'Regular Loss' scenario, the annual solar PV waste generation rate grows exponentially with time, reaching a maximum at around 2040. This is followed by a progressive decrease in the annual solar PV waste generation rate. This scenario suggests that there could be periods of scarcity of discarded solar PV modules for a national PV recycling industry in the future.

Figure 17's data allows for estimating what these end-of-life solar PV waste quantities would translate in terms of cumulative waste material mass for Canada. The results obtained are shown in Table 3.

Table 3: 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

3. Wind Energy

Wind energy can be converted into electricity using the kinetic energy created by air in motion to turn wind turbines or wind energy conversion systems. The amount of power that can be harvested from wind depends on the turbine's size and the length of its blades. The output is proportional to the dimensions of the rotor and wind speed.[58]

Modern wind turbines are increasingly cost-effective, reliable, and robust. Fierce competition and technological innovation at the global level have drastically reduced wind energy costs to unprecedented levels. According to a 2019 report by the US-based investment firm Lazard, the levelized cost of unsubsidized wind electricity is between $28-$54/MWh.[59] These falling costs have transformed wind energy into the cheapest option for new electricity supply, with jurisdictions worldwide reaping the benefits. In 2019, wind energy's global installed capacity was 5948.25 GW, an increase of 234% from 2010 levels.[60] Over 60% of this installed capacity is in China, the United States, and Germany, with Canada accounting for about 2%.[61]

In 2019, Canada had 13,417 MW of installed wind capacity (Figure 19).[62]

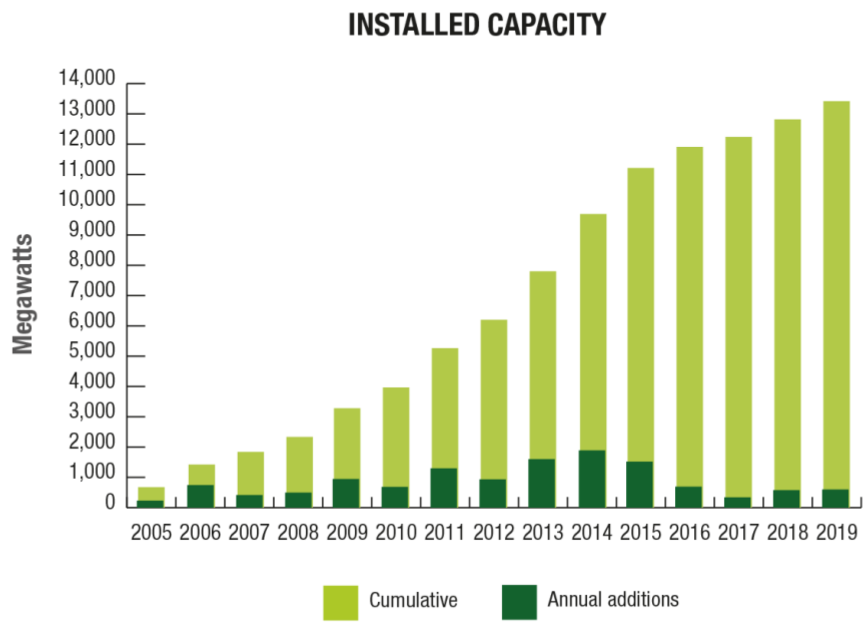


Figure 19: Installed Capacity of Wind in Canada.
Source: Natural Resources Canada

Canada's geography makes it ideal to capitalize on large amounts of wind energy. In 2019, Ontario had the most wind energy capacity with 5,436 MW of power, followed by Quebec with 3,882 MW of power.[63] Ontario and Quebec together account for 70% of installed wind capacity in Canada. Figure 20 illustrates installed wind capacity by province.

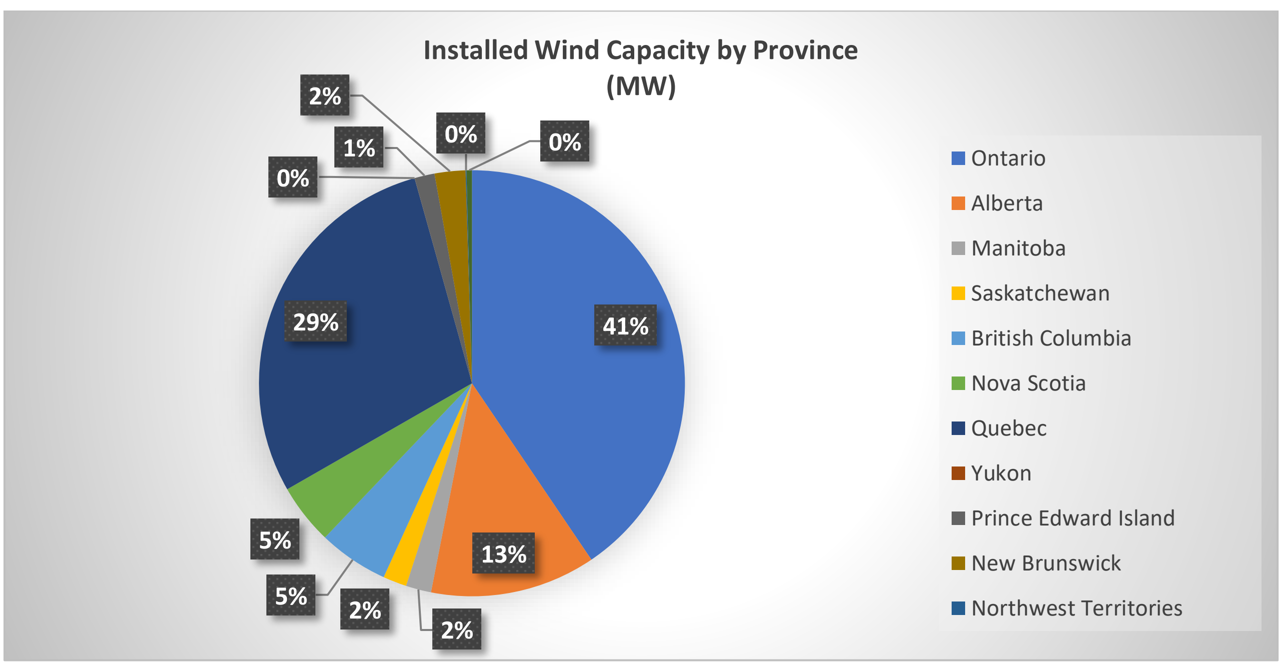


Figure 20. Installed wind capacity by province
Source: CanWEA[64]

3.1. Projected Growth

Similar to growth projections for installed solar PV capacity in Canada, Canada Energy Regulator's report also projects temporal evolution of installed wind capacity. Under its Evolving Scenario described in section 2.1, wind capacity is projected to grow from 13.7 GW in 2020 to approximately 23 GW in 2030 and 40 GW in 2050.[65]

3.2. Key Technologies and Their Material Composition

Modern utility-scale wind turbines are of two types, geared or direct drive. The standard lifetime of a wind turbine is approximately 20-25 years.

3.2.1 Geared turbines

Geared turbines use a gearbox to convert the turbine rotor's relatively low rotational speed (12–18 rpm) to a much higher speed (1,500 rpm) for input to a generator. The vast majority of these generators are double-fed induction generators, which use significant copper and iron amounts. Moreover, these turbines have a high number of moving parts resulting in more frequent maintenance. [66]

Over time, these have evolved to achieve a low cost with a high level of reliability. As a result, geared turbines dominate the global wind market, accounting for approximately 80% of global installed wind capacity. Geared turbines also dominate the market share of onshore wind installations where maintenance is relatively straightforward.[67]

3.2.2 Direct drive wind turbines

Direct drive wind turbines use generators fixed directly to the rotor and therefore turn at the same speed. Specific models employ a generator with permanent magnets consisting of rare earth minerals such as neodymium and dysprosium. In contrast, alternatives use an electrically excited rotor utilizing significant amounts of copper.

Direct-drive turbines tend to be more expensive per megawatt of energy produced. However, they require lower maintenance during the turbine's operation. Hence, they are the preferred technology for offshore wind farms, where maintenance is much more challenging.[68]

In terms of material composition and requirements, offshore wind turbines differ significantly from onshore turbines. Offshore wind turbines encounter harsher conditions relative to their onshore counterparts and thus need to be more resistant to corrosion, higher winds, and extreme weather. Offshore wind farms also require more significant material inputs in their foundations (mainly steel) and cabling to transmit the electricity onshore (for example, copper).[69] They also require some rare earth elements like neodymium and dysprosium.

A wind turbine consists of four basic parts: the foundation, tower, the nacelle, and the rotor blades (Figure 21).

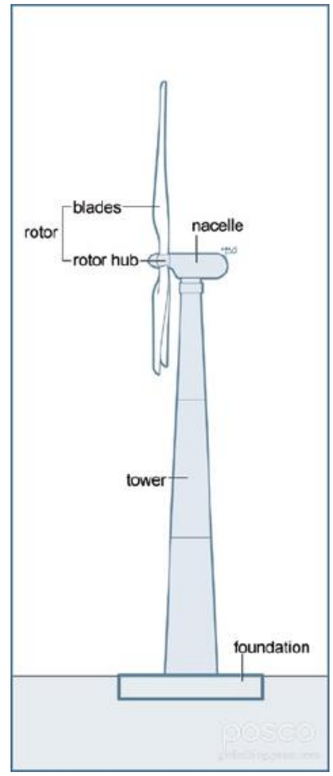
Foundation: Maintaining stability is critical for a wind turbine, and an appropriate foundation ensures this. Onshore wind turbines use either spread foundations or piled foundations depending on the soil type at the construction location. In the case of offshore wind, the type of foundation used differs based on the depth of the water, distance from shore, and wind turbine capacity. Turbines in shallow water (0-30 m) typically use a gravity or monopile foundation, while multi-pod type foundations are generally preferred in sea depths beyond 30m.[70] Wind turbine foundations are constructed mainly of concrete along with some iron and steel.

