

Wind turbine blade circularity: an overview of composite recycling methods, global markets and policies, and opportunities for Canadian development

Prepared for:

Natural Resources Canada, Energy Efficiency and Technology Sector, Building and Renewables Group

Prepared by:

Keelia LaFreniere, Research Engineer, Building and Renewables Group
Natural Resources Canada, CanmetENERGY

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Executive Summary

Wind turbine blades are typically comprised of glass or carbon fibre bonded with resin. This material is technically recyclable, but due to the complexity of these recycling processes, has been almost exclusively landfilled worldwide up until now. However, with the rise in national composite landfill bans, and the anticipated surge in wind turbine blade waste in the next few decades due to a global exponential increase in the adoption of the technology, landfilling is rapidly becoming an unfavourable end-of-life option. This paper reviews the existing recycling options for decommissioned wind turbine blades (grinding, cement kiln co-processing, pyrolysis, solvolysis, high voltage fragmentation, and refurbishment), as well as the utility of recycled composite fibres in industry, including the emissions profile deriving from the recycling methods themselves. The Canadian wind energy market is discussed, highlighting the lack of recycling facilities or infrastructure, despite the recent increase in wind farm installations countrywide. Decommissioning requirements for new Canadian wind farms lack detail on blade disposal plans. Several research pathways are identified and recommended to improve circularity and environmental outcomes: the development of an interactive tool that allows wind farm operators to select turbine models and understand what kinds and amounts of recyclates will result from that model at their end of life, a comprehensive logistical analysis of wind turbine decommissioning costs to help inform wind farm operational decision making, inclusive WTB recycling method environmental impact evaluation (accounting for water use, energy use, and pollutant generation), the investigation of industrial uses for recycled fibres from WTB and other composite waste streams, and a review of current international forums on wind turbine circularity to ensure that no data sharing potential is being overlooked.

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Glossary

ASMC	Advanced sheet moulding compression
CD	Critical [transport] distance
CF	Carbon fibre
CFRP	Carbon fibre reinforced polymer
EoL	End of life
EPRI	Electrical Power Research Institute
DPR	Decommissioning Plan Report
GF	Glass fibre
GHG	Greenhouse gas
GWP	Global warming potential
HVF	High voltage fragmentation
LCF	Lignin-based carbon fibre
MAP	Microwave-assisted pyrolysis
PET	polyethylene terephthalate
rCF	Recycled carbon fibre
RP	Reinforcement potential
SMC	Sheet moulding compression
TRL	Technology readiness level
UD	Unidirectional
vCF	Virgin carbon fibre
vGF	Virgin glass fibre
WTB	Wind turbine blade

1. Introduction

Wind turbines are experiencing worldwide exponential growth in the race to transition to a sustainable global economy. A wind turbine is comprised of four main components: a foundation, a tower, a nacelle, and blades. Most turbines installed today are horizontal-axis wind turbines (HAWTs) with three blades. Foundations are made of concrete, the tower of steel and concrete, and the nacelle of primarily steel and copper. These materials are historically relatively easy to recycle. The blades, however, are typically made of composite materials, which present major environmental concerns at their end-of-life due to how difficult these materials are to recycle [1].

Currently, wind turbine blades (WTBs) are almost exclusively landfilled once they are decommissioned due to the ease and simplicity of this disposal method [1]. However, landfilling is not a sustainable practice, and policies designed to divert turbine components from landfill are becoming more common. Globally, several countries have imposed a cost-per-tonne to landfill WTBs, or have banned the landfilling of composite materials outright [2]. In addition to the issue of where to put WTBs when they are decommissioned, there is the matter of volume. Wind turbines typically have lifespans of 20-25 years [3]. This means there is an approximately 20-year lag between turbine installation and the influx of WTBs to the waste stream, at which time the problem of composite recycling presents itself again. For example, Canada is expected to generate an average of 8.9 kt/year of WTB waste between 2020-2050. However, this waste stream is not linear. There is an anticipated peak of 29,000 kt/year between 2036-2040 due to the rapid deployment of wind turbines during 2011-2015 [4]. Wind power is prevalent in the daily lives of Canadians, but the burden of WTB disposal arising from wind turbines in operation today will not be felt for many years. The need for robust recycling methods and centres to accommodate the anticipated surge in composite waste is soon to become critical, as this type of waste may soon be unsuitable for landfilling in many parts of the world.

To that end, this paper reviews the currently available WTB recycling methods, and the comparative utility, ecological benefits and challenges associated with these methods. Focus is put on the unique challenges experienced in the Canadian domain, including the state of the Canadian wind energy market, and current decommissioning guidelines and policies. Finally, a list of recommendations on next steps to further the effectiveness of existing wind turbine circularity efforts is delineated, as well as proposals regarding hitherto unexplored areas of circularity research.

2. Recycling Methods

WTBs are comprised of a number of different materials, shown in cross section in Figure 1. WTBs are built with glass, carbon, or aramid reinforcement fibres, a polymer matrix (epoxies, polyesters, vinyl esters, polyurethane, or thermoplastics), a core material (typically balsa wood or polyethylene terephthalate (PET)), a coating of polyethylene or polyurethane, and finally an assortment of metals in the form of copper wirings, steel bolts, or lightning protection strips made of copper and aluminum [5], [6].

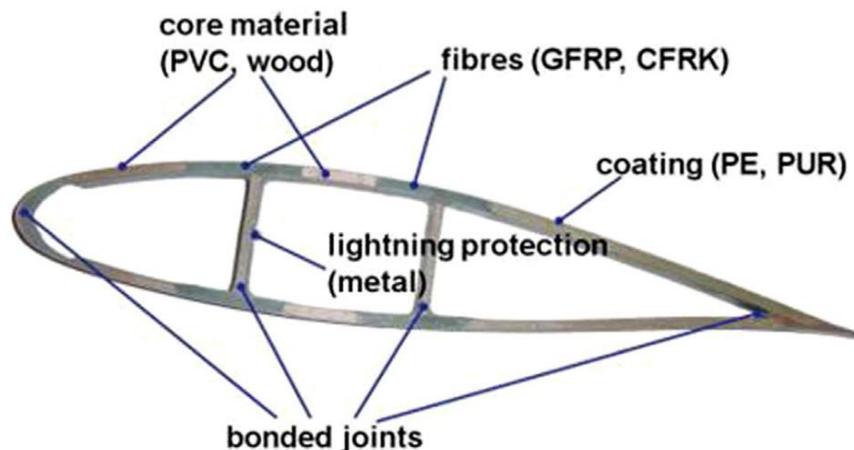


Figure 1: A typical wind turbine blade cross section [1]

Roughly 80-90% of the materials in a turbine are recyclable, excluding the concrete turbine base [7]. This is due to the large amount of easily recoverable materials comprising wind turbines, such as metals and woods. However, WTBs and their fibre thermoset composites are most commonly disposed of in landfills or incinerated at their end-of-life [7]. As of 2024, decommissioned wind turbines are now tracked in a publicly available database by the US Wind Turbine Database (USWTDB), with support from the US Department of Energy's Wind Energy Technologies Office. There are currently over 11,600 records of decommissioned wind turbines in this database [8].

For every megawatt of wind energy decommissioned, approximately 10-13 tonnes of composite material are added to the waste stream [9], [10]. It is estimated that Canada will have accumulated approximately 275,000 tonnes of WTB waste by 2050, with 70% of this waste originating from Quebec and Ontario alone [4]. Globally, it's anticipated that there will be 43 million tonnes of WTB waste by 2050, and that wind energy will provide 15-18% of the world's electricity by the same year [11].

As wind turbines approach their end-of-life, decisions must be made regarding the most judicious next step in their operation. As shown in Figure 2 below, each decision point must take into account several criteria; cost associated with the decision, the technical

feasibility, whether current legislation permits the desired path, and the decision's environmental impact [12]. The ideal is to condemn as little material as possible to disposal, to maintain a circular material stream.

