Waste Prediction and Life Cycle Assessment of Wind Turbine Blades in Canada until 2050

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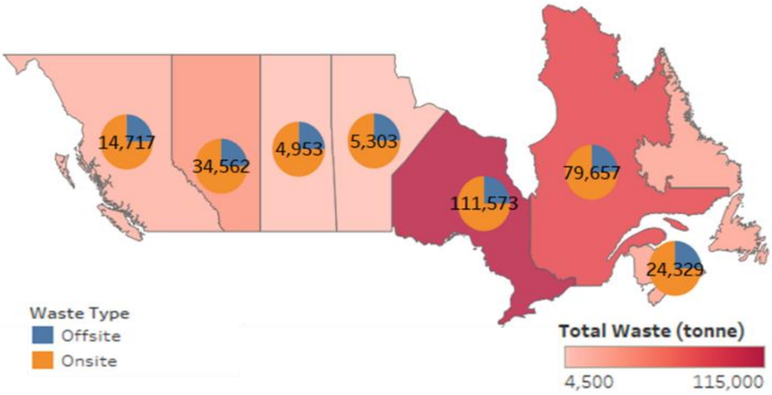
Abstract

Electricity production by wind turbines is considered a clean energy technology, but the life cycle of wind turbines could introduce environmental risks due to waste generation, especially at the decommissioning process. This study predicts the future wind turbine blade waste arising in Canada, throughout all life cycle stages, from manufacturing until end of life, based on the installed capacities of existing Canadian wind farms and projected future installations. Four alternative strategies for managing this waste stream are assessed in terms life cycle greenhouse gas emissions and primary energy demand, including landfilling, incineration, and mechanical recycling. For the base case scenario, it is observed that the total cumulative waste until 2050 is 275,299 tonnes, with on-site waste accounting for around 75% of this total. Waste generation is concentrated in provinces with greater wind power deployment: Ontario and Quebec alone account for 70% of total blade waste. Life cycle environmental impacts of waste management strategies are dependent on background energy systems, with incineration a significant source of greenhouse gas emissions, particularly when displacing low-carbon grid mixes. Mechanical recycling can achieve substantial reductions in primary energy demand and greenhouse gas emissions, but achieving financial viability would likely require substantial regulatory support.

Graphical abstract



1 Introduction

Canada is a world leader in wind energy, ranked 9th globally in onshore installed capacity as of 2019.[1] Over the past decade, the wind energy installed capacity in Canada has grown by an average rate of 1,012 MW/year, leading to a total installed capacity of 13,413 MW in 2019, of which more than 80% is located in three provinces: Ontario (5,436 MW, 40%), Quebec (3,882 MW, 29%), Alberta (1,685 MW, 13%). Wind power capacity is expected to continue to grow at an annual rate of 510 MW/year to 2040.[2] While wind power serves as a clean energy solution that can help to reduce the carbon footprint of the electricity sector, the environmental impacts associated with waste generation from wind turbines are often neglected in many studies. To ensure the sustainable deployment of wind power in Canada and globally, it is essential to better understand the potential life cycle environmental impacts of managing wastes arising during manufacture, operation, and end-of-life (EoL) of wind turbines.

Improving the sustainability of waste management is a key policy priority in Canada, as evidenced by federal, provincial, and municipal regulations, for example those governing the recycling of ELVs and the handling of resulting waste streams (e.g., the Canadian National Mercury Switch Recovery program known as “Switch out”).[3] In contrast to such goals, however, the vast majority of composite waste at present is not recovered and instead landfill or incinerated.[4, 5] Recycling has been recognized as a desirable waste management option to deal with composite wastes with the potential to recover value from the waste materials rather than being disposed in landfill or incineration, fulfilling legislative and sustainability targets.

To date, few studies have addressed the concern related to the waste generation from the wind power sector. Liu & Barlow (2017) conducted a study to estimate the wind turbine blade waste until 2050, mainly for China, the United States, and Europe.[6] The waste was carefully estimated throughout all the life cycle stages, from the manufacturing process to the EoL. Lefeuvre et al.(2019) performed a similar study to quantify the carbon fibre waste generated from the wind power sector until 2050.[7] These global studies are by default broad, employing generalized assumptions, and so overlook important variations at the country and sub-country level, such as the projected future deployment of wind power, and the geographical concentration of wind farms within a country.

The life cycle environmental impacts of managing composite wastes, and specifically wind turbine blade waste has been considered in previous studies. Our previous work, and that of others, has considered a range of technologies for recycling carbon fibre-based composites that would be similarly suited to recycling wind turbine blades comprised of glass fibre composites, including mechanical recycling,[8] pyrolysis,[9, 10] fluidised bed,[11] and chemical recycling.[12, 13] A very limited number of studies have considered the environmental impacts of managing wind turbine blade waste. Liu et al. (2019) provided a life cycle analysis of EoL wind turbine blade waste treatment methods which evaluated the energy consumption without considering location-specific background energy systems.[14] Life cycle impacts of waste management, however, can be highly sensitive to the background energy systems. The greenhouse gas (GHG) intensity of electricity generation varies substantially between countries and regions, which will influence both the impact of waste treatment processes consuming electricity, as well as the benefits of processes that generate electricity as a product (e.g., incineration). Consideration of national and regional variability in energy systems is essential to accurately estimate environmental impacts of wind turbine waste management.