Tower: The tower provides structural support upon which the nacelle and rotor blades stand. Wind turbine towers are typically constructed using tubular steel, concrete, or steel lattice.

Nacelle: Mounted on top of the tower is the nacelle. The nacelle is a strong, hollow shell that contains the inner workings of the wind turbine. Most nacelles have standard components, such as a hub, rotor, gearbox, generator, inverters, hydraulics, and bearings. The major materials found in the nacelle are iron, steel, aluminum and copper, while fibre glass and resin are typically used for the nacelle cover.[71]

Rotor blades: Wind turbine blades are considered a composite structure and can be made of various materials depending on the blade type and manufacturer. However, they are generally composed of:[72]

- Reinforcement fibres e.g. glass, carbon, aramid or basalt;
- Polymer matrix 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);
- Coatings e.g. polyethylene (PE), polyurethane (PUR);
- Metals e.g. copper wiring, steel bolts.



Wind Turbine

3.3. Global Value Chain

The global wind energy value chain comprises several distinct steps – spanning from the supply of critical raw materials to final electricity transmission. Figure 22 provides a holistic view of the entire wind energy value chain:

Figure 22: Wind Value Chain.
Source: NEXTENERGY.

Analysis indicates that there are ample opportunities for new players at every stage of the value chain except for the 'Wind Turbine Companies' segment. The 'Wind Turbine Companies' segment has a concentrated original equipment manufacturer (OEM) market and is dominated by ten top players.

However, the wind energy industry has seen a trend over the past decade with incumbents vertically integrating their value chains.[73]

OEMs such as Gamesa, Vestas, and GE now have an in-house supply of generators and controllers to bypass supply chain bottlenecks. However, vertical integration has not always been a straightforward process. In their 2018 report, Wood Mackenzie Power & Renewables claim that North American turbine OEMs will seek to outsource partnerships with Chinese component suppliers to squeeze costs further.[74]

Additionally, the industry is under pressure to adapt to the pace of technological developments rapidly. As turbines get more powerful, longer blades and taller towers are required. This, in turn, creates logistic challenges that will require novel solutions such as on-site/closer-to-site manufacturing.[75]

For this reason, many experts believe that some wind development supplies are best sourced locally.[76] Alberta has a long history of wind project development, and in 2016, approximately 32% of Canada's total installed wind capacity was developed by Alberta-based companies.[77] In recent years, provincial governments have been encouraging European wind turbine manufacturers to build local factories. 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. They include rotor blades, casting and forgings, assemblies and covers, and the tower sections.[78]

3.4. Material Criticality

Wind turbine production requires various mineral products and metals. Many of these are designated as critical minerals in Canada, based on their necessity for economic growth and national security. These include copper, aluminum, chromium, molybdenum, manganese and nickel. [79]

As noted in previous sections, the main components of turbines (towers, castings, nacelle, shafts, and so on) are primarily made up of steel. Steel is manufactured using a mix of iron ore, carbon, and other elements. According to the same study by the World Bank cited in section 2.4., iron accounts for about 85% of the mineral demand from wind through 2050 (under a IEA modeled scenario with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100). Iron reported here is used directly in the turbine, in either the generator core, the mainframe, or the rotor hubs; it does not include the iron needed for the steel components. This is followed by copper at 4.4%. All other minerals combined represent nearly 11 % of demand, primarily for the permanent magnets (neodymium), gearboxes (nickel), or cabling (aluminum). Minerals not included in this analysis include dysprosium, which is used in permanent magnet direct-drive turbines.[80] See Figure 23.

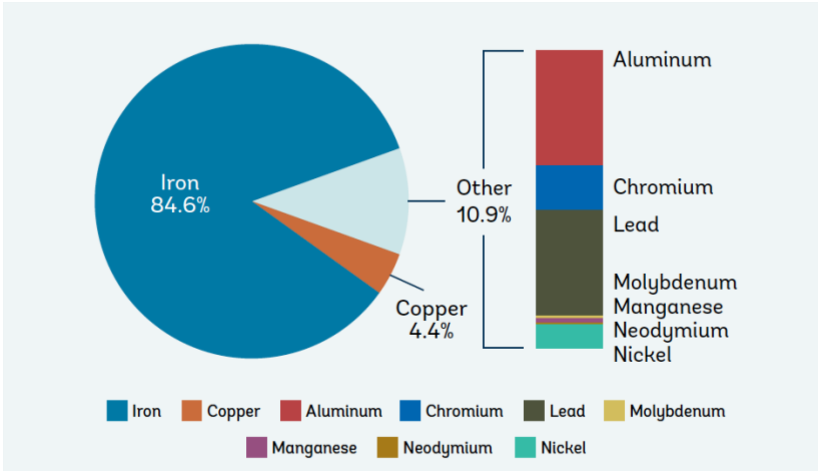


Figure 23: Share of Mineral Demand from Wind through 2050

Source: World Bank (2020)

The same study also found that under all technology-based mitigation scenarios modelled by the IEA and IRENA, demand for all minerals grows through 2050, with the highest increase seen in IRENA's REmap ambitious scenario that limits the rise in global temperature to "well below" 2°C above preindustrial levels by 2100. [81] In this scenario, the demand of iron will over 350 million tonnes through 2050 (Figure 24).

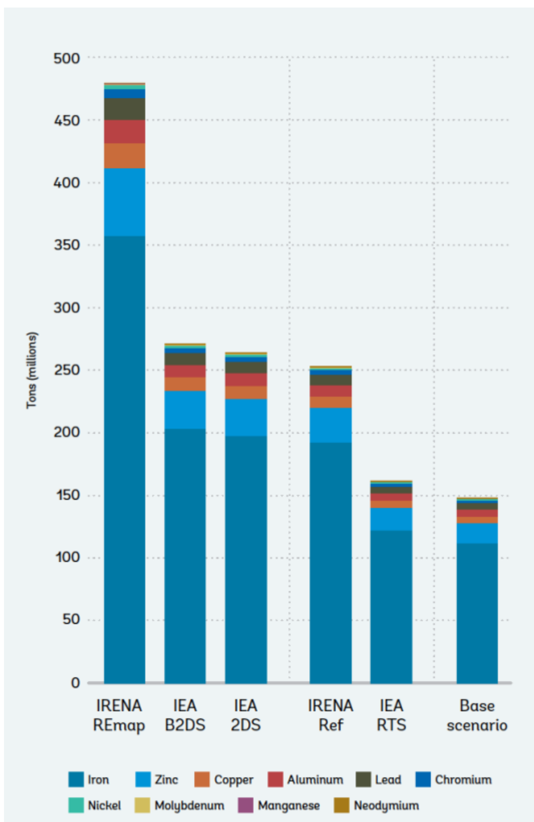


Figure 24: Cumulative Demand for Minerals Needed for Wind through 2050.

Source : World Bank (2020)

Further, with the exception of zinc, all the minerals used to construct wind turbines are also needed to build other clean energy technologies and hence have a relatively stable demand. Almost all of zinc's demand from across an array of clean energy technologies comes from the wind industry as zinc is predominantly used to protect wind turbines from corrosion.[82]

Moreover, similar to solar PV, there are trade-offs in mineral demand for wind depending on the sub-technology market's evolution. Neodymium, which is only used in permanent magnet direct-drive turbines, is a crucial mineral affected by these technologies' balance. Under the IEA's 2 degree scenario (with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100), neodymium demand in 2050 has a dramatic uncertainty range (65% below base case or 48% above) depending on which wind power sub-technology dominates the market. [83] See Figure 25.

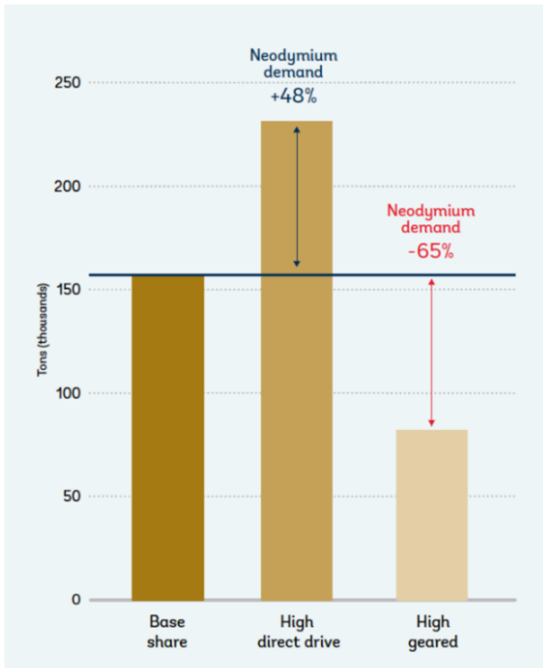


Figure 25: Cumulative Demand for Neodymium from Wind Subtechnologies Through 2050.
Source : World Bank (2020)

In addition to neodymium, praseodymium and dysoprsium are other rare-earth elements used in wind turbines to produce the permanent magnet electric generators used in direct drive turbines (which account for one-third of all wind power generation). As mentioned above, direct-drive turbine technology is more prevalent in offshore wind turbines, which are expected to grow rapidly and increase their global share in installed wind capacity. These rare-earth elements are produced only in a few countries, making them relatively scarce and at risk of experiencing future supply constraints. One study by Li et al (2020) that looked into whether the supply of rare-earth elements can keep up with global demand for wind power found that the current supply capacity of neodymium, praseodymium and dysoprsium may fall short unless efforts are made to expand production capacity, material recycling, technology efficiency or find substitutes. It estimates that the combined demand for these three rare-earth elements will increase significantly from 9,500 tonnes gigagrams during 2011-15 to between 105,900 - 230,900 tonnes in 2046-2050. These estimates are between 2-4 times that of current production capacity. Moreover, since these rare-earth elements have a cross-cutting demand, the demand-supply gap is likely to be even larger.[84]

3.5. Waste Streams

Similar to solar PV panel waste, wind turbine waste is typically generated during the four primary lifecycle phases of a turbine. These are:

- turbine production
- turbine transportation
- turbine installation and use
- turbine end-of-life disposal

While no studies that calculate total wind turbine waste could be found, several studies have attempted to quantify wind turbine blade waste. Of these, the most comprehensive study by Liu and Barlow on onshore blade waste, estimates that the end-of-life materials stream will annually generate more than 2 million tonnes in 2050 and cumulative blade waste in 2050 will lie between 21.4 million tonnes and 69.4 million tonnes with the most probable waste level being 43.4 million tonnes.[85] See Figure 26.