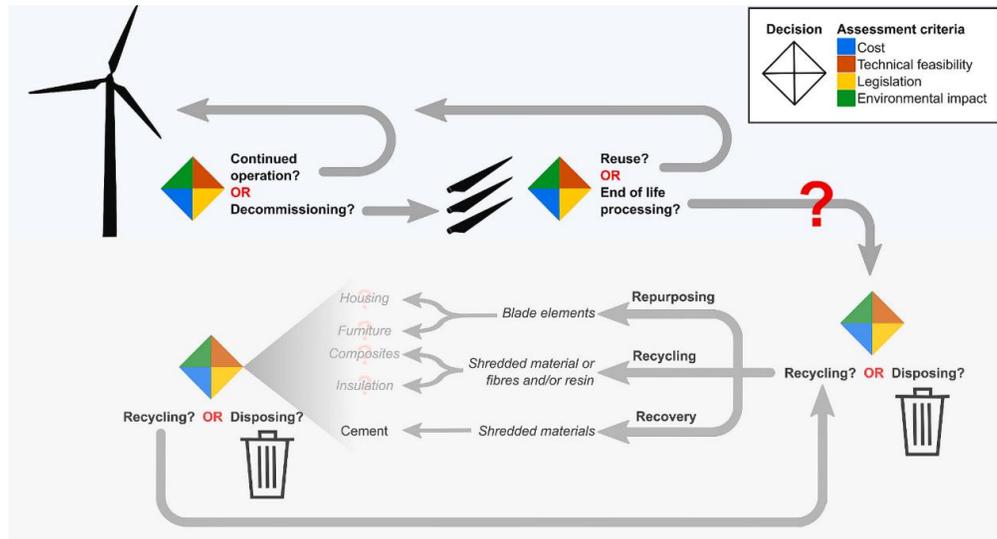


Figure 2: Value chain at WTB end-of-life [12]

There are currently five different categories into which wind turbine blade recycling processes fall: mechanical, thermal, chemical, high voltage fragmentation (HVF), and reprocessing/repurposing [9]. These methods are described in Sections 2.1 to 2.4 below.

2.1 Mechanical Recycling

2.1.1 Grinding

Mechanical recycling of WTBs involves cutting, shredding, milling, or crushing blade material down into a smaller, more uniform substance. This process destroys the mechanical properties of the fibres, however, which makes the end product less commercially appealing [9], [13]. This resultant WTB recycle is then classified based on its subsequent size using cyclones or sieves. This process does not separate resin from the fibres, so the recycle is a combination of the two [9]. The recycle may then be used as a filler for other applications, depending on the quality of the recycle itself. If the WTB was built from a thermoset composite material, the recycle is best used as a filler material for other applications, due to the irreversible nature of the curing process undergone by thermoset composites. WTBs made from thermoplastic composites, however, can have their recycles re-extruded for re-use [9], [14].

2.1.2 Cement Kiln Co-Processing

Shredded WTB recycle may also be used in cement kiln co-processors. Recycle ground from WTBs made of glass fibre composites can be mixed with other fuel and

used to feed cement kilns (carbon fibres are unsuitable for incineration for health and safety reasons) [15]. The organic content of the recycle, *i.e.* the resin, adhesives, and core materials, burn in the kiln to help fuel the process, reducing the need for other carbon-heavy fuels such as coal. The glass fibres concurrently provide the required minerals to produce clinker, which is then used to create cement [9]. Figure 3 indicates the cement kiln co-processing procedure, where WTB recycle is added to the kiln feed and burned alongside the fossil fuels to produce clinker.

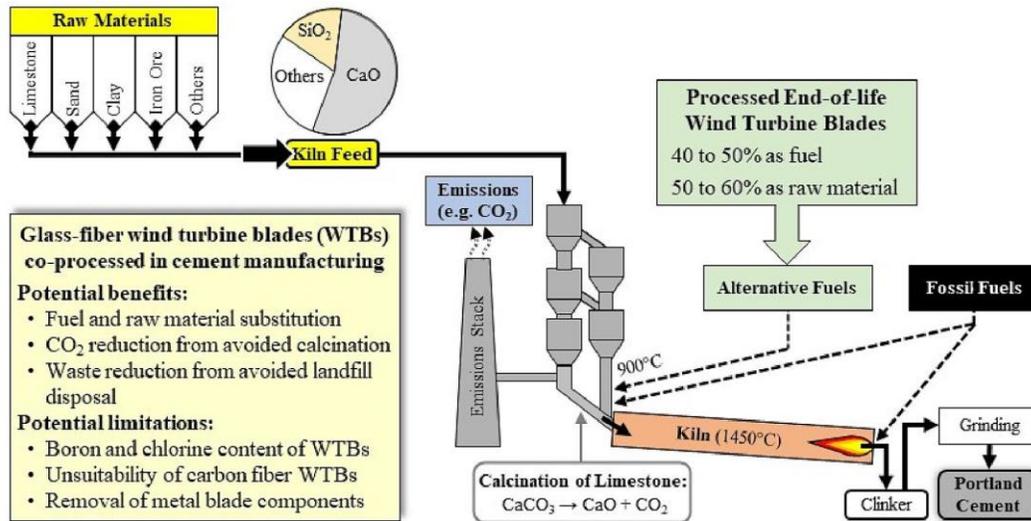


Figure 3: Diagram of cement kiln co-processing using recycled WTBs as feedstock [16]

In 2022, the Electrical Power Research Institute (EPRI) estimated that cement kiln co-processing could displace between 0.4-0.5 tonnes of coal, 0.1 tonnes of calcium oxide, and 0.3 tonnes of silica oxide for every tonne of WTB recycle burned. Use of WTB recycle prevents these reagents from being sourced and mined as virgin materials [17]. While this is a technologically mature and readily available method of waste management for WTB, it also downcycles the fibres in the ground recycle, making it a potentially less desirable mode of recycling [9], [15].

2.2 Thermal Recycling (Pyrolysis)

Pyrolysis separates resin from the fiberglass or carbon fibres of a composite material by heating the material in a vacuum to very high temperatures (450-700°C). The combination of high temperatures and low pressure converts the resin polymer matrices into gas, oil, and char, leaving behind the composite fibres for later recovery. The process is not perfect, however, and the recovered fibres can become fouled with the char, as well as mechanically degraded by the process itself. Char is removed from the recovered fibres through an additional oxidation step [15]. A study of the pyrolysis and subsequent oxidation of a glass fibre composite indicated that the recovered glass fibres retained 35% of their strength as compared to virgin fibres when pyrolyzed at

450°C, 52% of their strength at 500°C, and 49% of their strength at 650°C [18]. Additional studies have determined that pyrolysis produces glass fibre recyclates with 52% of their strength compared to virgin fibres, and carbon fibre recyclates with 80% strength [11]. Pyrolysis for decommissioned WTBs occurs in four different types of reactor designs: batch or semi-batch, fixed bed, microwave assisted, and fluidized bed.

2.2.1 Batch and Semi-Batch Reactors

Batch reactors are comparatively simple – the pyrolysis reaction takes place entirely within a closed vessel. This means that there is a high conversion rate of reactants into products; however, it also means that no additional reactant inputs nor product extractions can take place during reactions [19]. Semi-batch reactors are similar but allow for the addition of reactants and the removal of products during the reaction. This presents the new problem of reproducibility, as purities of the reactant conversion can vary between batches due to the interim additions and removals of reagents [19], [20]. A simplified model of a batch and semi-batch reactor is shown in Figure 4.

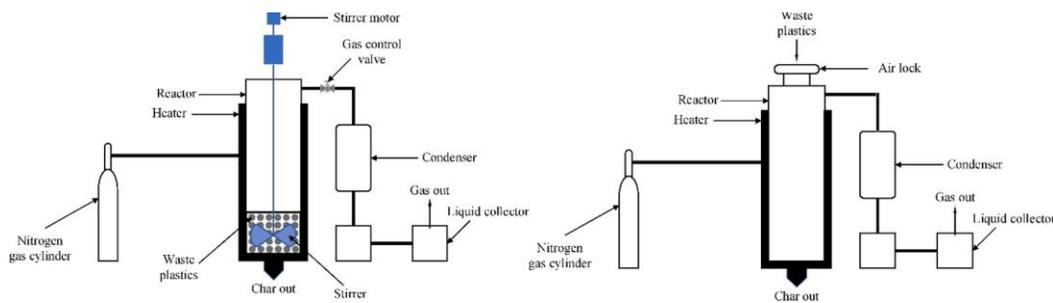


Figure 4: Simple diagram of a batch (left) and semi-batch (right) pyrolytic reactors [21]

2.2.2 Fixed-Bed Reactors

Fixed-bed reactor systems are often built with tubular reactors and external heaters. These reactors allow for the removal of oil and gas pyrolysis products in-situ, and solid products are collected after the reaction is complete [19]. A simplified model of a fixed-bed reactor is shown in Figure 5.