Appropriate management of wind turbine blade waste is essential to ensure that ongoing deployment of wind power delivers a net environmental benefit. The present study builds on past work by considering a markedly higher geographical resolution (sub-national analysis), enabling a better understanding of how the concentration of wind power deployment within larger regions influences the life cycle environmental impacts of alternative waste treatment routes. We estimate the cumulative waste contributed by wind turbine blades until 2050 in

Canada at the national and provincial levels based on historic and projected wind power deployment. Alternative waste treatment routes are assessed and compared, considering the variation in background energy systems within Canada on a province level. It should be recognized that the wind power development in Canada is mostly regulated at the provincial level, which suggests the need for the results to be generated with higher resolution methods. The location-specific estimates of waste generation and impacts of treatment processes will help to inform decision-makers in planning wind power development and waste management strategies to maximize the net benefit of exploiting this renewable resource.

2 Methods

The present study estimates the cumulative waste inventory in Canada at the national and provincial levels until 2050 and quantifies key life cycle environmental impacts (primary energy demand (PED) in terms of GJ and greenhouse gas (GHG) emissions in terms of tonnes carbon dioxide equivalent (tCO_2 eq.)) associated with alternative waste treatment options. The three main contributors that affect the total waste inventory are considered: the predicted growth rate of the installed capacity, the rate of waste generation during manufacture and useful life (routine servicing; unexpected incidents), and the lifespan of the blades, at the end of which all blade material enters the waste stream. Given uncertainty in predicting these factors, we consider high and low estimates of waste generation in addition to the base case scenario (additional detail can be found in Supporting Information (SI), Table S1).

2.1 Wind turbine deployment in Canada

Data related to wind energy development in Canada were gathered from Canadian Wind Energy Association[15] and Wind Energy Market Intelligence.[16] For each existing wind farm in Canada, the information gathered includes the total installed capacity, year of commissioning, location (at provincial level), numbers of turbines, turbine manufacturer and model, and turbine diameter. Based on the database, most of the wind turbines in Canada to date were made by five manufacturers, which are GE Energy (25.5%), Vestas (27.2%), Siemens (18.5%), Enercon (14.0%), and Senvion (9.5%). Less than 1% of wind power capacity to date has been installed in Canada's territories, and therefore these areas are excluded from the present study.

In the present study, the base case scenario assumes a growth rate of 510 MW/year based on a reference case's projection published by National Energy Board.[2] This annual growth rate would result in total installed capacities of 24,126 MW in 2040 and 29,226 MW in 2050. In 2040, the total installed capacity of wind power would provide approximately 13% of the total projected electric generating capacity. Canadian Wind Energy Association estimated the annual installed capacity could increase to 816 MW/year if 50% of the non-emitting energy is contributed by wind energy by 2040,[17] and the present study adopts this annual growth rate in the high estimate scenario.

2.2 Estimating wind turbine blade mass

The turbine material is assumed to be glass fibre reinforced plastic (GFRP) based on the available data provided in the manufacturers' website.[18-22] The turbine blade mass data is not available for most wind turbine models installed in Canada to date; data from the above manufacturers are assumed to be representative of all producers. We estimate blade mass based on turbine blade diameter,[6] and calculate the weighted average blade weight per unit power based on current wind turbines installed in Canada. The weighted average for the modelled blade mass per unit rated power is estimated to be 12.35 tonnes/MW by considering 47 different turbine models (see Figure S2 in SI).

2.3 Prediction of wind turbine blade waste

Wind turbine blade waste is estimated by considering waste generation at manufacturing, operational & maintenance (O&M), and EoL stages (Figure S3 in the SI). Manufacturing and O&M wastes are estimated following a similar approach by[6], and waste generation rates are shown in Table S1 in the SI**.** Manufacturing waste arises due to in-process wastes, blade testing process, and defective blades. Although blade manufacturing occurs outside of Canada and, therefore, this waste arises outside of the country, we include this waste in the estimate as it is associated with wind turbine deployment in Canada. Blade testing and defective blades represent very small fractions of produced blade mass (<=0.2%).

The waste generated during the O&M process could be due to planned events such as routine maintenance and services or unplanned events such as adverse weather that damage the blade, unexpected failure of the blade, fire incident, and structural failure. We assume a small percentage of the waste generated during the O&M processes for every year, as it is difficult to predict the exact years where a planned or unplanned event occurs. The generated wastes due to the unplanned event of O&M processes are estimated based on the incident statistics published by Caithness Windfarm Information Forum,[23] an online resource that documents the incidents related to the wind power sector internationally. From this resource, the present study complied the incident records over the past 10 years in Canada related with all unplanned events. The fraction of turbines impacted by unplanned events is assumed to be representative of future incident rates. It is assumed that the fire and structural failure would require full replacement of all three blades, while the incidents due to adverse weather and unexpected failure would only require replacement of two out of three blades. Low and high estimates of waste generation from unplanned events are considered at half and double the historic incident rate, respectively. Combining the O&M wastes due to both planned and unplanned events, the annual percentage is estimated to be 0.02%, 0.04%, and 0.09% for the low, base case, and high estimate scenarios, respectively.

The EoL waste, comprising 100% of blade material, is generated once the wind turbine reaches its lifetime limit. Wind turbines could operate for a typical lifespan of between 20 and 30 years.[24] The present study assumes 25 years for the best estimate, with 20 year and 30 year lifespans considered for the low and high waste estimate scenarios, respectively.