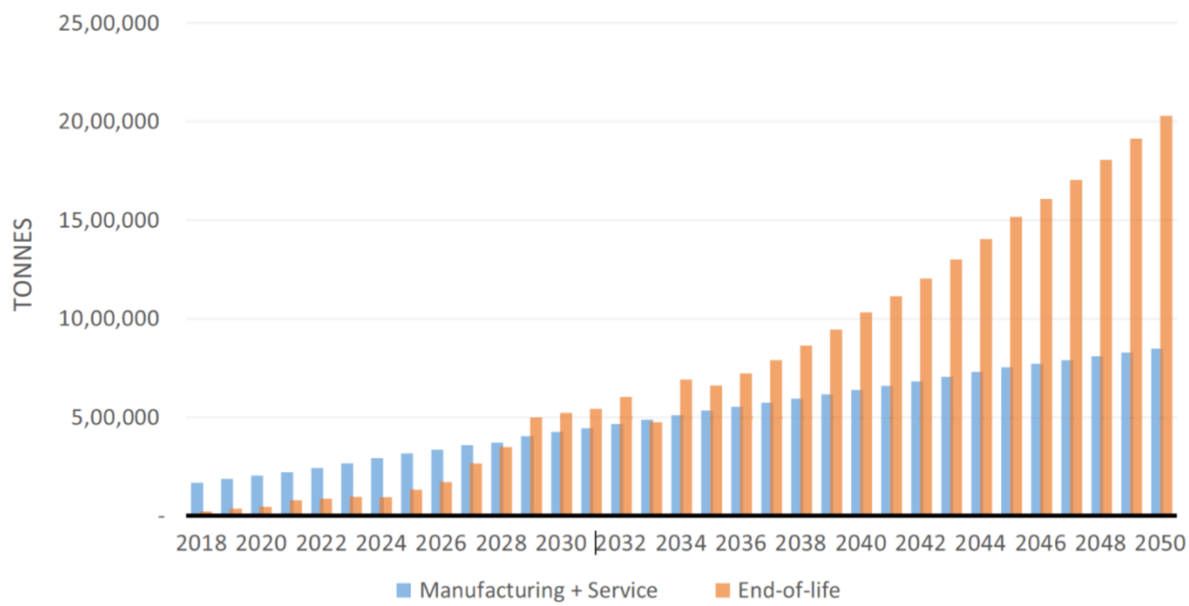


Figure 26: Cumulative Global Wind Turbine Blade Waste Projection up to 2050.
Source: Lui and Barlow (2017)

Blade waste consists of manufacturing waste, service (O&M) waste and end-of-life waste. Manufacturing waste is the waste generated in manufacturing stage and consists mainly of dry fibre offcuts, composite offcuts, resin residue and vacuum consumables. Service waste is the material used during the lifetime of the blade for routine maintenance, repair of accidental damage and blade upgrading and is mostly fibre fabric and resin. End-of-life waste refers to the retired blades (after a life span of about 20 years) and comprises of composite material, PVC, balsa and small traces of metal, paint and putty.

Unlike the IRENA report that provides insights into solar PV waste evolution in Canada, there is a knowledge gap regarding Canada's wind turbine blade waste and end-of-life wind waste in general. To close this gap, this project adopts the methodology used to estimate solar PV waste projections in Canada to project wind turbine waste to 2050. The project utilises data from Canada Energy Regulator's "Canada's Energy Future 2020" report for projected increasing wind capacity in the 'Evolving Scenario.' Table 4 shows projections for installed wind capacity in Canada.

Table 4: Installed Wind Capacity Projections up to 2050 for Canada
Data Source: Canada Energy Regulator (2020)

Year	2015	2020	2025	2030	2035	2040	2045	2050
Installed Wind Capacity(MW)	10,643	13,700	17,000	24,000	29,780	33,350	36,800	40,000

3.5.1 Modelled Wind Waste Projections

Figure 27 illustrates the temporal evolution of cumulative wind waste in Canada. Cumulative wind turbine end-of-life waste rises to approximately 831,000 tonnes by 2030 and 4,500,000 tonnes by 2050.

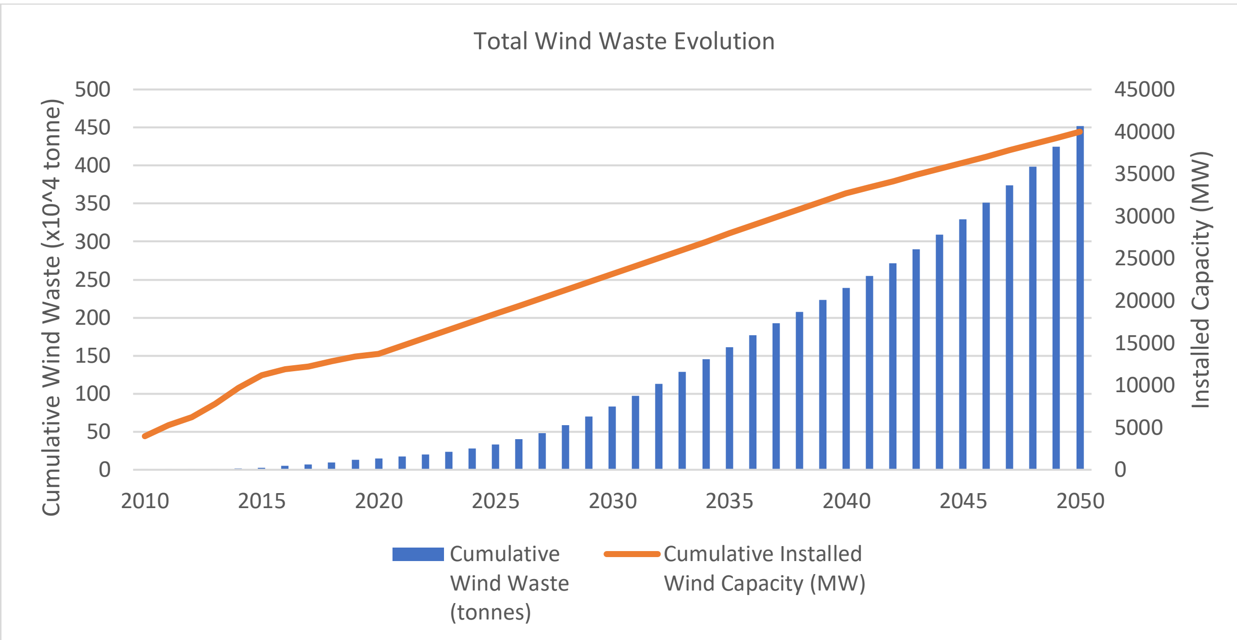


Figure 27. Cumulative Wind Waste Evolution

Data from figure 27 allows to estimate annual end-of-life wind waste. Figure 28 illustrates this trend.

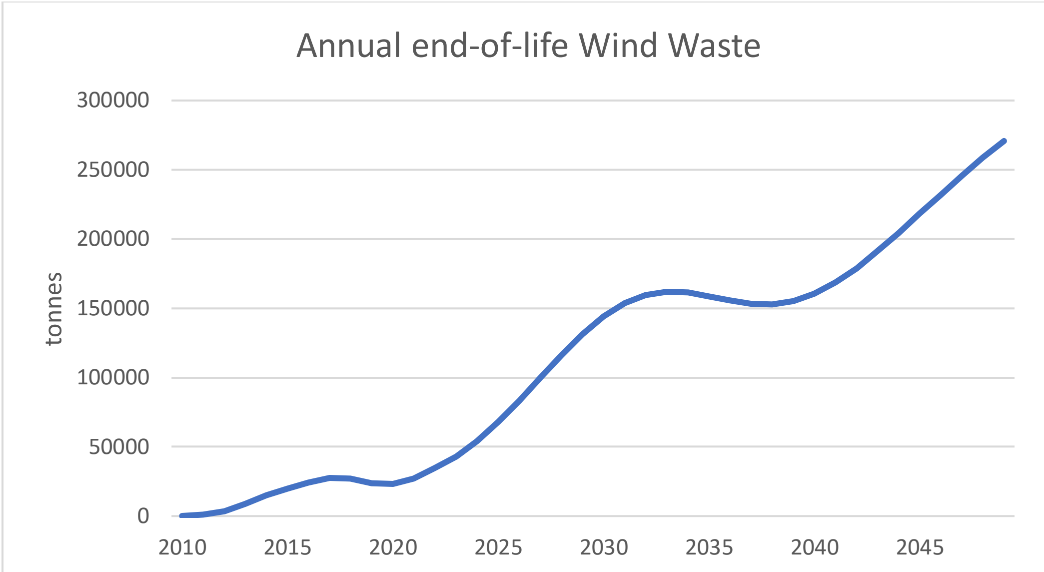


Figure 28. Annual wind waste evolution

Data on wind turbine material composition† helps estimate cumulative wind turbine waste by turbine component. Figure 29 illustrates this trend.