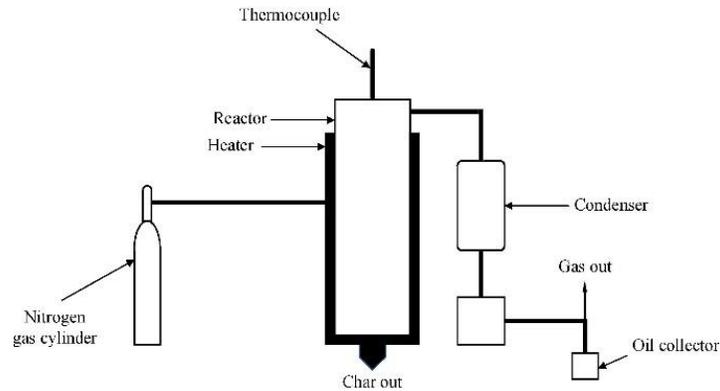


Figure 5: Simple diagram of a fixed-bed pyrolytic reactor [21]

2.2.3 Fluidized-Bed Reactors

Fluidized bed reactors take shredded composite and place it into a bed of silica. The silica is then fluidized by injecting it with hot air. This process takes place at lower temperatures than other pyrolytic methods (450-500°C), which degrades the resin polymer matrix as in other pyrolysis processes and frees the composite fibres. Fibres are collected from the mass of silica, air, and pyrolysis products via a rotary sieve separator. Once fibres have been separated and collected, the remaining fluidized mixture is sent to a secondary combustion chamber and burned at much higher temperatures (1000°C) to safely oxidize the residual organic compounds present in the fluid [22]. Fluidized bed reactors recover approximately 44% of glass fibres and 60% of carbon fibres by weight, yielding 52% and 75% of their strength compared to virgin fibres, respectively [11]. A simplified model of a fluidized-bed reactor is shown in Figure 6.

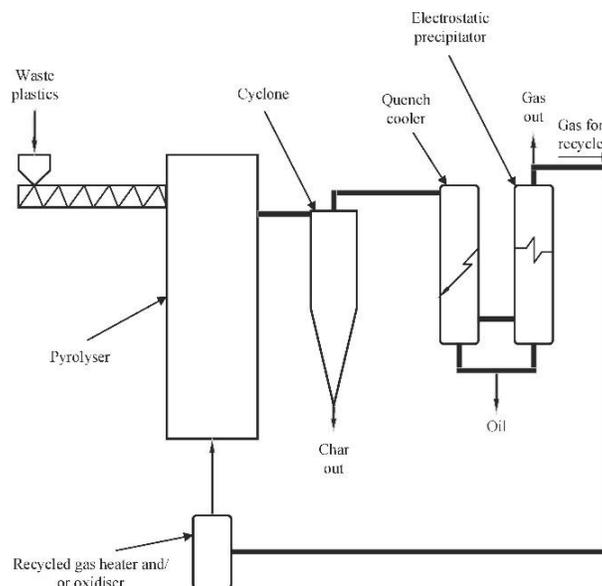


Figure 6: Simple diagram of a fluidized-bed pyrolytic reactor [21]

2.2.4 Microwave-Assisted Reactors

Microwave-assisted pyrolysis (MAP) reactors use high frequency microwaves as a heat source, as opposed to more conventional pyrolysis reactors. Microwaves provide more rapid and even heating [19], and are capable of pyrolyzing WTB materials using roughly 53% less energy than conventional pyrolysis heating methods [23], [24]. MAP reactors recover approximately 52% of glass fibres' tensile strength compared to virgin fibres, and 80% of carbon fibres' tensile strength compared to virgin fibres [24].

2.3 Chemical Recycling

2.3.1 Solvolysis

In solvolysis, a solvent (often alcohol, water, or acid) is employed to break down the bonds between the resin and the fibres of the recyclate. The solvent depolymerizes the bonds in the thermoset polymers with the addition of heat and pressure, permitting the recovery of both the resin and the fibres, both glass and carbon [10]. Supercritical water has been used as a solvent for recycled wind turbine blades, along with catalysts and other additives, requiring the maintenance of 250-370°C and 100-180 bar. Supercritical fluid solvolysis of carbon fibre recyclate has recovered fibres with up to 98% of their tensile strength compared to virgin fibres [25]. Though this method yields high rates of fibre recovery and excellent tensile strength retention, it is typically viewed as unfavourable due to its comparatively large energy demand and its environmental impact through the liberal use of chemicals [22], [25].

2.3.2 High Voltage Fragmentation (HVF)

HVF uses local shockwaves, similar to lightning strikes, to disconnect materials with different conductivities at their interface. The applied energy follows the electrons present at the boundaries of the material, leading to fragmentation [26]. HVF recovers 90% of glass and carbon fibres during the recycling process, with 88% tensile strength retention compared to virgin fibres for glass fibres and 83% tensile strength retention for carbon fibres [24]. While the process maintains a high level of fibre tensile strength, it is also energy intensive – HVF consumes 2.6 times more specific energy than the mechanical shredding of other thermoset resin samples [27].

2.4 Refurbishment and 'Upcycling'

Every recycling process requires a certain amount of energy, labour, and infrastructure to perform. Figure 7 compares the specific energy required to produce virgin glass and carbon fibres, compared to several recycling methods discussed above. These recycling methods have also been colour-coded to indicate their relative capital expenses. Note that while landfill and incineration are considered low-cost, low-energy solutions, there are environmental concerns that are not captured by the metrics of this graph [25].

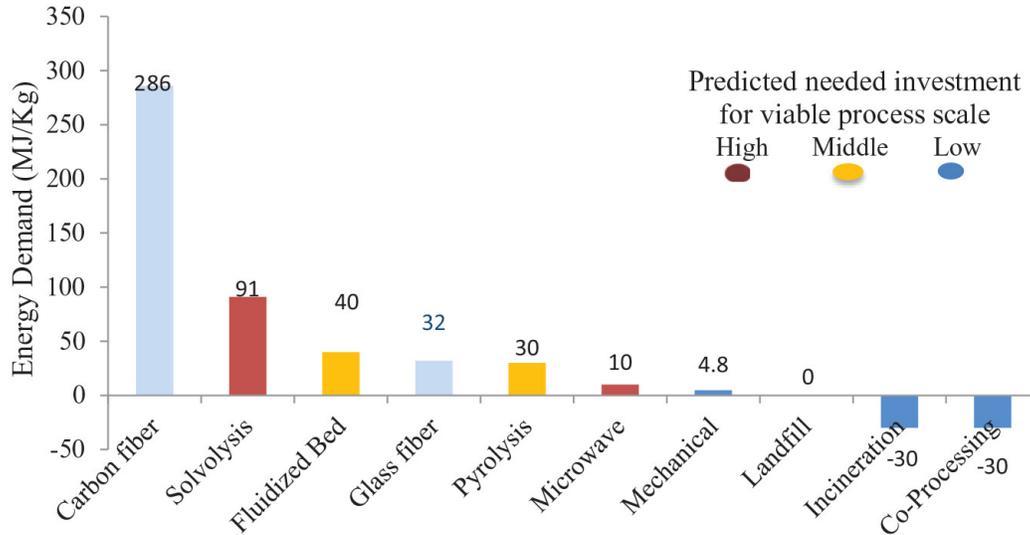


Figure 7: Demand for energy in the production of glass and carbon fibres, compared to recycling processes [25]

Given the persistent cost and energy consumption for WTB recycling processes, sometimes blades are destined for alternative end-of-life (EoL) options. Blades can instead be refurbished, or 'upcycled', their parts used as pieces for other construction projects while maintaining the original shape of the composite fibres [28].

One option for upcycling is using either blade sections, or entire blades, as structural supports in aquaculture nets. Aquaculture involves the farming of both animals and plants in a marine or freshwater environment. Figure 8 shows an example of a submerged marine aquaculture net, followed by four hypothetical cage designs that could be built from recycled WTBs. Building a secure facility in a marine environment has been a historical challenge, thanks to the forces of tides and waves. The aerodynamic shape of the WTBs reduces shear force experienced by the tank. This design is currently purely theoretical, and while it has technical merit, the potential impact on marine life has not been examined [29].



Figure 8: Marine aquaculture net and sample cage designs using recycled WTBs [29]

Anmet is a company that was established in 1999, originally as a recycling company focusing on steel, aluminum, and composite waste, among other feedstocks. In 2015, they expanded to include decommissioned WTBs into their portfolio [30]. They designed and installed an 8.5 metre pedestrian bridge using two retired WTBs on October 21st, 2021, seen below in Figure 9 [31].