2.4 Life cycle environmental impacts of blade waste management

Life cycle environmental impacts are assessed for different waste management options in terms of PED (GJ) and GHG emissions, reported as tonnes carbon dioxide equivalent ($tCO_2eq.$) based on 100-year global warming potentials.[25] Four waste management options are analysed in the present study: landfill, incineration, mechanical recycling with landfilling of residual waste materials, and mechanical recycling with incineration of residual waste materials. For all waste management options, an equivalent set of activities are considered: waste preparation; transport; waste treatment processes; and use of product outputs of waste management (energy, recyclates). The functional unit is per tonne of blade waste, and the inventory data were obtained from available literature and Ecoinvent database.

2.4.1 Waste preparation and transport

For all the options, the waste needs to be first shredded into smaller sizes before being sent to the waste management plants. Transport distances of 200km are assumed between each activity location (wind turbine installation to waste management facilities; between waste management facilities). Materials are assumed to be transported by truck with 16 to 32 tonne capacity.

2.4.2 Landfilling

Wind turbine blade materials sent to landfill are assumed to be treated as plastic waste mixture in a sanitary landfill. We assume that no further GHGs (e.g., methane emissions associated with landfill gas) are emitted following the deposit of this material in landfill, due to its inert nature. Likewise, no energy recovery from landfill gas is associated with the disposal of this material by landfill.

2.4.3 Incineration

Incineration of wind turbine blade materials in a combined heat and power facility generate useful electricity and heat for subsequent use. We assume generation efficiencies of 13% and 25% for electricity and heat, respectively. Generated heat and electricity are assumed to displace generation that would otherwise occur elsewhere. For electricity produced by incineration, we account for the province-specific electricity grid mix to estimate the avoided energy demand and GHG emissions associated with this energy output. For heat, we assume heat would otherwise be generated by combustion of natural gas in a boiler. Non-combusted materials (e.g., glass fibre; ash) are transported to landfill for disposal as inert materials (see Section 2.4.2).

2.4.4 Mechanical Recycling

Mechanical recycling of the composite wind turbine blades enables recovery of glass fibre and fine material suitable as a filler for composite polymer applications. Of the input waste material, 24% is recovered as glass fibre and 19% as polymer filler.[26] Recovered glass fibre can be used to displace the manufacturing process of virgin glass fibre. However, the mechanical properties of the recycled glass fibre may be degraded, while incomplete separation of glass fibre from polymer resin can further reduce quality. A material substitution ratio of 0.78, indicating that one tonne of recovered glass fibre can avoid the production of 0.78 tonnes of virgin glass fibre, based on relative retained tensile strength of recycled and virgin glass fibre.[14, 27] Recovered filler material can substitute calcium carbonate; however, as the energy inputs and GHG emissions associated with production of calcium carbonate are very low, this benefit of recycling is excluded from the current study. The remaining 57% coarse portion cannot be usefully repurposed and is thus considered to be transported to either incineration and/or landfill for final waste treatment. Energy requirements for mechanical recycling process are estimated previously.[11]

2.4.5 Electricity generation sources in each province

The life cycle environmental impacts of managing wind turbine blade waste is strongly dependent on background energy systems in place. Energy inputs to waste management processes contribute to a significant share of environmental impacts. Similarly, avoided impacts associated with the production of energy outputs (heat, electricity) depend on the source of generation they are displacing. In particular, the electricity generation mix varies significantly by province within Canada, and the present analysis accounts for this difference (Table S4) in assessing province-specific impacts of the selected waste management routes.

3 Results and Discussion

3.1 Prediction of the total waste inventory

Cumulative wind turbine blade waste associated with Canada's wind power sector will total approximately 275,299 tonnes by 2050 (Figure 1 and additional details in SI **Error! Reference source not found.**4). Average annual waste generation is predicted at 8,881 t/yr, although this is expected to peak between 2036 and 2040 at nearly 29,000 t/yr. This peak reflects the rapid deployment of wind turbines 25 years prior (2011 to 2015) that reach their EoL during this period; at the same time, additional wind turbines are installed to replace this capacity and thus associated manufacturing process wastes arise. In contrast, up to 2030, blade waste generation will be minor (less than 3,000 t/yr), reflecting the small number of turbines reaching their EoL within this period. From mid-2040s, waste generation is driven primarily by assumed rates of wind power deployment after 2019, rather than historic data, and so approaches a linear trend. The dynamic pattern of the waste generation over years observed in Figure 1 is mainly due to the manufacturing waste and EoL waste.