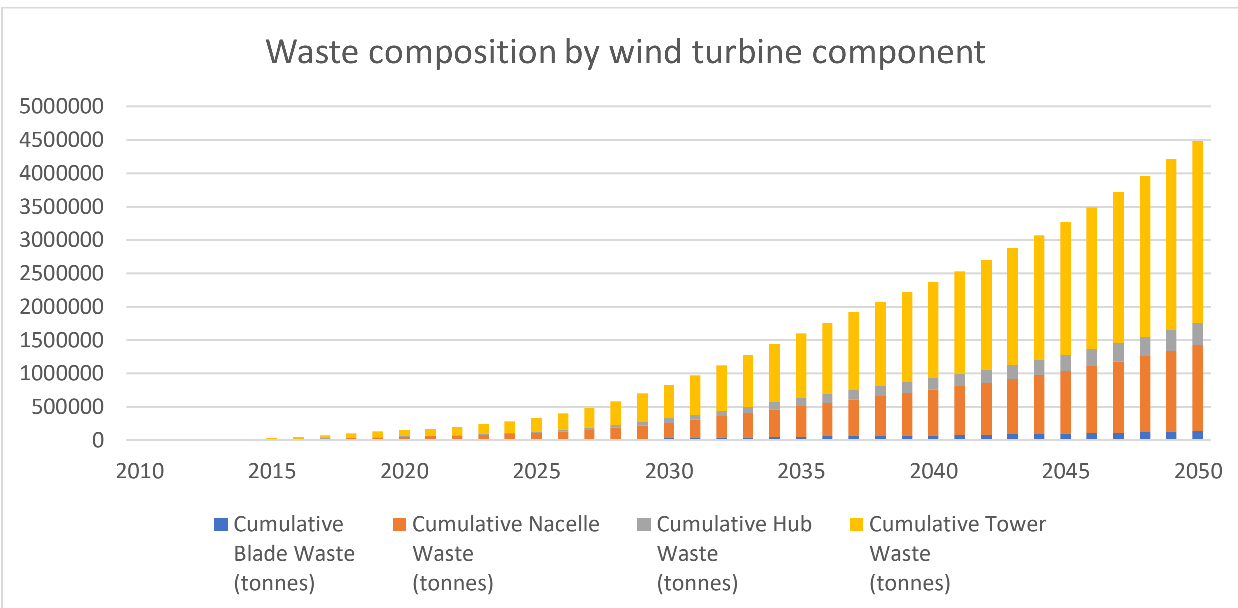


Figure 29. Cumulative Wind Waste Composition by Turbine Component

End-of-life blade waste represents a small fraction of cumulative end-of-life wind turbine waste. However, the lack of established economically viable recycling pathways for blade waste warrants a further look into its temporal evolution. Figure 30 illustrates this trend.

† See Section 4 for assumptions and uncertainty on wind turbine material make-up composition

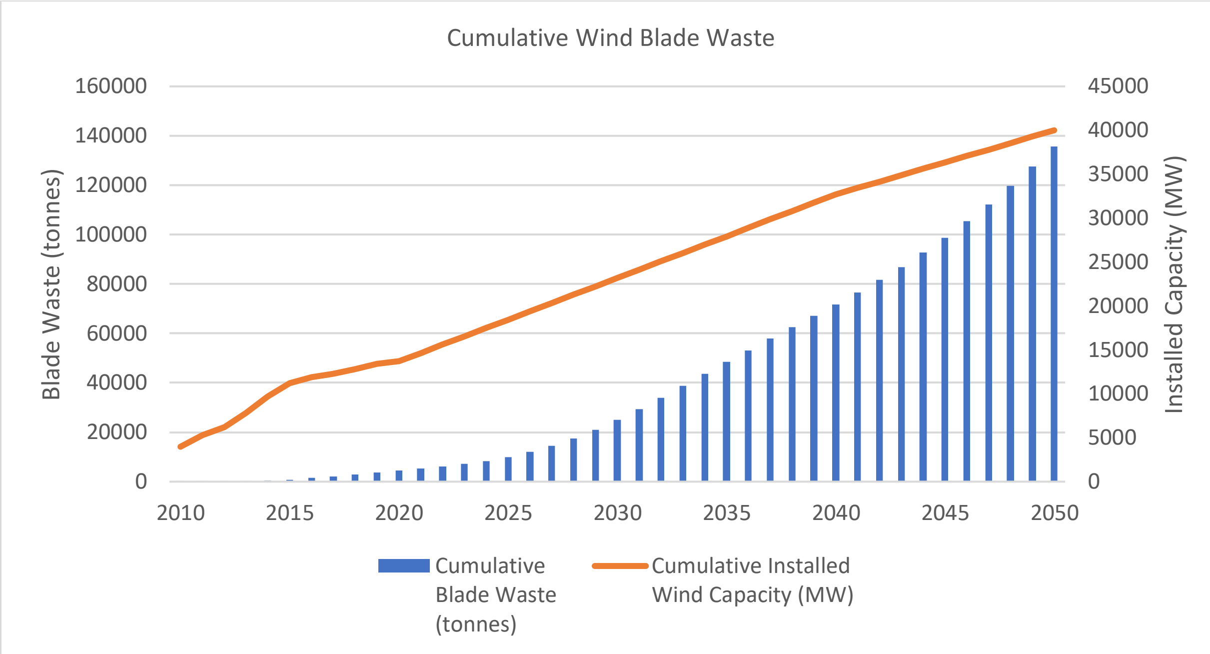


Figure 30. Cumulative Wind Turbine Blade Waste Evolution

Cumulative end-of-life blade waste rises to 25,000 tonnes by 2030 and 135,000 tonnes by 2050. Comparative examples of decommissioned wind farms globally indicate that end-of-life blade waste remains a challenging turbine component to economically recycle, with the majority of blades ending up in landfills (for further discussion, see Part 2 p.16) . As cumulative end-of-life blade waste grows in Canada, there is a need for appropriate policy intervention to prevent this waste from being redirected to landfills.

Finally, data from figure 27 allows for estimating what these end-of-life wind waste quantities would translate in terms of cumulative waste materials mass for Canada. The results obtained are shown in Table 5.

Table 5: 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

4. Limitations, Data Gaps and Uncertainties

Several assumptions were described throughout the report that could potentially affect the projected end-of-life solar PV and wind waste streams. Ideally, the reliability of the waste projections would be validated by comparison with real world data of end-of-life solar PV and wind waste collected in Canada over the past decade. However, currently, no such waste inventory exists.

The lack of a national waste inventory makes it impossible to validate the projections of the modelling exercise. Filling in data gaps will be essential to not only accurately estimate the magnitude of the challenge that lies ahead in terms of end-of-life waste management, but also to establish recycling targets and better understand the socio-economic opportunities that accompany the CE transition.

Several assumptions on key parameter values were employed when projecting future solar PV and wind turbine waste streams due to the lack of publicly available data. This section outlines these key assumptions and highlights data gaps that will improve the accuracy of modeled results.

Uncertainty on the projection for the installed capacity of solar PV and wind

The solar PV and wind capacity projection in Canada is one of the most important uncertainties in the waste stream calculations. This study uses data from the Canada Energy Regulator (CER) 'Canada's Energy Future 2020' report for projected increasing solar PV and wind capacity in the 'Evolving Scenario'.[86] CER does not specify what absolute GHG reduction target or what equivalent temperature rise scenario their projections for non-hydro renewable energy growth correspond to.

At first glance, a look at policy stringencies under the 'Evolving Scenario' –specifically the carbon price modeled for 2050 ($125 in 2019 real terms) suggests that solar PV and wind technologies' real development potential in Canada could be underestimated. Deeper emission reduction targets and stronger action to limit global temperature rise will understandably increase the installed solar PV and wind capacity in Canada. Hence, the forecasted waste of solar PV and wind technologies should be considered conservative.

A sensitivity analysis on a more ambitious solar PV and wind capacity growth scenario was conducted, using the High Hydro scenario from Canada's Energy Outlook (Appendix A). This scenario sees an exponential growth in solar PV and wind capacity in Canada out to 2050. Solar PV capacity grows to 45 GW by 2050 – 25 GW more relative to the CER scenario. Similarly, wind capacity grows to approximately 75 GW – 35 GW more relative to the CER scenario. As such, both these scenarios see more cumulative and annual growth in end-of-life solar PV and wind waste streams.

Uncertainty with the mass-to-power ratio

In order to convert the annual installed solar PV and wind power into mass, a temporal tonne/MW conversion factor was defined. For solar PV, this conversion factor was derived from IRENA[87] and Santos.[88] For wind technologies, this factor was derived from a 2 MW Vestas V90 turbine datasheet.[‡] Its temporal evolution was assumed to be constant due to the lack of an empirically estimated value. Future waste streams for wind are therefore likely slightly overestimated due to this assumption.

Moreover, even for solar PV, the mass-to-power ratio's temporal evolution was obtained by simply extrapolating data corresponding to PV modules' nominal power and weight from 1990 to 2013. This introduces uncertainty in converting the installed PV power into mass, especially for the later periods.