Figure 9: Anmet members beside the newly installed 8.5m WTB pedestrian bridge over the Szprotawa River in Poland [31]

The Re-Wind Network is a multinational collaboration of research institutions that develops sustainable EoL strategies for WTBs [28]. They have been developing a variety of uses for upcycled wind turbines, such as floating solar panel platforms, jetties and piers, buoys, and an assortment of pedestrian bridges with differing support mechanisms (cable supported, low-profile, multi-girder, etc.) [32].

While upcycling WTBs is a promising and low-impact method of recycling retired blades, it is not without its own risks. Dutch architecture firm Superuse Studios designed a children's playground made entirely of sections of retired and repainted WTBs, installed in October of 2008. The playground was dubbed 'Wikado' [33]. However, as early as six months after installation, problems started to emerge. Leaching was observed on the blade surfaces of an oily substance, the precise composition of which is still unknown. The substance was indicated as potentially harmful. Of greater concern was the presence of glass fibre shards on and around the structures themselves. The use and weathering of the repurposed WTBs caused the material to become brittle over time, and edges of epoxy resin and glass fibres are exposed over the entirety of the structure. This introduces not just the risk of eye, skin, and lung irritation, but also the condition known as fibreglass dermatitis [34]. Fibreglass dermatitis can result from direct skin contact with the substance, or airborne fibres that accumulate on fabric and in skin folds [35].

3. Composite Recycling in Industry

3.1 Fibre Reinforcement Potential and Industrial Use

When composite fibres are recycled, they retain a portion of their virgin tensile strength. The fibres are therefore downgraded in quality during the recycling process; sometimes by significant margins, depending on the process used. Figure 10 show the breakdown of recycling processes, starting with a piece of composite material, dividing the recycling methods roughly into low- and high-level material reclamation brackets, with landfill and incineration serving as the 'base case' for comparison [36].

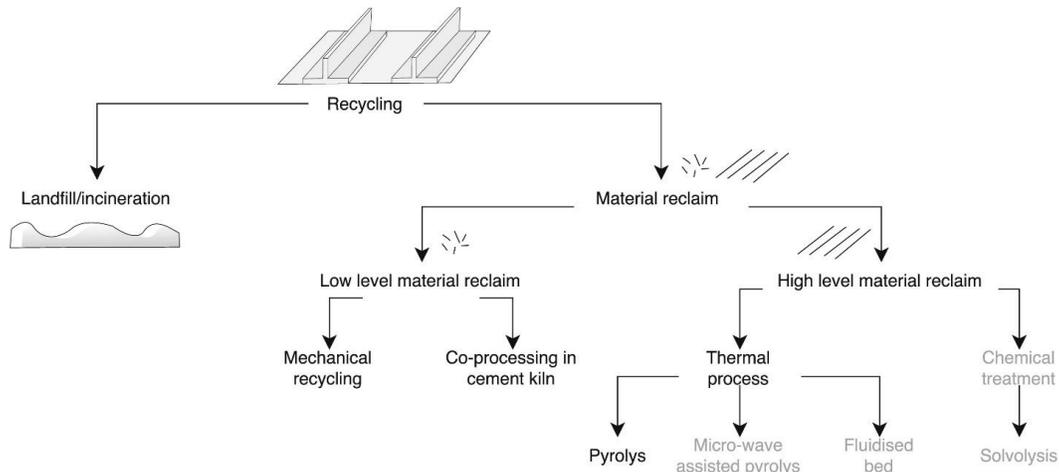


Figure 10: Recycling methods matched with level of material reclamation [36]

A more in-depth view of this information is show in Table 1, which shows the same recycling methods categorized by technology readiness level (TRL), waste management score, predicted investment needed, and retained tensile strength. Waste management score is a mixed metric based on recycling method output and TRL features; better recycling output and higher TRL scores result in higher waste management scores. Technologies with high TRL scores such as mechanical (grinding) and co-processing score no higher than a 'middle' waste management score, since while these methods are cheap and presently available, they are not a sustainable process and in the case of grinding, produce low quality recycle. The highest waste management scores belong to technologies with the highest predicted investments needed: microwave pyrolysis and fluidized bed pyrolysis. These technologies have low TRLs, as they are currently in

their infancy, but they produce high quality recyclate [25]. Note that co-processing is only applicable to glass fibres, not carbon fibres [17].

Table 1: Summary of current WTB recycling techniques [25]

Recycling methods	TRL	Waste management score	Predicted needed investment	Retained TS	
				GF (%)	CF (%)
Mechanical	9	Low	Low	78	50
Co-processing	8-9	Middle	Low/middle	-	-
Pyrolysis	7	High	Low/middle	52	78
Microwave pyrolysis	4	Middle/high	High	52	80
Fluidized bed	4/5	Middle/high	Middle	50	75
Solvolytic	5/6	High	High	58	95

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9	TRL 10
Technology research	Technology concept	Proof-of-concept	Technology demonstration	Conceptual design and prototype	Preliminary design and prototype validation	System demonstrated at engineering scale	Prototype tested and qualified	Plant operational	Commercial scale

Figure 11 displays the relation between the global warming potential (GWP) and Product Circularity Indicator (PCI) of the different WTB recycling methods. The PCI metric was developed to assign numerical values to industrial processes. These values permit the comparison of products' overall circularity by analyzing the product's manufacturing process, including virgin material use, recycled material reclamation, reused components, and unrecoverable waste [37]. From Figure 11, it can be seen that pyrolytic recycling methods have both a low PCI and high GWP, whereas solvolytic methods have on average higher PCIs and lower GWPs [38].

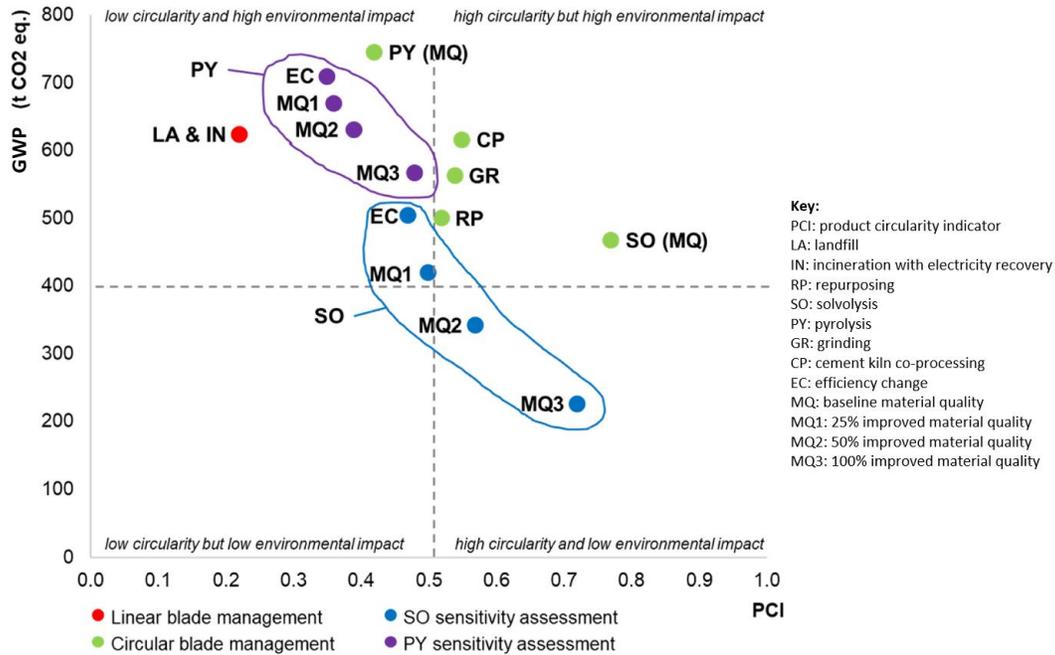


Figure 11: Correlation between the product circularity indicator and global warming potential results of the life cycle management of WTBs [adapted from 38]

Tensile strength retention determines the applicability of the recycled fibres use as fibre reinforcement in industry. Hagnell *et al.* has outlined a closed-cycle material loop for composite material recycling in Figure 12, starting with the highest grade (and most expensive) fibre application- aeronautics. Aeronautics require high quality, unidirectional (UD) fibres for the construction of structural components, and as such are typically comprised of virgin carbon fibres (vCF). However, high quality recycled carbon fibres (rCF) still have reinforcement potential (RP) in the aeronautics industry, as well as lignin-based carbon fibres (LCF) and virgin glass fibres (vGF). Fibres of a lesser quality, say rCF and rGF, are suitable for use in the automotive industry, which uses advanced sheet moulding compression (ASMC) techniques to generate their composites. These composites are comprised of higher grade fibres, but they are not UD as in the case of aeronautics. The marine industry uses a further reduced quality of fibre, using regular sheet moulding compression (SMC) and lower quality composites with shorter average fibre lengths. Finally, Hagnell *et al.* recommends that beyond the level of non-structural marine component builds, at the fibres' lowest RP, composites should be continually recycled into the lowest grade of thermoplastic powder filler to landfill for as long as possible.