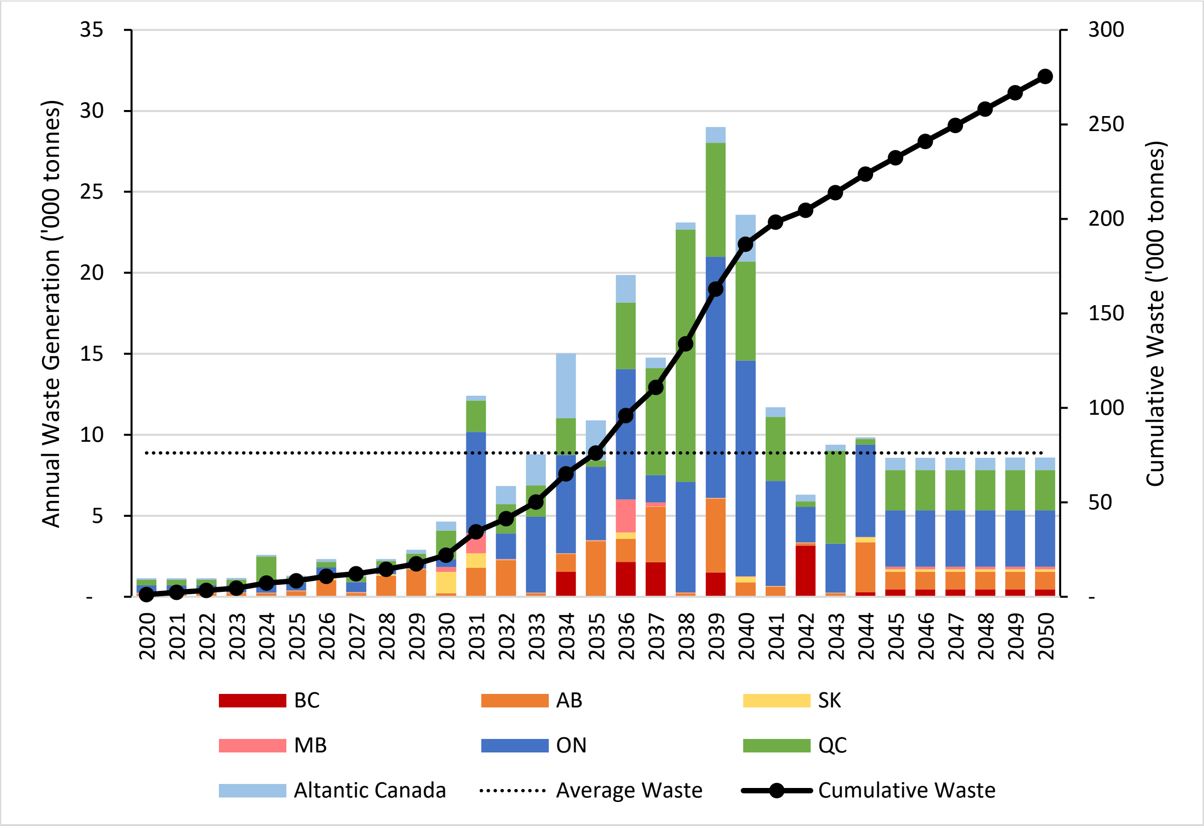


Figure 1: Annual and cumulative wind turbine blade waste generation until 2050 for the best estimate scenario. BC = British Columbia; AB = Alberta; SK = Saskatchewan; MB = Manitoba; ON = Ontario; QC = Quebec; Atlantic = New Brunswick, Newfoundland, Nova Scotia, and Prince Edward Island.

Within Canada, the quantities of waste created are not evenly distributed, but follow location of historic and projected deployment of wind turbines. As a result, blade waste is concentrated in Ontario and Quebec, which will see cumulative wastes of 111,573 tonnes and 79,657 tonnes, respectively. In contrast, blade waste in other jurisdictions will be significantly less: Alberta, 34,562 tonnes; Atlantic Canada, 24,329 tonnes; British Columbia 14,717 tonnes; and Manitoba/Saskatchewan 10,256 tonnes (Figure S4**Error! Reference source not found.**). Of this total waste, approximately 25% is related to the manufacture of wind turbine blades. Manufacturing wastes associated with each Province's/Region's wind power sector are included in the above totals but may not be generated within the same area. Many wind turbine blade manufacturers are based outside of Canada, except for GE Energy in Quebec. It is difficult to quantify the portion of the blades that will be manufactured inside and outside of Canada in the future, thus it is not clear where this portion of wastes will arise and thus be entered into waste management processes.

3.2 Sensitivity analysis of the total waste inventory

Waste quantity prediction is sensitive to assumptions about the growth rate of Canada's wind power sector, uncertainties in manufacturing and O&M waste generation, and the lifespan of installed wind turbines. Low and high estimates, 217,920 tonnes and 461,755 tonnes, respectively, bound the central base case estimate of 275,299 tonnes (Figure S5). Results are most sensitive to the projected growth of wind power within Canada by 2050, which directly influences wastes produced during manufacture, O&M, and at EoL. The lifetime of wind turbines is also an important factor, as shorter lifespans result in more turbines reaching their EoL by 2050; additionally, manufacturing wastes increases as new wind turbines must be commissioned to replace EoL turbines. The rate of manufacturing waste generation is also a significant factor, contributing approximately 7% and 16% variation from the best estimate case for the low and high estimates, respectively; O&M wastes are relatively small (1 - 4% of total) and so uncertainty in estimating these losses do not significantly impact results.

3.3 Life cycle environmental impacts of blade waste management

The environmental impacts of managing wind turbine blade waste are dependent on both the waste treatment route considered and the local energy sources that are consumed (or displaced). The primary energy demand (PED) (Figure S6 in SI) and GHG emissions (Figure 2) per tonne waste are calculated for each province based on their energy mix.

Landfilling of blade waste exhibits a small energy requirement associated with waste transport and landfilling operations. GHG emissions for landfilling are also low, due to the inert nature of the blade material that avoids generation of methane-rich landfill gas.