Uncertainty with modeled degradation scenarios for solar PV and wind

Another key uncertainty is related to the parameter values employed, namely the shape factor values used to model the degradation scenarios for solar PV modules and wind turbines.

For solar PV, the shape factors for the 'Regular Loss' scenario and the 'Early Loss' scenario were derived from work by IRENA[89] and Santos.[90] However, the comparison of shape factors obtained from various studies based on the degradation of installed solar PV capacity shows a wide dispersion. This dispersion

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[‡] Data from CanREA was used to estimate the average rated power of a wind turbine in Canada. Average rated power was obtained by dividing the cumulative installed wind capacity with total number of wind turbines. The average rated power of a wind turbine in Canada was subsequently assumed to be 2 MW and the assumption was validated by industry experts as part of the interview process. This assumption was also important to estimate the average wind turbine material make-up composition (Figure 29)

highlights the importance of empirically estimating the shape factor and the characteristic lifetime for solar PV in Canada. This would help account for local environmental conditions and their subsequent impact on the evolution of losses in a solar PV panel.

Similarly, for wind turbines, a typical wind turbine's degradation was modeled by means of a modified Weibull function. The Weibull function's suitability to describe the temporal evolution of solar and wind technologies' failures has been previously established [91,92] however, there is a lack of reliable data to extract the shape parameter and characteristic lifetime of a wind turbine in Canada. This study's shape factor to model the degradation scenario for wind turbines was chosen to ensure the probability of failure for a wind turbine installed in year i was 99.99% at the time step i+30.[§]

Uncertainty with PV Waste definition

The final uncertainty pertains to the definition of waste itself. From the manufacturer's context, for solar PV, it is defined as the point where the maximum power loss in the module is more than 20%. This criterion is used to determine the Weibull parameters from the modules' degradation rate installed in the field. However, modules that have power losses over 20% still deliver enough power to be reused. While the North American market's nature[**] makes the reuse of these modules unattractive, there is a growing market for these used modules outside North America. Therefore, the solar PV waste mass available to be recycled could potentially be lower than projections.

Moreover, even modules discarded due to severe failures and deemed inappropriate for reuse can avoid entering the waste streams given repair and refurbishing potential. Owners of PV plants can also hold onto damaged modules to create a stock of secondary materials, thus reducing the modules' waste stream versus the modeled results.

5. Summary

The rapid decline in the levelized cost of energy production coupled with low carbon footprints makes solar PV and wind energy critical to Canada’s transition to a low carbon future. Installed non-hydro renewable capacity is expected to grow exponentially in the coming decades as global action to combat climate change ramps up. The CER projects cumulative installed Canadian solar and wind capacity to reach 20 GW and 40 GW respectively by 2050. [93]

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

Renewable energy technologies require significantly more materials than fossil-fuel-based electricity generation counterparts. Research indicates that scenarios modeled to achieve the Paris Agreement's goals will require global production of certain minerals to grow twelvefold to 2050, relative to today's production levels.[94] This does not include the demand for other advanced technology applications which will undoubtedly compete for the limited mineral supplies. However, while the cumulative demand for renewable energy technologies represents a small share as compared to overall material demand by other economic sectors, the demand and sufficient availability of critical minerals in particular is a cause for concern. [95] Several critical metals and minerals occur in low concentrations within the earth's crust. The timeline required to scale critical metal and mineral production rates is another important issue. New mines can take a decade or more to open and operate and mining corporations require global, long-term

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[§] Assuming a characteristic lifetime of 20 years for the average wind turbine

[**] Demand is moving towards the use of high-power modules with the lowest price, which is mainly materialized by using new modules

investment assurances to fund new mining and refining operations.[96] These concerns are exasperated given that mining of many of these minerals takes place only in select countries while refining them takes place in even fewer countries. [97]

Further, while any low-carbon pathway will increase the overall demand for minerals, the change in demand for individual minerals will depend on the choice of technology and sub-technology deployed, possible material substitution as well as expected technological improvements. Since different technologies require different minerals and carry different mineral demand implications, the technology pathways that will eventually emerge to decarbonize electricity production will shape the minerals that will experience the largest increases in demand.

Importantly, while recycling and reuse 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. [98] As a resource-rich country with a strong emnvironmental, social, and governance reputation and reserves of many of the critical minerals that will be required to support a low-carbon future, 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 appropriate decommissioning of end-of-life solar panels and wind turbines. The majority of this decommissioned waste is currently directed to landfills.[99,100] This represents a significant lost opportunity to recover materials, some of strategic value, whose potential value is not being maximized. Moreover, this waste is only a fraction of what is expected to follow in the coming decades as more and more solar panels and wind turbines come to their end-of-life. To illustrate, by 2050, 469 tonnes of silver, 4,691 tonnes of copper, and 23,455 tonnes of silicon will have accumulated in Canada's end-of-life solar PV materials, and 64,729 tonnes of copper from end-of-life wind turbines (Tables 3 and 5).

Robust global climate policies tied in with circular economy practices are required to address critical mineral dependence and rising end-of-life waste issues. Moreover, there seems to be a logical, temporal or volume threshold sequence to the adoption or phase-in of these policies. In this regard, it is important to distinguish legacy stock from flows and to this end, the appendix includes standalone projections for future end-of-life waste streams from legacy solar PV and wind installations in Canada.[††]

[††] See Appendix B

Appendix A: Sensitivity analysis on the annual installed Solar PV and Wind power

As mentioned in section 4, the projections for the future development of solar PV and wind in Canada introduce one of the most important uncertainties in future waste stream calculations. In this regard, a simple sensitivity analysis on an alternative solar PV and wind capacity growth scenario was conducted.

The 'ambitious scenario' uses projections for solar PV and wind capacity from Canada's Energy Outlook – 'High Hydro' scenario.[ci] This scenario is based on a net 80% reduction in GHG emission from 2005 levels by 2050 and the scenario observes a mix of hydro and wind energy dominating Canadian electricity generation. Figures 31 and 32 illustrate projected solar PV and wind capacity growth under the ambitious scenario.

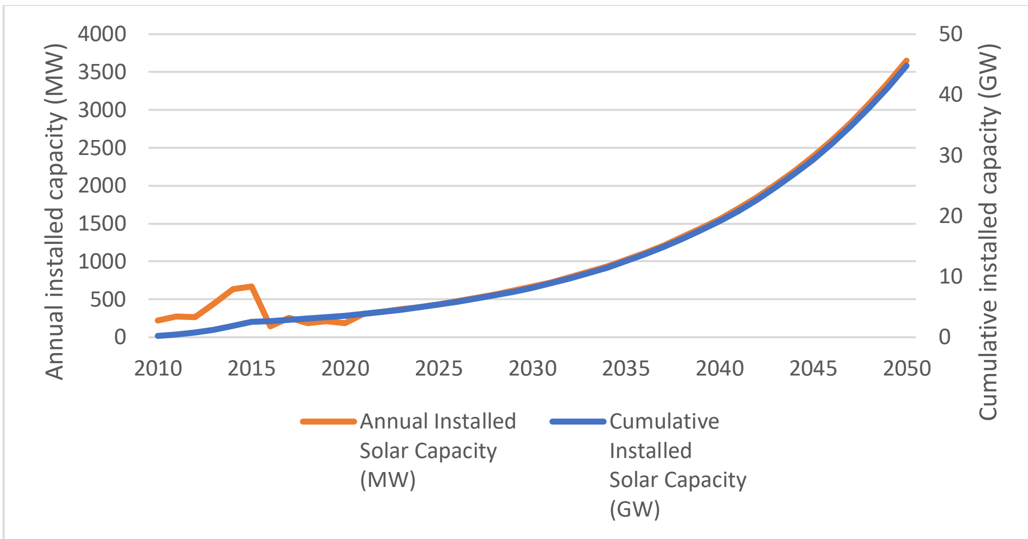

Figure 31. Projected solar PV capacity growth (ambitious scenario)

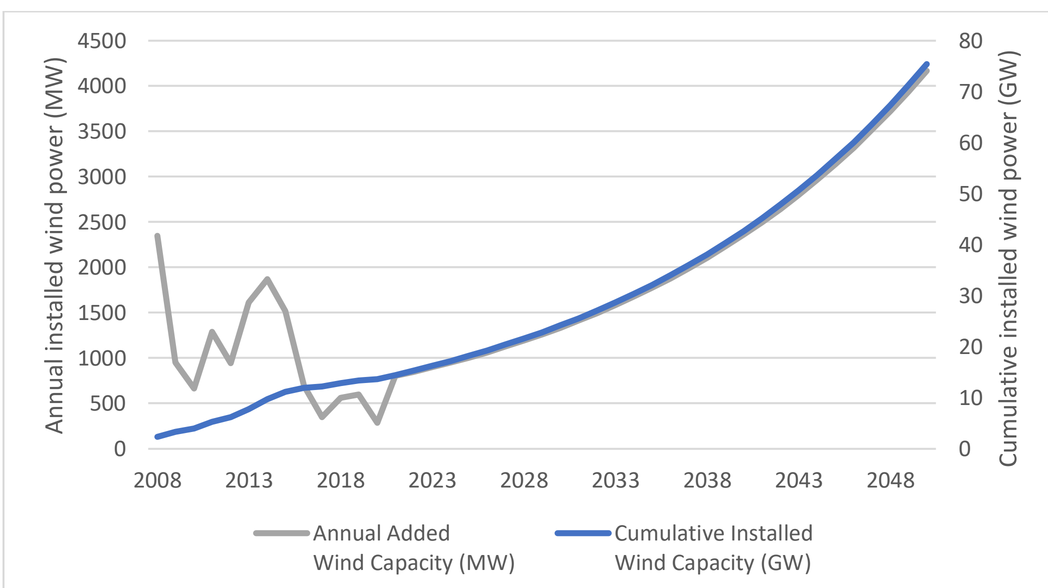

Figure 32. Projected wind capacity growth (ambitious scenario)

As figures 31 and 32 illustrate, the ambitious scenario sees an exponential growth in solar PV and wind capacity in Canada out to 2050. Solar PV capacity grows to 45 GW by 2050 – 25 GW more relative to the CER scenario. Similarly, wind capacity grows to approximately 75 GW – 35 GW more relative to the CER scenario. As such, both these scenarios see more cumulative and annual growth in end-of-life solar PV and wind waste streams. The following figures illustrate these trends.