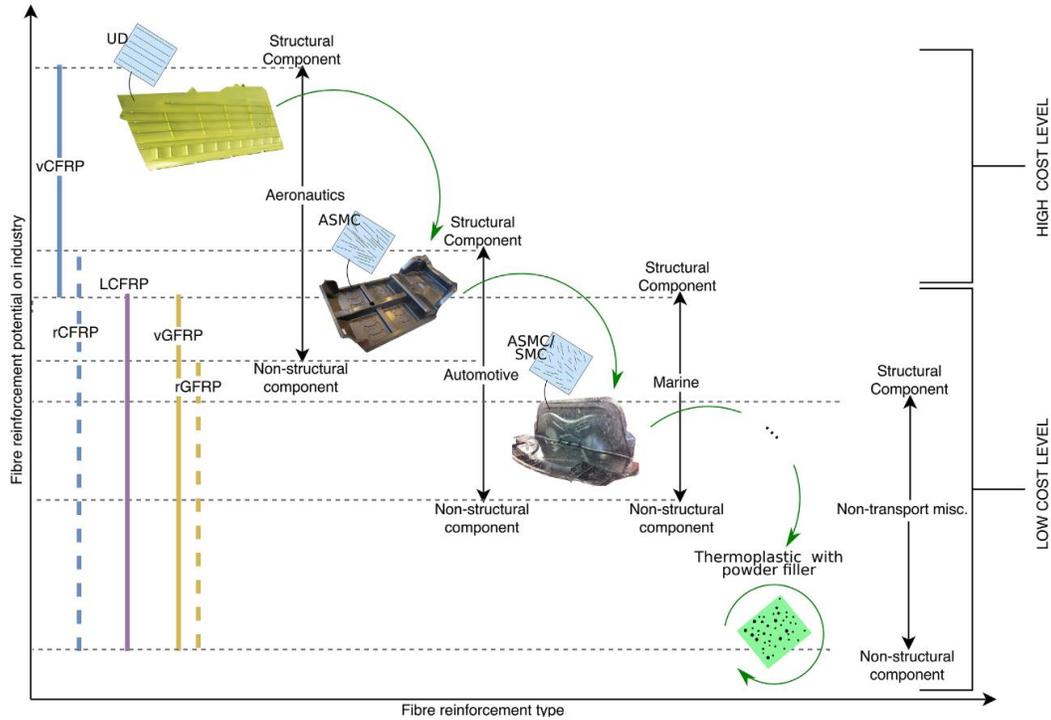


Figure 12: Applications for recycled composite materials organized by grade [36]

3.2 Composite Recycling and Pollution

Recycling is about mitigating harm but does not reduce it altogether. Table 2 summarizes the environmental impacts and GWP in terms of kg CO₂ equivalent per kg of carbon fibre reinforced polymer (CFRP) processed. This list is not comprehensive but shines a light into the still-present ecological harm produced by recycling composite materials.

Table 2: Composite recycling methods and their environmental impacts

Recycling Method	Environmental Impacts	GWP (kg CO ₂ eq./kg CFRP) [39]
Landfill	–	0.14
Landfill + Grinding	–	0.11
Cement Kiln Co-Processing	Release of toxic persistent organic pollutants (dioxins, furans) ¹ [40]	–
Pyrolysis	High energy use, generation of harmful gases (carbon monoxide/dioxide, methane, benzene, phenols, etc.) [41]	2.90
Chemical	High water use, use of solvents, high energy use [25], [39]	1.53
HVF	High energy use [42]	–
Upcycling	‘Leaching’ of unknown substance from repurposed blade sections into environment [34]	–

Note that some technologies in Table 2 do not have listed impacts, and some are missing GWP values. This does not mean that the methods do not have impacts or GWP, however, only that reliable sources for these values are lacking. For example, the embodied energy of vCF was found to be almost ten times greater than the specific energy required to process rCF via mechanical grinding. This makes a significant case for the use of rCF in composite applications requiring short fibre length [43]. However, note that an absence of mention of specific environmental impacts does *not* indicate that a recycling method is impact-free, only that the method has been determined to be less impactful in some regard than the business-as-usual approach.

3.3 Wind Turbine Blade Global Recycling

WTB recycling methods are still in their naissance; expensive to implement and not yet widely supported by infrastructure. Therefore, despite the numerous recycling methods currently available, WTBs are still almost exclusively landfilled worldwide [1]. The amount of WTBs that are landfilled versus recycled is so overwhelmingly weighted to the former that ‘percent recycled’ statistics are essentially unreported. It’s expected that by 2050, 42 million tons of WTBs will be landfilled, the equivalent to three times the annual waste produced by New York City [44]. This is not a sustainable practice, for obvious reasons, but is a particularly pressing matter for countries lacking the vast undeveloped tracts of land that would serve as suitable landfill sites. Such is the case in many European countries, and thus composite landfilling has been, or is soon to be,

¹ Processing solid waste in cement kilns releases dioxins and furans; however, there is evidence that co-processing solid waste releases a lower concentration of these pollutants than other industrial plants (e.g. waste incinerators, metallurgical smelters) [40]

banned in many countries. Some countries like the UK have implemented a charge per tonne to landfill WTB waste [45].

In Figure 13, the cost and calculated value of different recycling methods for WTB blades in China are shown in USD and forecasted out to the year 2050.