Incineration recovers the energy content of the blade material and displaces energy use by other sources for heat and electricity, resulting overall in a reduction in PED. Where provinces rely on fossil fuels for electricity generation, this net energy gain is relatively greater. For example, more than 80% of the electricity generating sources in Saskatchewan and Alberta are coal and natural gas; displacing these energy-intensive electricity generation routes results in a net reduction in PED by ~30 GJ/t blade waste. Similar results are found for other provinces that rely on non-renewable electricity sources (Ontario – nuclear; New Brunswick – nuclear and coal; Nova Scotia – coal and natural gas). In contrast, provinces where electricity generation is dominated by renewable sources (e.g., British Columbia, Quebec) realise more modest reductions in PED of ~23 GJ/t blade waste. Incineration of blade waste increases GHG emissions in all provinces, as the emissions related to the combustion of the polymer matrix material exceed the benefits of displacing other sources of heat and electricity production. Provinces with greater reliance on fossil fuels for electricity generation (Alberta, Saskatchewan, Nova Scotia) have correspondingly greater emissions reductions from producing electricity from blade waste, and thereby realise lower GHG emissions (~1.0 $tCO_2eq./t$ blade waste) than provinces with less carbon-intensive electricity sectors (~1.8 $tCO_2eq./t$ blade waste).

Recycling blade waste can reduce PED by displacing the manufacture of glass fibre with recovered fibre. The mechanical recycling process considered in the present study generates considerable quantities of residual materials: incineration of residues further reduces PED by displacing heat and power generation. As for the incineration route, the relative benefits of energy recovery from residues is dependent on the background electricity generation mix, with greater reductions achieved in provinces more reliant on non-renewable sources. Mechanical recycling with landfilling of residual materials is the only waste treatment route considered that can achieve a net reduction in GHG emissions, as the benefits of recovering glass fibres outweigh emissions associated with the recycling and landfilling processes. However, if residues are incinerated, emissions associated with polymer combustion negate the benefits achieved by glass fibre and energy recovery and result in a net increase in GHG emissions.

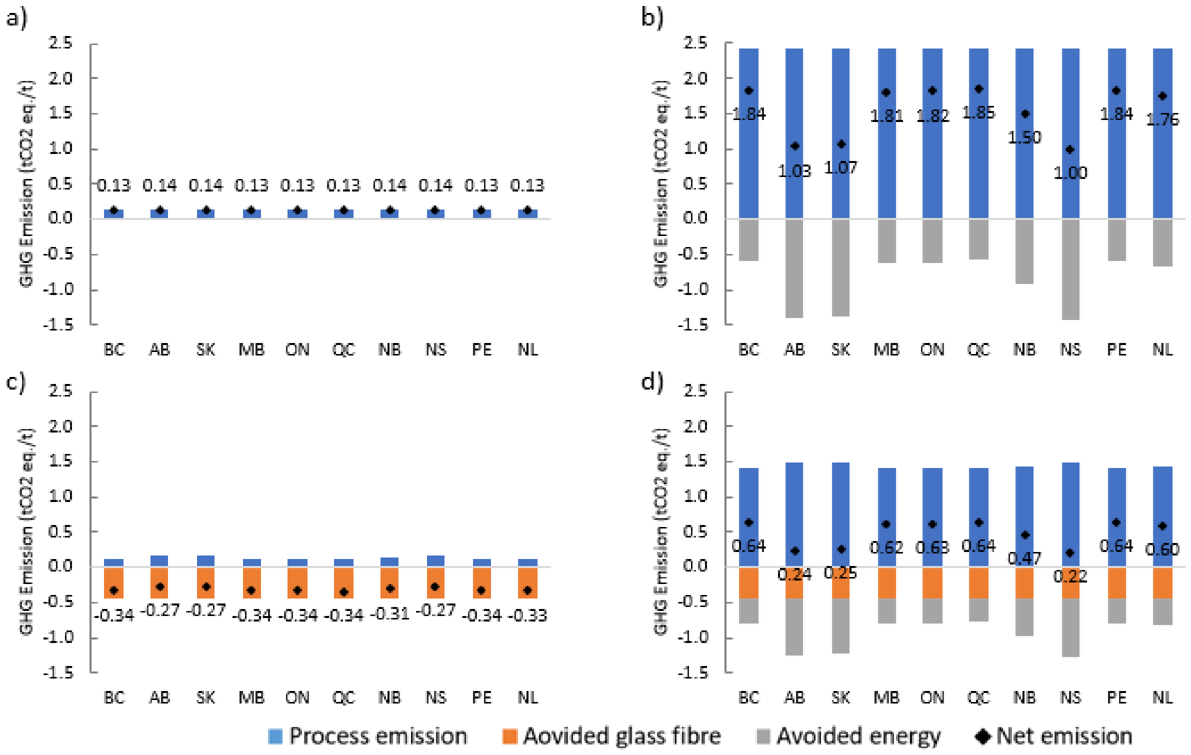


Figure 2. Province-specific life cycle greenhouse gas emissions associated with treating one tonne wind turbine blade waste by a) landfilling; b) incineration; c) mechanical recycling and landfilling of residues; d) mechanical recycling and incineration of residues.

3.4 Spatial and temporal distribution of life cycle environmental impacts of blade waste management

The generation of wind turbine blade waste, and therefore the resulting impacts of managing these wastes, is modest within the next 10 years, with GHG emissions for incineration estimated to reach only 34 ktCO$_2$eq. by 2030 (Figure 3). Similarly, PED associated with wind turbine blade waste management is also expected to be modest over the next decade (Figure S7 in the SI). However, the rapid growth in waste generation between 2030 and 2040, which reflects turbines installed between 2005 and 2015 reaching their end of life and being replaced, results in a corresponding order of magnitude increase in life cycle environmental impacts associated with waste management. By 2040, GHG emissions associated with incineration are predicted to reach 310 ktCO_2eq., whereas mechanical recycling with landfilling of residuals could avoid 60 ktCO_2eq. by this time. Beyond 2040, impacts of wind turbine waste management continues to be generated, but growth is more subdued, reflecting more modest rate of installations from 2015 to present and projections to 2025.