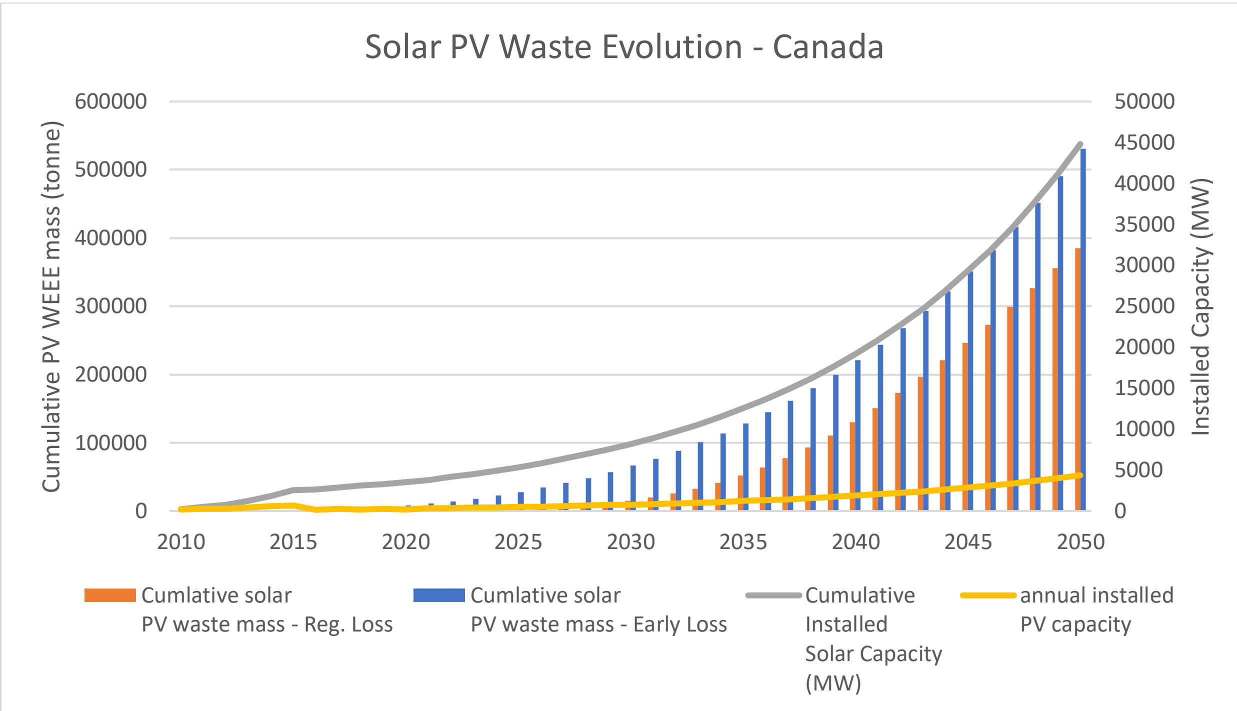

Figure 33. Cumulative solar PV waste evolution (ambitious scenario)

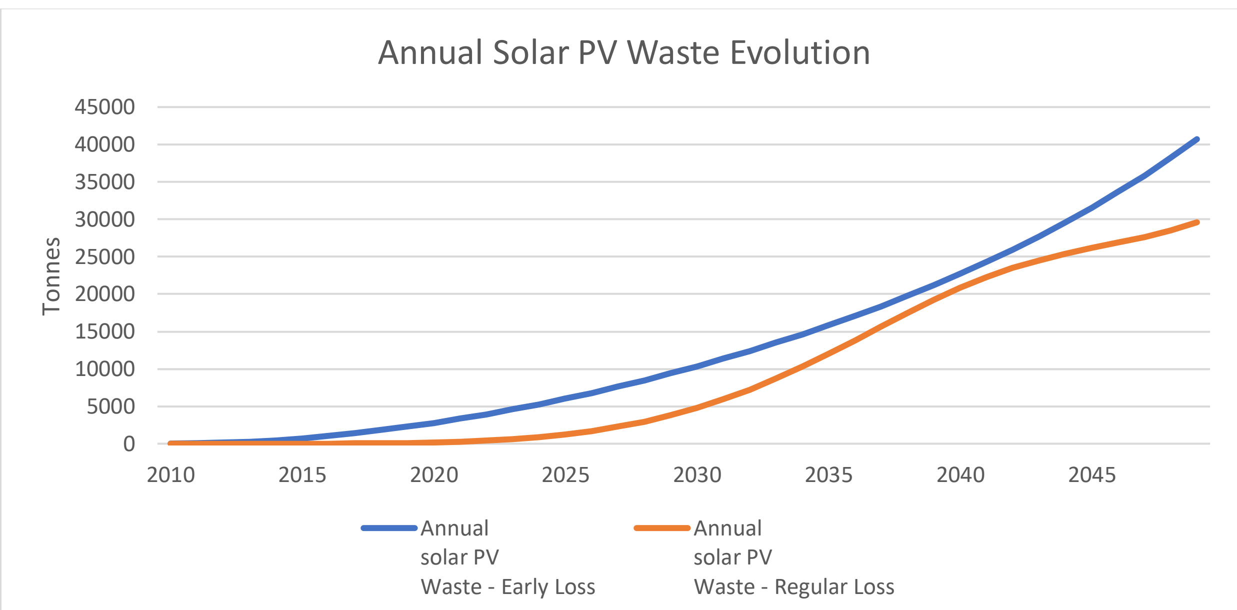

Figure 34. Annual solar PV waste evolution (ambitious scenario)

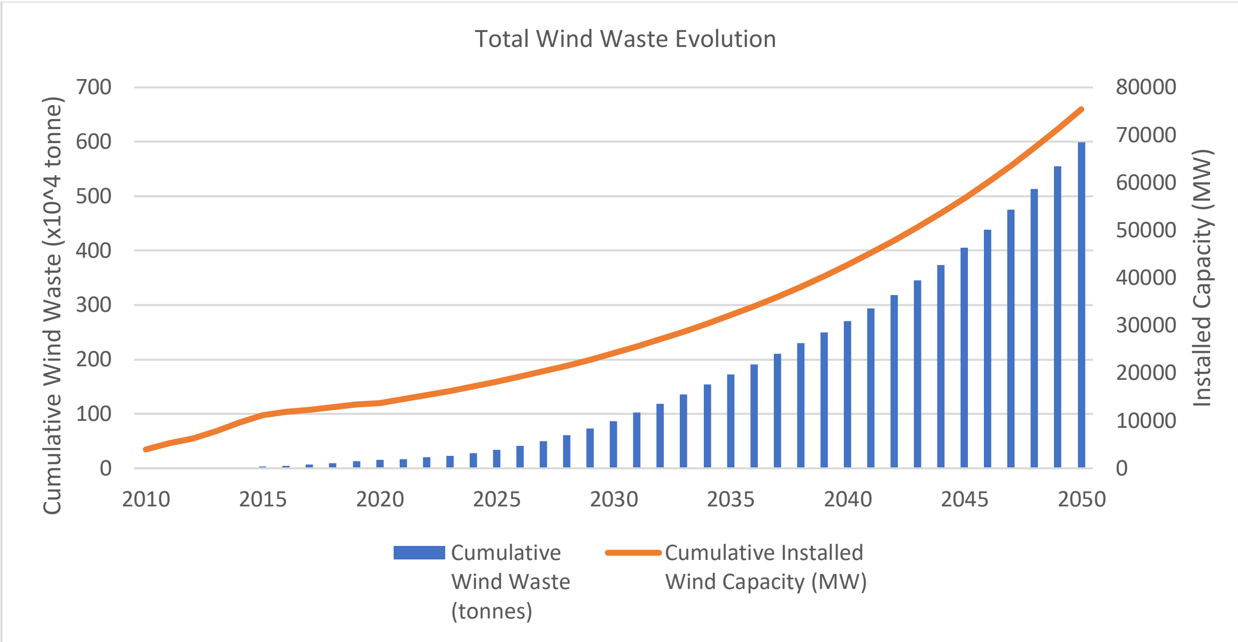

Figure 35. Cumulative wind waste evolution (ambitious scenario)