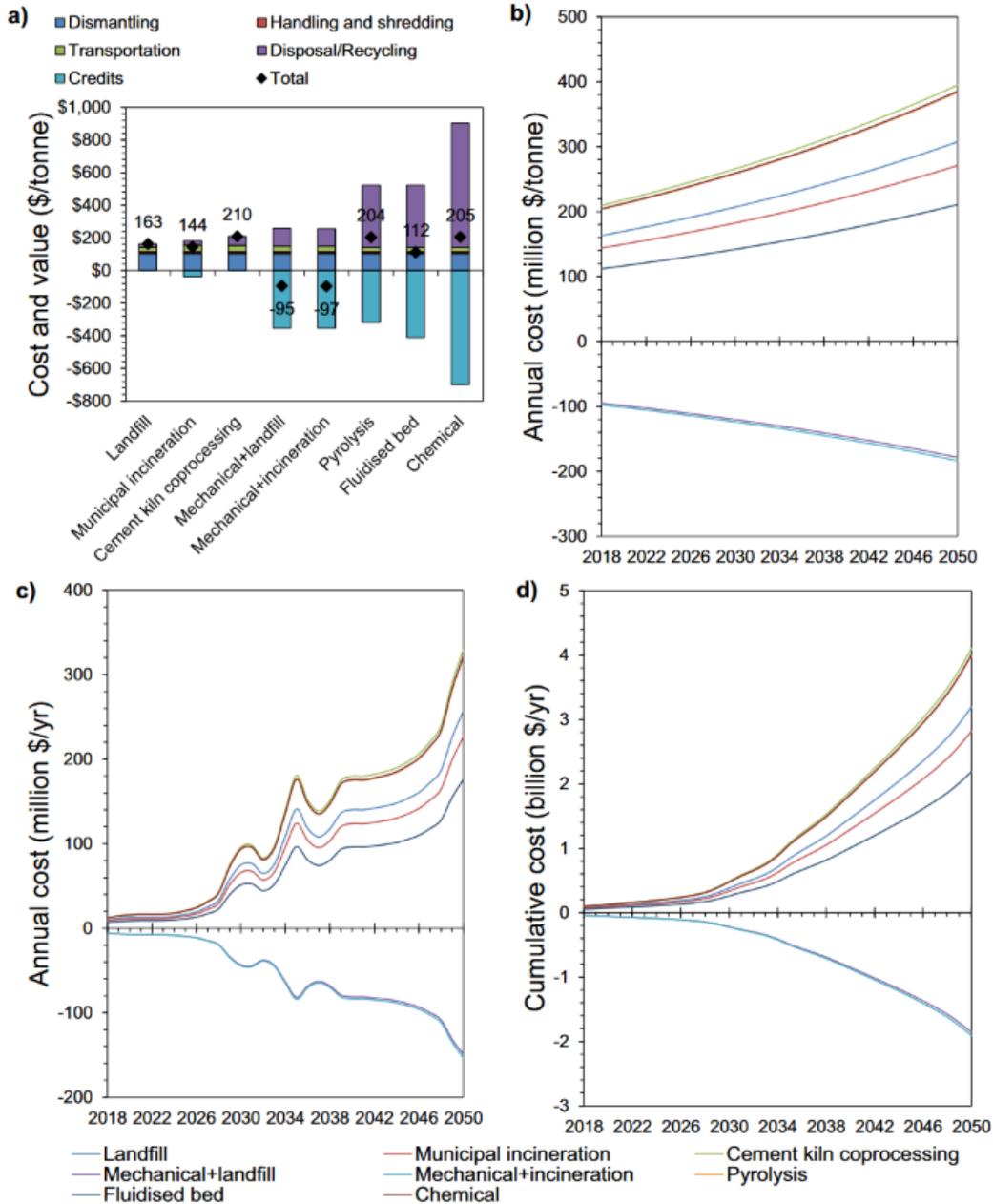


Figure 13: Chinese cost of wind turbine blade waste treatment from 2018-2050 [46]

Per Figure 13, mechanical separation and landfilling or mechanical separation and incineration are the only two recycling methods that are currently profitable, and those

costs per tonne are forecasted to continue to fall from now to 2050. All other methods are expected to increase in per unit cost. However, this figure neglects to indicate the newly implemented China Solid Waste Law, which bans the landfilling of composites, effectively nullifying the low-cost benefit of landfilling [46].

Vattenfall, one of Europe’s largest electricity and heat producers, announced an initiative to stop landfilling WTBs from their wind farms. Their goal was to recycle 50% of decommissioned WTBs by 2025, and 100% by 2050 [47]. In Germany, the Netherlands, Austria, and Finland, the landfilling of WTBs is already banned outright [2]. The writing is on the wall: despite its convenience and low cost, landfilling is rapidly becoming obsolete.

4. The Canadian Context

4.1 Canadian Wind Generation

By the end of 2023, Canada had 16,986 MW of installed wind capacity. This figure is expected to reach 40,000 MW by 2050 [48]. Figure 14 below shows the increase in wind capacity installations in Canada over time, both year-over-year and cumulative. The largest single-year increase in wind turbine capacity occurred in 2014, with over 2,000 MW installed [49] in that year.

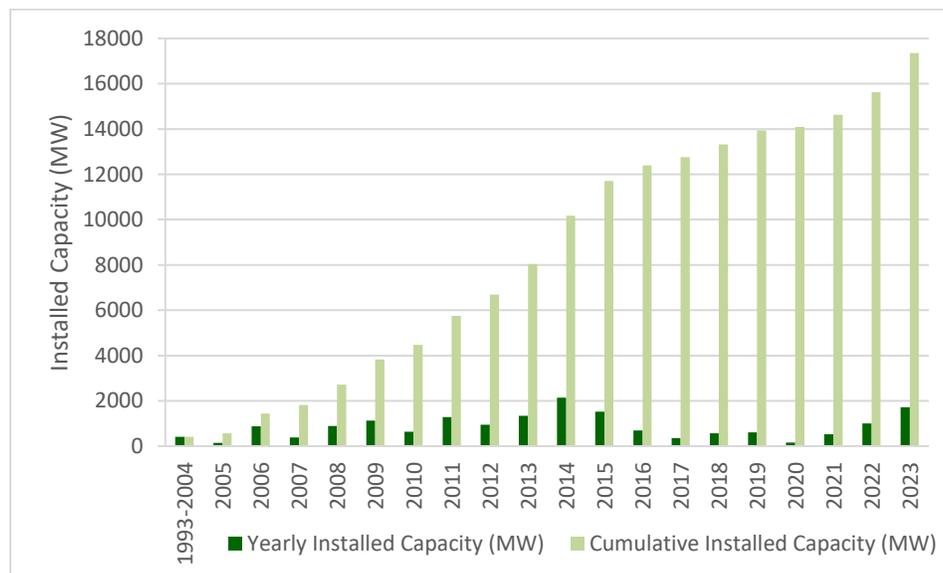


Figure 14: Installed wind capacity in Canada, cumulative and year-over-year [50]

In direct connection to this installation trend, Figure 15 below shows the anticipated retired WTB waste stream forecasted from 2020 to 2050. This figure was generated by Heng *et al.* (2021) to forecast the Canadian WTB waste stream and considers three key factors affecting the total waste inventory: the predicted growth rate of the installed capacity, the rate of waste generation during manufacturing and typical lifespan (*e.g.* service, damaging incidents), and blade lifespan. Wind turbines have an average life expectancy of 20 to 25 years [3]. The decade of 2030-2040 is expected to experience a surge of WTB feedstock – approximately 20 years after the wind installation surge Canada experienced in the 2010s, corresponding to the retirement of these wind farms [4], [48]. Additionally of note in Figure 15 is the concentration of waste in specific parts of the country; most WTB waste is expected to be produced in the provinces of Quebec and Ontario, compared to the relatively small contributions from Atlantic Canada (comprising New Brunswick, Newfoundland, Nova Scotia, and Prince Edward Island combined) [4].

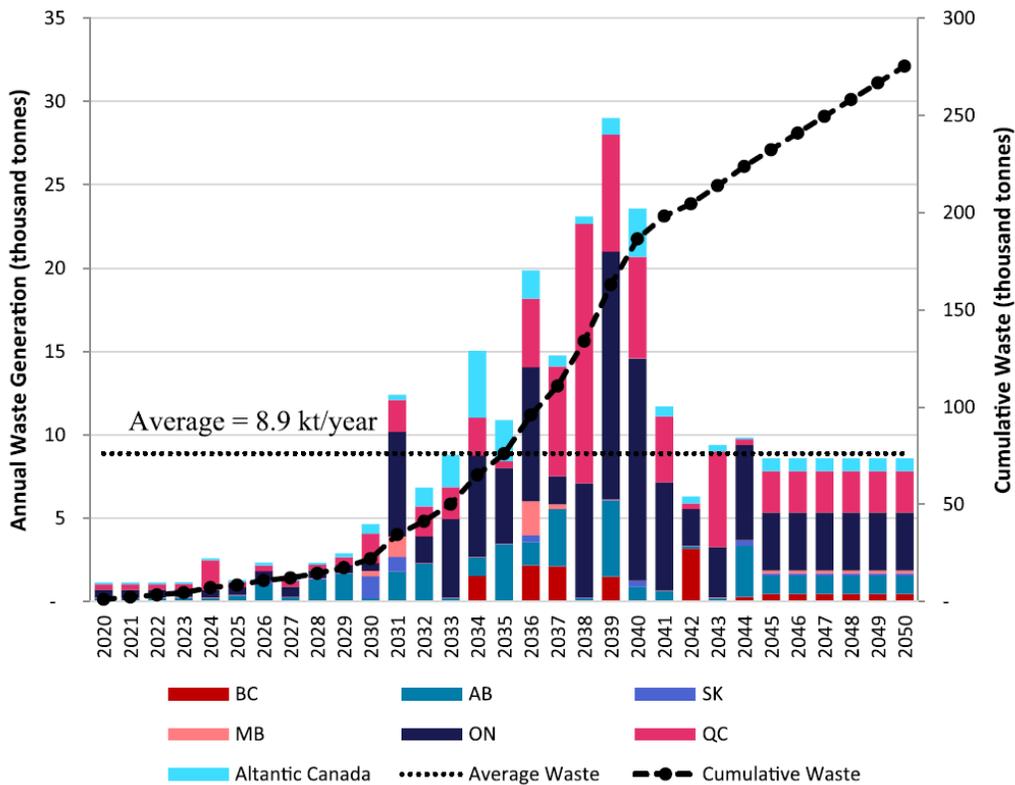


Figure 15: Canadian WTB blade waste accumulation over time by region [4]

The number of wind turbines is not the only thing that has been growing in Canada- WTB size has been increasing historically as indicated in **Error! Reference source not found.**, generated with data from the Canadian Wind Turbine Database. The weight of blade stock diverges from the number of wind turbines as the blade radii increase over time. WTB stature is growing alongside worldwide wind energy use.