Life cycle environmental impacts associated with managing wind turbine blade wastes varies significantly by province, due to spatial variations in the quantity of waste generated (discussed previously in Section 3.1) and the GHG-intensity of provincial electricity mix (discussed previously in Section 3.3). Integrating these findings reveals that environmental impacts are concentrated in Ontario and Quebec due to their large share of current and projected wind turbine installations. These two provinces represent approximately 65% to 80% of total national emissions related to wind turbine blade waste management (Figure 3 and Figure S7. The impacts of incineration are particularly pronounced in these two provinces, due to the large role of renewable and nuclear electricity generation routes. The different patterns observed in the predicted waste quantity (**Error! Reference source not found.**) and the net environmental impacts (**Error! Reference source not found.**) for different provinces indicate the importance of considering local energy systems to achieve a higher accuracy in estimating net impacts of waste management systems.

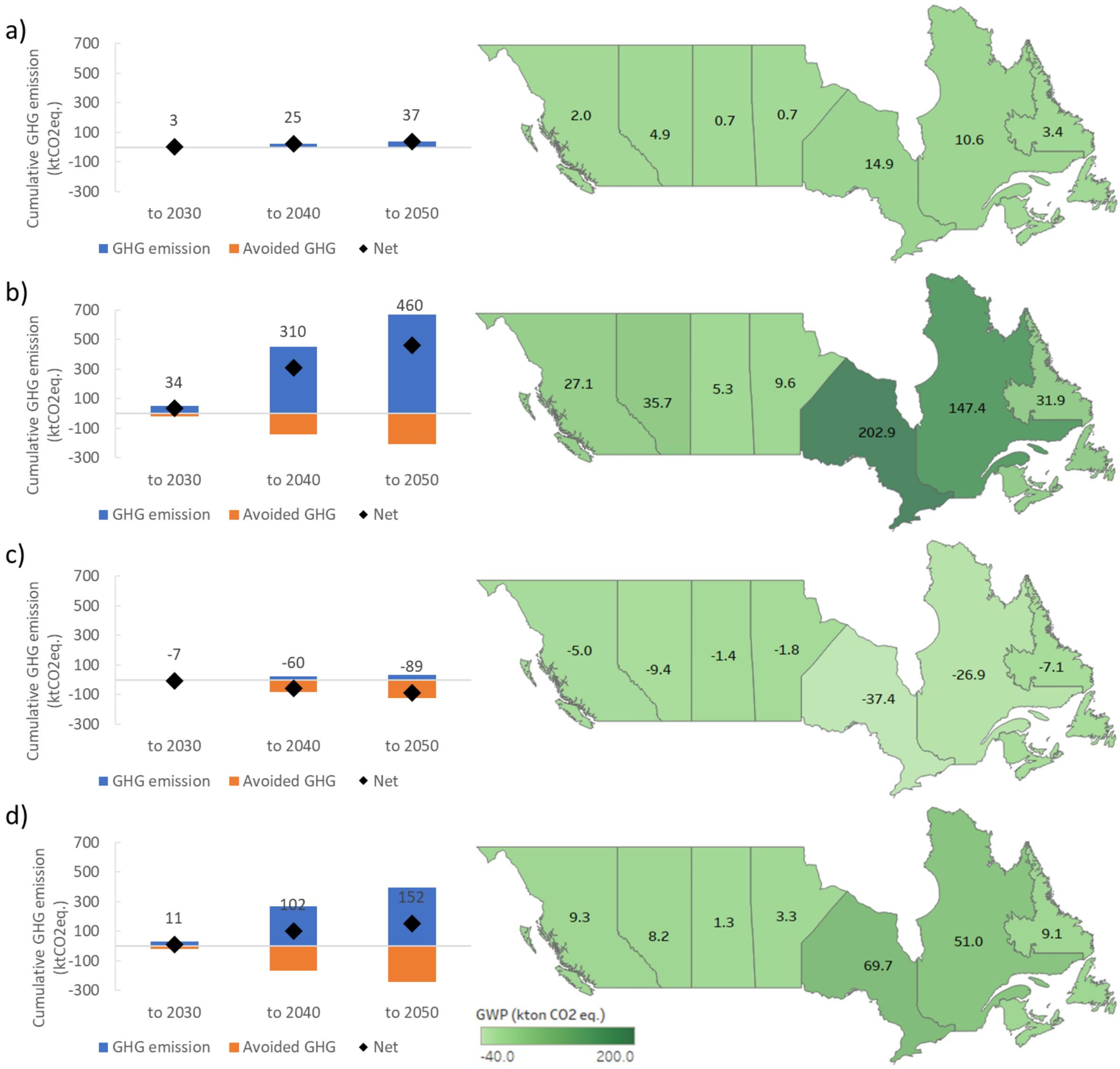


Figure 3. Spatial and temporal distribution of greenhouse gas emissions associated with wind turbine blade waste management: a) landfilling; b) incineration; c) recycling and landfilling of residues; d) recycling and incineration of residues. Charts: national cumulative greenhouse gas emissions associated with wind turbine blade waste management to 2050; Maps: cumulative greenhouse gas emissions by province to 2050.