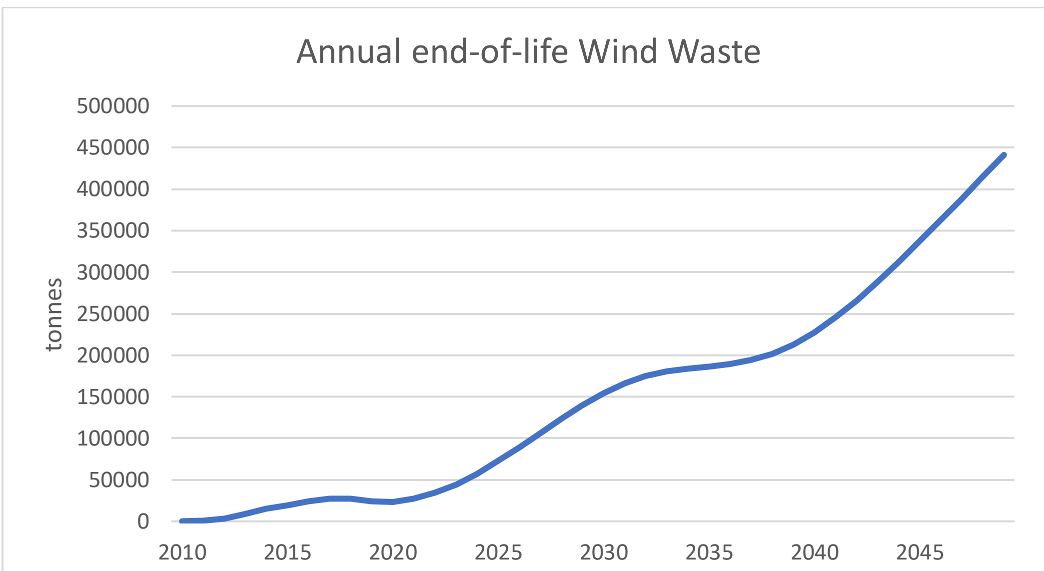

Figure 36. Annual wind waste evolution (ambitious scenario)

As figures 33 – 36 illustrate, cumulative and annual end-of-life solar PV and wind waste volumes for the ambitious scenario are larger than the CER 'Evolving Scenario'. The obtained results are quite similar between the two scenarios in the midterm (2030) since solar PV and wind waste is primarily determined by already existing solar PV plants and wind turbines. However, the differences between the waste projections increase in the long term (2050). The following table illustrates this trend.

Table 6: Effect of solar PV and wind capacity projection on the cumulative end-of-life solar PV and wind waste in 2030 and 2050

Technology	Year	Cumulative solar PV and wind waste mass in 2030 – 2050 (tonnes)	
		Evolving Scenario	Ambitious Scenario
Solar PV[7]	2030	14,716	14,729
	2050	363,023	385,109
Wind	2030	831,600	867,328
	2050	4,516,647	5,994,620

[7] Values for end-of-life solar PV waste are for the Regular Loss scenario

Appendix B: Legacy Stock Analysis

As mentioned earlier, there may be logical, temporal or volume threshold sequences to the adoption or phase-in of policies required to address critical mineral dependence and rising end-of-life waste issues.

Policies should distinguish between legacy stock (i.e., stock in place as of 2020) and future stocks. Municipalities and regional waste authorities bear the onus for end-of-life management for legacy stock. Depending on the differing rates of panel degradation under the two modelled scenarios, the annual end-of life volumes from the legacy stock of solar peak at 2037 at 9,550 tonnes or in 2042 at 17,347 tonnes. For wind, annual end-of-life volumes from legacy stock peak in 2034 at 125,000 tonnes. The following figures illustrate this trend.