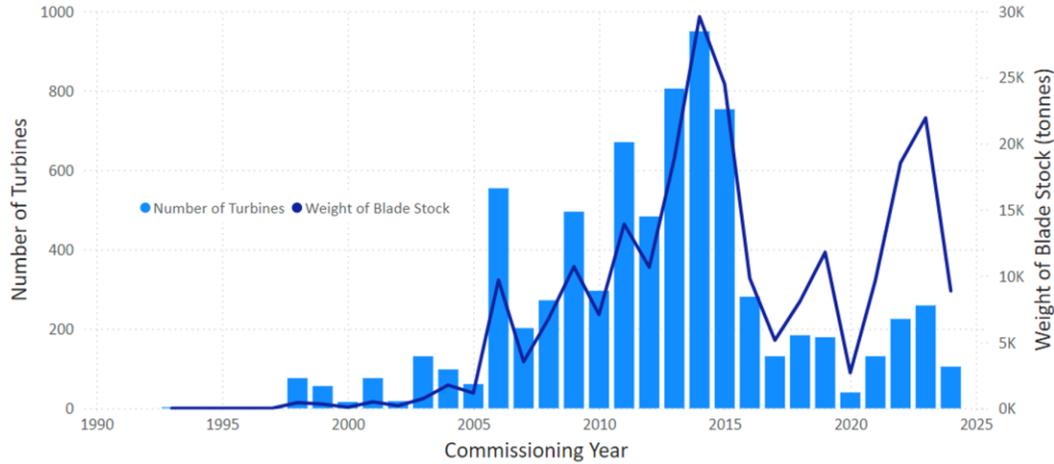


Figure 16: Number of Canadian wind turbines versus weight of blade stock over time [60]

The uneven distribution of wind turbines across Canada is a key factor when considering different EoL options. Wind farms are often located large distances from recycling facilities, thus incurring transportation costs and emissions to move the WTBs. Thus, any benefits from avoided greenhouse gas (GHG) emissions through recycling WTBs may be offset by the distance required to transport the WTB parts to recycling plants. In their study to assess the carbon reduction potential of EoL WTBs disposal scenarios in China, N. Cong *et al.* developed Equation 1 to estimate the critical transport distance (CD) - the distance you can transport a load of WTB recyclate after which you will be emitting more GHG from the transportation than you will be saving through the recycling process. M_i is the mass of material being transported (WTB recyclate, in this case), and CEF_i is the carbon emission factor of material M_i . CEF_t is the carbon emission factor of the transport vehicle being used, and W is the total weight of the transported goods. CEFs in N. Cong *et al.* account for the production, construction, operation and maintenance, transportation, decommissioning, and WTB recycling of a wind turbine, and as such, change depending on which recycling method is selected for the EoL WTBs. [51]. Equation 1 produces a result in units of distance. If the WTB recyclate must be transported a greater distance than the calculated CD, transporting the load will generate more GHG emissions than will be avoided through the act of recycling.

$$CD = \frac{M_i * CEF_i}{CEF_t * W}$$

Equation 1: Critical transport distance calculation [51]

4.2 Wind Turbine Decommissioning in Canada

Based on installed capacity and projected future installations as of 2021, Heng *et al.* predicts that Canada will produce over 275 megatonnes of wind turbine blade waste by

the year 2050 [4]. To put this amount in context, in 2016, the entire country generated 34 megatonnes of municipal solid waste [52]. Canada is projected to generate eight times the waste by weight by 2050 in decommissioned wind turbine blades than the entire country generates in municipal waste over a full year. Using the estimate of 10-13 tonnes of composite material per megawatt of installed capacity as described in Section 2, Canada's 17,000 MW of installed wind capacity (as of the end of 2023) will translate to between 170,000 and 221,000 tonnes of composite material entering the waste stream [50], [9], [10].

Since 2009, the province of Ontario has mandated a Decommissioning Plan Report (DPR) to be included as part of all renewable energy projects submitted to the Ministry of the Environment and Climate Change, excepting projects employing turbines between 3 and 50 kW in size. The DPR obligates wind farm owners to address three strategies: site dismantling procedures, site restoration procedures, and waste management procedures. However, these strategies focus on the remediation of the site on which the turbine was built. Focus is put on moving waste off-site and the restoration of the land back to pre-construction status. Materials such as wind turbine blades must be removed, and their destination indicated, but there is no obligation or impetus to recycle or otherwise reuse these components. Simply denoting that the materials are destined for a landfill is considered adequate for a completed DPR [53]. For example, a 2011 DPR simply indicated that 'wind turbine blades manufactured from composite materials... will require disposal in landfill' [54]. Another from 2012 simply states 'as the turbine is being disassembled, the various components will be transported off-site' [55], and a third from the same year states 'turbine components would be temporarily stored at the staging area at each turbine site until removed from the site by truck' [56].

Other provinces have similar mandates – the Alberta Utilities Commission requires a decommissioning plan to be submitted alongside wind development plans, covering, among other aspects, equipment and infrastructure dismantling procedures, restoration of municipal access roads and rights of way, removal of turbines and turbine foundations up to a depth of one metre, and general environmental remediation. Once again, explicit arrangements for the relocation and recycling of wind turbine components are not required for decommissioning plans to be accepted [57]. Nova Scotia has similarly vague requirements for decommissioning – the NS government's *Proponent's Guide to Wind Power Projects* states that decommissioning objectives should include the "removal of roads, equipment and structures... and should include comprehensive details with the goal of restoring the site to its natural state" [58].

Canada does not share the problem of land scarcity experienced by places like Europe [59]. In fact, the opposite is true – Canada has a comparatively large landmass with a small population spread across it. This means that locating sites for wind turbine farms is not an issue, but rather establishing and maintaining access to these sites becomes of primary concern. This problem presents itself during initial construction, again whenever maintenance is required, and once more during a turbine's end-of-life care

(decommissioning or repowering [upgrading and/or retrofitting existing wind turbine sites [59]]). This WTB waste is broadly spread across Canada's large landmass, evidenced in the bubble chart in Figure 17 which shows the blade weight in tonnes of each wind farm in Canada, totaling an estimated 236,000 tonnes (as of the end of 2024), which is closely aligned to the estimate of between 170,000 and 221,000 tonnes using the simplified tonne per MW approach. Tonnage in Figure 17 is directly proportional to the area of each bubble. This underlines the importance of the critical transport distance discussed in Section 4.1, especially when paired with the knowledge that there are currently no dedicated wind turbine recycling facilities in Canada [48].

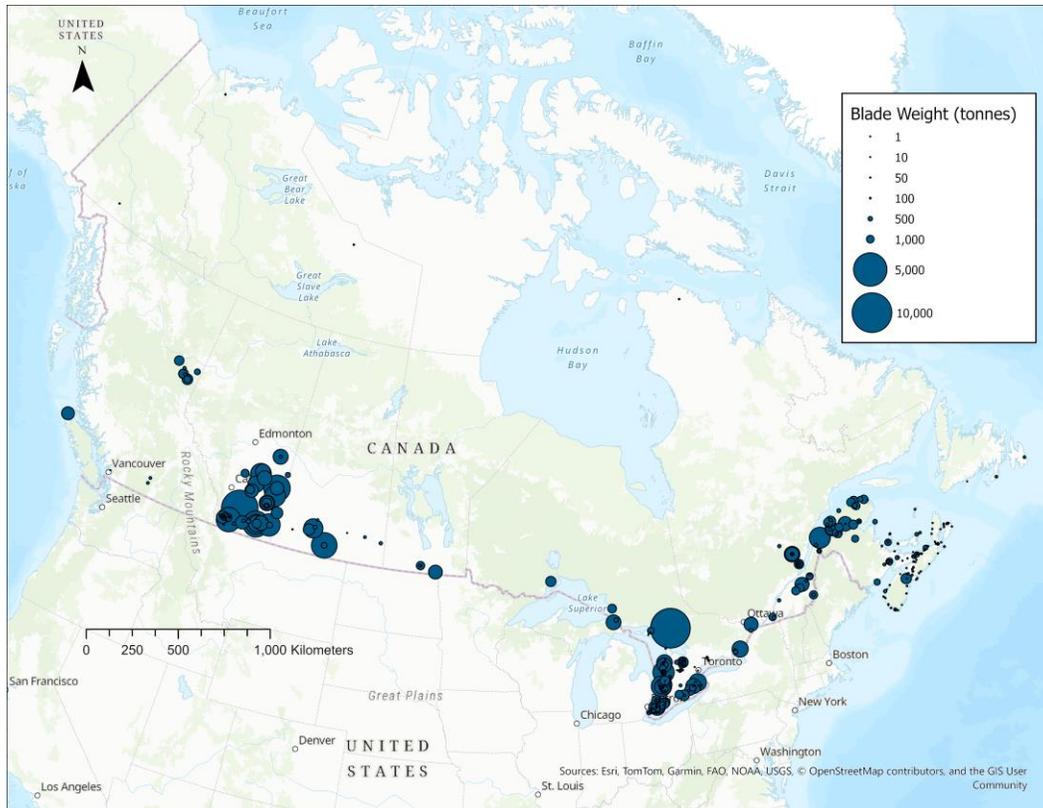


Figure 17: Spatial distribution of wind farms by blade weight across Canada based on installed capacity at the end of 2024 [60]