3.5 Wind turbine blade waste management and life cycle environmental impacts in context

To ensure the sustainability of wind power installations, it is necessary to plan for and regulate the management of inevitable wastes arising from manufacturing, O&M, and end of life. The present study demonstrates the potential GHG emissions advantage of developing and deploying viable recycling routes for wind turbine blade wastes. However, current wind turbine blades, primarily comprised of GFRP, are a challenging component to effectively recycle due to the nature of their constituent material. Globally, there are very few examples of composite recycling processes in operation, and these are based on recovering higher value carbon fibres[11, 28] rather than comparatively low value glass fibres. Achieving viable glass fibre recycling systems in practice will be challenging, due to costs associated with disassembly and recovery of glass fibres from wastes,[8] the reduction in their mechanical properties and size, and competition with low cost primary production of glass fibres. Policy support, in mandating or otherwise encouraging more circular management of wind turbine blade wastes, is likely to be required. In the absence of financially viable recycling routes, or where cost is not justified by achieved benefits (e.g., social cost of carbon), landfilling represents a low-impact alternative that can achieve very low GHG emissions for waste management. The inert nature of the material ensures other environmental impacts associated with landfilling will be minimal. While incineration offers the recovery of energy from blade waste, associated GHG emissions make this an unattractive option.

Increasingly, offshore wind turbines are using carbon fibre reinforced plastics as blade material rather than glass fibre. The higher financial value of carbon fibre may help to justify recycling as a waste management route, and we have previously demonstrated the technical, financial, and environmental viability of carbon fibre recycling with reuse in the automotive sector[29, 30]. While offshore wind has yet to be deployed in Canada (as of 2018), this is a future opportunity with substantial wind resource in the Great Lakes and the Pacific and Atlantic coasts. As carbon fibre is a high-value product, high cost associated with recycling/dismantling/transportation can be justified by potential environmental benefits and thus can be the focus of future work looking at advanced technologies recovering high values while avoiding conventional landfill and incineration.

In a broader context, the overall impacts of wind turbine blade waste management appear small. Cumulative blade waste generation of 275 kt by 2050, estimated in this study, is equivalent to only 1% of waste disposed in Canada in a single year at present.[31] The GHG emissions implications of blade waste management are also modest. Based on an average capacity factor for wind turbines in Canada of approximately 30%,[32] even the highest GHG emissions case for blade waste management (incineration) would represent an emissions rate of 0.4 $gCO_2eq./kWh$ produced, equivalent to 4% of life cycle emissions associated with wind power. In contrast, life cycle GHG emissions associated with natural gas combined cycle generation would be approximately 1000 times this estimated impact of blade waste management.

Uncertainty in how blade wastes will be managed in future does not bring into question the role of wind power in transitioning Canada towards low carbon energy systems. However, the timing of these impacts will coincide with the timeline for commitments net-zero carbon emissions by 2050. While the deployment of wind power to date has demonstrated the ease of achieving reductions in GHG emissions by displacing fossil fuel generation, management of associated wastes indicate some of the challenges in reaching net-zero emissions targets.

Associated Content

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: XXX.

Supporting Information includes additional details on wind turbine blade mass estimation, waste prediction and life cycle environmental impacts of different blade waste management methods. Figures S1 presents wind energy installed capacity in Canada for the past decade. FigureS2 modelled blade mass per unit rated power based on the existing wind turbine models in the Canadian wind farms. Figure S3 displays the model used in the total waste generation prediction. Figure S4 shows the geographical distribution of the blade waste generation until 2050 in Canada. Figure S5 presents the sensitivity analysis for the total cumulative waste inventory in 2050. Figure S6 illustrates province-specific life cycle greenhouse gas emissions associated with treating one tonne wind turbine blade waste by waste management options. Figure S7 demonstrates spatial and temporal distribution of primary energy demand associated with wind turbine blade waste management. Table S1illustrates the assumptions for three scenarios. Table S2 displays the PED and GHG emission values for each process Table S3 details the mix of the electricity generation sources in 2017 by province. Table S4 displays the PED and GHG emission quantified in every process for each waste management option.

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Notes

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Abbreviations

Canadian Provinces and Territories:

AB	Alberta
BC	British Colombia
MB	Manitoba
NB	New Brunswick
NL	Newfoundland and Labrador
NS	Nova Scotia
ON	Ontario
PE	Prince Edward Island
QC	Quebec
SK	Saskatchewan

Other terms:

CFRP	Carbon fibre reinforced plastic
EoL	End of life

GFRP	Glass fibre reinforced plastic
O&M	Operation and maintenance
GHG	Greenhouse gas
PED	Primary energy demand

References

(1) Global Wind Energy Council. Global Wind Report 2019. *Wind energy technology* **2020**, 78.

(2) National Energy Board *Canada's Energy Future 2016: Update - Energy Supply and Demand Projections to 2040*; 2369-1479; 2016.

(3) Environment Canada *Final Report: Pollution Prevention Planning in Respect to Mercury Releases from Mercury Switches in End-Of-Life Vehicles Processed by Steel Mills*; 2013.

(4) Shuaib, N. A., et al. Resource Efficiency and Composite Waste in UK Supply Chain. *Procedia CIRP* **2015,** *29*, 662-667.