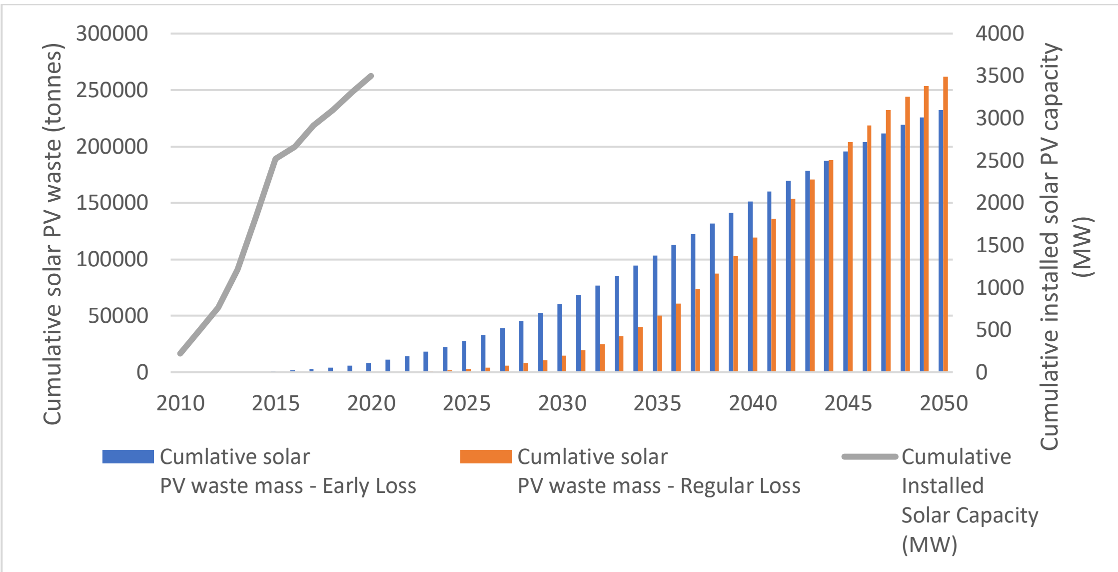

Figure 37. Cumulative end-of-life solar PV waste for Legacy Stock

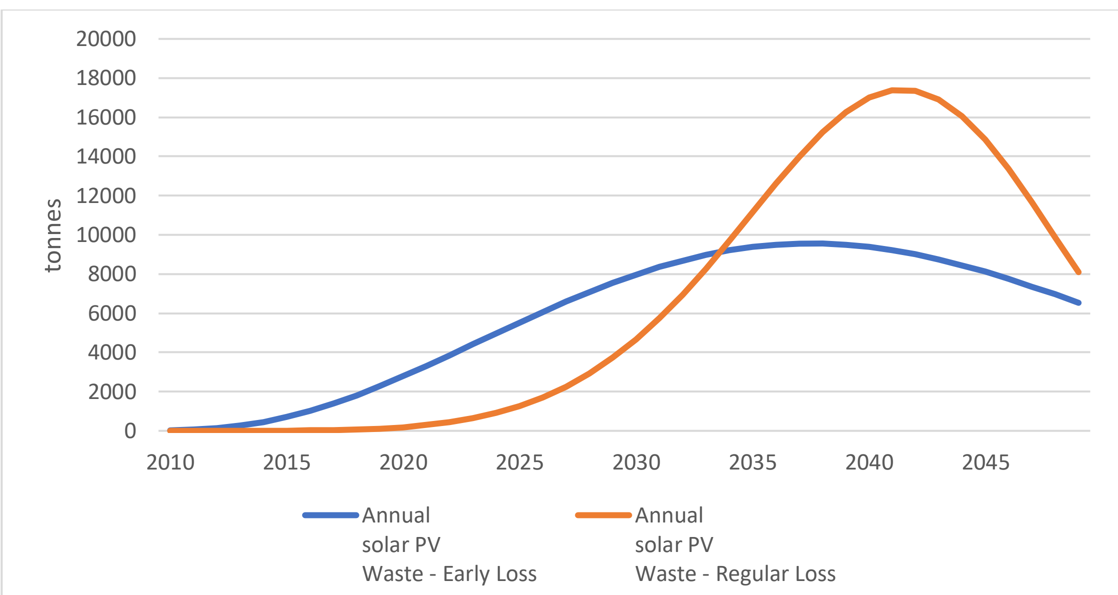

Figure 38. Annual end-of-life solar PV waste for Legacy Stock

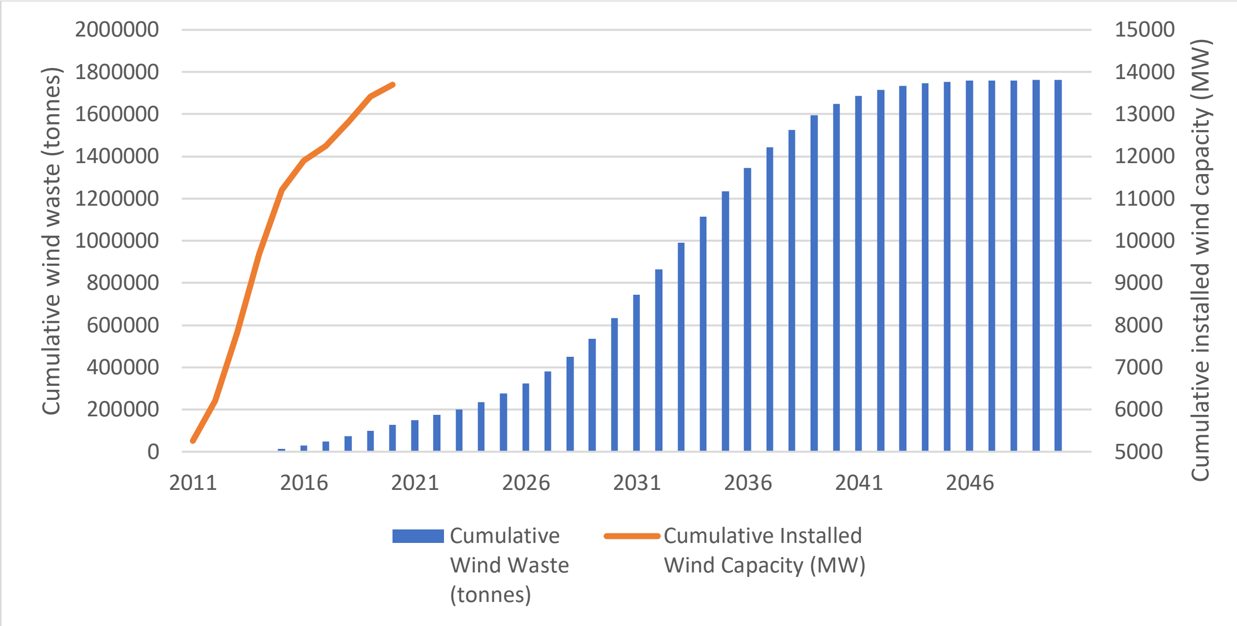

Figure 39. Cumulative end-of-life wind waste for Legacy Stock

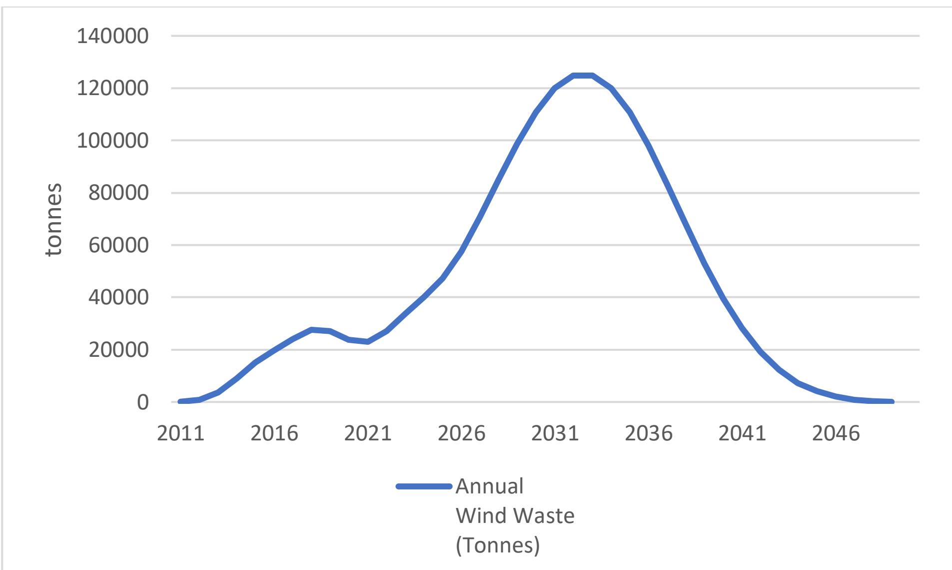

Figure 40. Annual end-of-life wind waste for Legacy Stock

Appendix C: Modeling Assumptions used in CER's Evolving Scenario

Table 7: Modeling Assumptions used in CER's Evolving Scenario

<table>
<tr><th>Assumption</th><th>Description</th></tr>
<tr><td>Future Policy Evolution

(build on key current policies such as the federal backstop carbon price, coal phase out mandate, energy efficiency regulations for buildings, vehicles, and appliances and renewable energy mandate)</td><td>Rising cost of carbon emissions
Carbon price rises beyond 2022, reaching $125 (2019$) by 2050
Credit for large emitters gradually reduced
Reduced emission intensity of end-uses
Energy efficiency regulations: stringency rises gradually over time across the economy and includes net-zero ready building codes, improving appliance standards, and increasing light-duty vehicle efficiency standards
Clean Fuel Standard: increased requirement to reduce average carbon intensity of fuel fleet over the projection period
ZEV mandate: share of ZEV's sold in new sales is gradually increased over the projection period
Continued support for clean technology and infrastructure such as carbon capture and storage and electric vehicle charging infrastructure expansion</td></tr>
<tr><td>Technology</td><td>Utility scale battery storage grows to approximately 3 GW by 2050
All new oil sands projects and project expansions utilize solvent-assisted methods for extraction
Increased market share for EVs and electrification of space and water heating
Gradual adoption of low carbon hydrogen in latter half of projection period for freight and industrial applications
Electrification of freight with electric trucks providing 3% of freight trucking needs by 2040 and 14% by 2050
Additional 15 MT/year of carbon sequestration via carbon capture and storage by 2040, rising to 30 MT/year by 2050</td></tr>
<tr><td>Crude oil and natural gas markets and infrastructure</td><td>Bent crude oil price declines to $50 (2019 US$/bbl) by 2050 - $25 (2019 US$/bbl) lower than the Reference scenario
Henry hub natural gas price rises slower than the Reference scenario – and is approximately $0.40 (2019 US$ per MMBtu) lower by 2050
Canadian LNG export volume peaks at 5 Bcf/d - approximately 2 Bcf/d lower than the Reference scenario</td></tr>
<tr><td>Electricity</td><td>Capital and levelized cost of solar energy falls by approximately 73% and 64% respectively from a 2020 baseline by 2050
Capital and levelized cost of wind energy falls by approximately 40% and 33% respectively from a 2020 baseline by 2050</td></tr>
</table>

Description of Weibull Waste Model Parameters is presented in the table below

Table 8: Solar PV module loss model methodology

Model	Data input and references
Step 1: Conversion of capacity to PV module mass (MW to MT)	
• The model's exponential regression function converts megawatt of solar PV capacity to metric tonnes of module mass • For each year, the annual onversion factor is calculated	• Standard module 1990-2013 data sheets cii are used to extract supporting data for the exponential fit. Typical module data were used in five-year periods from the biggest producers • Standard module data are predicted using the 2019 International Technology Roadmap for Photovoltaic (ITRPV) as a baselineciii as well as other literature[civ, cv cvi cvii cviii cix]
Step 2a: Probability of solar PV module losses	
• Infant failure • Midlife failure • Wear-out failure	• Assumptions on early losses were based on reports by TUV, SGS, and others[cx cxi cxii cxiii]
Step 2b: Scenarios for annual waste stream estimation (regular-loss and early-loss scenarios)	

Regular-loss scenario input assumptions:
• 30-year average module lifetime
• 99.99% probability of loss after 40 years
• Extraction of Weibull model parameters from literature data (a = 5.3759)[cxiv]
 	
Early-loss scenario input assumptions:
• 30-year average module lifetime
• 99.99% probability of loss after 40 years
• Inclusion of supporting points for calculating non-linear regression:
   o Installation/transport damages:0.5%
   o Within first 2 years: 0.5%
   o After 10 years: 2%
   o After 15 years: 4%
• Calculation of Weibull parameters (a = 2.4928)
	• The 30-year average module lifetime assumption was taken from literature[cxv]
	• A 99.99% probability of loss was assumed as an approximation to 100% for numerical reasons using the Weibull function. The 40-year technical lifetime assumption is based on depreciation times and durability data from the construction industry
	• The early-loss input assumptions were derived from different literature sources[cxvi cxvii cxviii cxix]
	• Weibull shape factors reported in literature[cxx cxxi cxxii cxxiii]

Appendix D: Canadian Solar PV and Wind Turbine Waste Modeling Methodology Used for This Project

In order to calculate and project solar PV and wind waste until 2050, SPI has developed the following methodology (depicted in Figure 41 below). The model draws on methodology developed by IRENA and Santos et. al to project solar PV and wind turbine waste evolution in Canada by:

Step 1: Calculating annual installed capacity using data on historical and forecasted cumulative installed capacity (MW) for solar and wind energy

Step 2: Accounting for the temporal evolution of progressive losses in installed solar and wind systems by estimating a density function (Weibull curve) for the probability of loss. Data from literature is used to estimate shape factors and characteristic lifetime – two key parameters shaping the Weibull curve.

Step 3: Calculating annual power loss (annual re-powering need) for the entire solar and wind fleet in an iterative process until re-powering needs are negligible.

Step 4: Calculating corrected annual installed capacities by accounting for annual re-powering needs.

Step 5: Converting annual installed capacity (MW) into mass (tonnes) using a mass-to-power ratio (tonnes/MW). The mass-to-power ratio is adjusted to incorporate the temporal evolution of solar PV and wind systems (solar PV panels and wind blades becoming more powerful and lighter over time.

Step 6: Calculating waste streams (tonnes) using corrected annual installed capacity (tonnes).

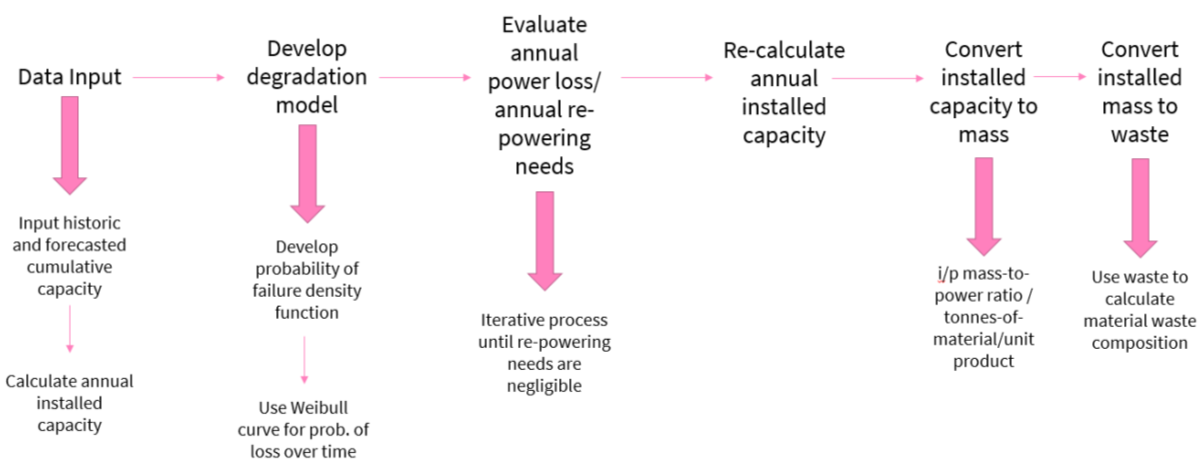

Figure 41: Steps to Calculate and Project Solar PV and Wind Waste Volumes for Canada to 2050.

Appendix E: 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

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