To generate the estimates in Figure 16, blade weights were amassed first by pulling information directly from project documentation. In the event that this information was missing, blade mass was calculated by employing the methodology proposed by Eberle *et al.* represented by Equation 2, where m_{blade} is the mass of the WTB, l_{blade} is the length of the WTB, and x , the fiberglass blade mass scaling exponent, is set to 2.39 in conjunction with the blade lengths provided in project documentation. The scaling exponent is a function of spar-cap reinforcement fibre (CF or GF, assumed to be GF for the purposes of this analysis as this is the typical material choice for onshore wind), and varies based on whether the turbine in question is offshore or onshore, and based on

design configurations and wind classifications. The value of 2.39 is therefore an average based on recent turbine design models [61]. In the few instances where documentation on blade length was unavailable, blade lengths were assumed to be half of the quoted rotor diameter.

$$m_{blade} = l_{blade}^x$$

Equation 2: Wind turbine blade mass scaling relationship with length [61]

5. Conclusions

5.1 Research Gaps & Opportunities

There are several opportunities for wind turbine circularity research that were identified in this review. First, recycling methods are focused entirely on standard wind turbine blades, rather than blades that have been adapted for use in Northern regions. Some passive ice protection techniques modify the physico-chemical properties of blade surfaces, and the implications that these modifications may have on current recycling processes have not been currently addressed in literature [63]. Similarly, the substance witnessed leaking in the Wikado playground as discussed in Section 2.4 above has been observed but not analyzed. Given the recent increase in popularity of ‘upcycling’ retired WTBs, proper investigation of the consequences of close human contact with aging blade coatings should be performed.

WTBs are recycled *en masse* as wind farms come to the end of their service life. Unlike municipal waste, which is a steady and predictable source of waste, WTB waste comes in fits and starts with periods of no additional waste being added, and sudden large surges of recyclate being added to the waste stream. The extreme variability of volume in WTB waste makes generating an industry around waste management difficult, as the flow cannot be anticipated or regulated when limited to smaller regions. A better understanding of the timing, volume and composition of wind turbine blade waste on a national scale would support the strategic siting and design of recycling facilities, provide data to support end of life decision-making by wind farm owners, and could be used to inform future regulatory and reporting requirements related to wind farm decommissioning, should Canada follow global trends. With improved forecasting of recyclate material, WTBs could be stockpiled and released at a set rate to recycling centres, to ensure a steady flow of recyclate. Stockpiles could be bolstered by adding composite waste from other sources. As a final resort, WTB waste could be exported to other countries, but it is better from a lifecycle emissions perspective that waste be treated as close to the site of origin as possible.

Research Opportunity 1- Interactive waste stream estimation tool: The development of an interactive tool that allows operators to select the turbine model and the recycling method and outputs an estimate of key parameters including the quantity of ground recyclate, pyrolytic oils, GHGs, retained GF or CF, and others could simplify the decision-making process for operators and encourage national uptake of WTB recycling.

In addition to a scarcity of retired WTB tracking data, current decommissioning requirements in Canada only address what's required to return the land on which the turbine was located to its previous state. As such, there is a lack of knowledge on the costs, logistical challenges and impacts associated with different recycling pathways. Should more stringent requirements regarding decommissioning plans be prescribed in the future, for example if permitting applications for new wind farms require the submission of a plan explaining how the blades will be dismantled, transported offsite, and recycled, wind farm operators will benefit by having access to more reliable data to inform operational decisions.

Research Opportunity 2- Wind farm decommissioning logistical analysis: In service to the goal of increasing wind farm operator access to data informing operational decision making, a comprehensive analysis on the logistics and costs of a robust wind turbine decommissioning process in several different sites across Canada could be performed. In this analysis, every piece of the turbine is tracked from its point of origin to its recycling centre. Costs, transportation emissions, and avoided emissions from the recycling would be tracked in order to form a thorough picture of the actual costs and benefits associated with robust decommissioning.

Research on WTB recycling methods is primarily focused on the efficacy of transforming WTB recyclate into usable recycled materials. However, there is a lack of focus on examining the byproducts generated by these processes. This review identified knowledge gaps related to the chemical makeup of pyrolytic oils and gas, as well as the GHG emissions, water use, and energy intensity pertaining to the recycling methods discussed in Section 2.

Research Opportunity 3- WTB recycling method environmental impact assessment: The extent of a WTB recycling method's potential for pollution, whether through energy use, direct pollutant generation, or water use, should be established for every process using a credible and rigorous methodology.

WTB composition can be simply divided into two groups: CF and GF. However, there are increasingly more varieties of composites being introduced to the market. Some WTBs are now being built with biodegradable resins or fibres [64], and others still with specialized coatings to prevent ice accretion [63]. These blade compositions change how they react to certain recycling methods. An established methodology for classifying WTBs by their composite makeup recyclability would simplify and expedite the process of end-of-life care for wind farms. Similarly, the size, length, and direction of carbon and

glass fibres play a key role in determining their suitability for re-use in industry (see Section 3.1). Each recycling process yields a different mix of recycled fibres. A formalized grading system would expedite the aftermarket industry for WTB recyclate, as recycled composites could be neatly grouped under grades that are suitable for varying applications, making them easier to source and purchase.

Research Opportunity 4- Exploration of recycled composite fibre industrial

applications: Investigate industrial uses for different grades of recycled fibres (*i.e.* recovered fibres resulting from different recycling processes). Identify other sources of composite wastes or recyclates (*i.e.* automobiles, boats, aircrafts) and determine if and how WTB recyclate can be mixed into the circularity stream of these objectively larger waste sources. Develop a list of parameters that defines recycled fibres as suitable for certain industrial applications, or for mixing with other composite recycling sources.

To ensure that no single country is wasting time investigating a problem already solved by another, knowledge sharing is key. An open forum in which nations could share lessons learned, new technologies, organizational techniques, or any other relevant data to the problem posed by wind turbine circularity speeds the global pace of progress in this industry and fosters international relations. The International Energy Agency (IEA) steers the Wind Technology Collaboration Programme (TCP), comprised of many subtasks participated in by various countries. One such subtask is Task 45: Recycling wind turbine blades [65]. The goals of this task align with those outlined in this paper but lack specificity to Canada's unique challenges.

Research Opportunity 5- Coordination of international research: Investigating which international forums have already been established, such as the IEA TCP, will reveal where these international forums may be lacking and potentially permit the establishment of an international open forum. This would ensure that lessons learned, new technologies, organizational techniques, or any other relevant data to the problem posed by wind turbine circularity are shared in a timely manner, and research is never duplicated across countries.

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Contact:

Keelia LaFreniere
 Research Engineer
 Building and Renewables Group
 Natural Resources Canada, CanmetENERGY
keelia.lafreniere@nrcan-rncan.gc.ca

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Natural Resources Canada's CanmetENERGY is the Canadian leader in clean energy research and technology development. Our experts work in the fields of clean energy supply from fossil fuel and renewable sources, energy management and distribution systems, and advanced end-use technologies and processes. Ensuring that Canada is at the leading edge of clean energy technologies, we are improving the quality of life of Canadians by creating a sustainable resource advantage.

Head Office	Devon, Alberta	Ottawa, Ontario	Varenes, Quebec
580 Booth Street	1 Oil Patch Drive	1 Haanel Drive	1615 Lionel-Boulet Boulevard
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