(5) Marsh, G. Europe gets tough on end-of-life composites. *Reinforced Plastics* **2003,** *47* (8), 34-36. http://dx.doi.org/10.1016/S0034-3617(03)00839-7

(6) Liu, P.; Barlow, C. Y. Wind turbine blade waste in 2050. *Waste Management* **2017,** *62*, 229-240. 10.1016/j.wasman.2017.02.007

(7) Lefeuvre, A., et al. Anticipating in-use stocks of carbon fibre reinforced polymers and related waste generated by the wind power sector until 2050. *Resources, Conservation and Recycling* **2019,** *141*, 30-39. 10.1016/j.resconrec.2018.10.008

(8) Li, X., et al. Environmental and financial performance of mechanical recycling of carbon fibre reinforced polymers and comparison with conventional disposal routes. *Journal of Cleaner Production* **2016,** *127*, 451-460. 10.1016/j.jclepro.2016.03.139

(9) Naqvi, S. R., et al. A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy. *Resources, Conservation and Recycling* **2018,** *136*, 118-129. https://doi.org/10.1016/j.resconrec.2018.04.013

(10) ELG Carbon Fibre Ltd. LCA benefits of rCF. <http://www.elgcf.com/assets/documents/ELGCF-Presentation-Composite-Recycling-LCA-March2017.pdf>, (accessed June 2020).

(11) Meng, F., et al. Comparing Life Cycle Energy and Global Warming Potential of Carbon Fiber Composite Recycling Technologies and Waste Management Options. *ACS Sustainable Chemistry and Engineering* **2018,** *6*, 9854-9865. 10.1021/acssuschemeng.8b01026

(12) Prinçaud, M., et al. Environmental Feasibility of the Recycling of Carbon Fibers from CFRPs by Solvolysis Using Supercritical Water. *ACS Sustainable Chemistry & Engineering* **2014**. 10.1021/sc500174m

(13) Keith, M. J., et al. Recycling carbon fibre with an acetone/water solvent and zinc chloride catalyst: resin degradation and fibre characterisation. **2018**.

(14) Liu, P., et al. Wind turbine blade end-of-life options: An eco-audit comparison. *Journal of Cleaner Production* **2019,** *212*, 1268-1281. https://doi.org/10.1016/j.jclepro.2018.12.043

(15) Canadian Wind Energy Association. Wind Energy in Canada. <https://canwea.ca/>, (accessed June 2020).

(16) Wind Energy Market Intelligence. Online Access: Wind Farms: Canada. <https://www.thewindpower.net/windfarm_en_10142_ontario-wind-power.php>, (accessed June 2020).

(17) Canadian Wind Energy Association. A Wind Energy Vision for Canada. <https://canwea.ca/vision/#:~:text=It%20has%20provided%20%E2%80%93%20and%20will,quality%20and%20fighting%20climate%20change.>, (accessed June 2020).

(18) Enercon. Overview of ENERCON platform. <https://www.enercon.de/en/products/>, (accessed June 2020).

(19) GE Renewable Energy. GE’s onshore wind farm technology. <https://www.ge.com/renewableenergy/wind-energy/onshore-wind>, (accessed June 2020).

(20) Senvion. Overview of installed Senvion turbines. <https://www.senvion.com/global/en/products-services/wind-turbines/>, (accessed June 2020).

(21) Vestas. Product Portfolio. <https://www.vestas.com/en/products>, (accessed June 2020).

(22) Wind-turbine-models.com. Wind turbines models. <https://en.wind-turbine-models.com/models>, (accessed June 2020).

(23) Caithness Windfarm Information Forum. Summary of Wind Turbine Accident data to 30 June 2019. <http://www.caithnesswindfarms.co.uk/AccidentStatistics.htm>, (accessed July 2019).

(24) Canadian Wind Energy Association. Decommissioning/Repowering a Wind Farm. <https://canwea.ca/communities/decommissioningrepowering-wind-farm/#:~:text=Once%20a%20wind%20farm%20reaches,decommission%20or%20repower%20the%20facility.&text=Decommissioning%3A%20Wind%20farm's%20power%20production,more%20advanced%20and%20efficient%20technology.>, (accessed June 2020).

(25) Stocker, T., et al. IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. **2013**.

(26) Palmer, J., et al. Sheet moulding compound (SMC) from carbon fibre recyclate. *Composites Part A: Applied Science and Manufacturing* **2010,** *41*, 1232-1237. 10.1016/j.compositesa.2010.05.005

(27) Palmer, J. Mechanical recycling of automotive composites for use as reinforcement in thermoset composites. PhD thesis, University of Exeter, 2009.

(28) ELG Carbon Fibre Ltd. <http://www.elgcf.com/>, (accessed April 2020).

(29) Meng, F., et al. Environmental aspects of use of recycled carbon fibre composites in automotive applications. *Environmental Science & Technology* **2017,** *51* (21), 12727–12736. 10.1021/acs.est.7b04069

(30) Meng, F., et al. An assessment of financial viability of recycled carbon fibre in automotive applications. *Composites Part A: Applied Science and Manufacturing* **2018,** *109*, 207-220. 10.1016/j.compositesa.2018.03.011

(31) Statistics Canada. Disposal of waste, by source. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810003201>, (accessed May 2020).

(32) Natural Resources Canada. Renewable energy facts. <https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/renewable-energy-facts/20069>, (accessed June 2020).