



Closing the Loop: A Comprehensive Review of Circular Repurposing Options for Decommissioned Wind Turbine Blade Materials

REVIEW

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ABSTRACT

Growing global concern about how to dispose of wind turbine blades has sparked an investigation into more sustainable alternatives. This research delves into finding eco-friendly solutions for managing the waste generated by wind turbine blades, specifically by exploring options for repurposing them. To put this into action, this study has focused on a New Zealand wind farm with 196 wind turbine blades at the end of its life cycle. Through a thorough review of documents, 60 potential ways were identified to repurposing these blades. Options falling under the downcycling category were excluded, thus narrowing down to 45 promising solutions to repurpose. Further 7 practically applied global solutions are identified. Implementing these repurposing solutions would divert 331 tonnes of waste material from landfills from the New Zealand Wind Farm. This study is significant because it highlights the potential for a circular and sustainable approach and provides an example of how wind turbine blade waste can be diverted from landfill. The findings of this study contribute to practical insights and support initiatives across New Zealand to encourage the adoption of wind turbine blade repurposing. This, in turn, will foster environmentally conscious waste management practices within the renewable energy sector and promote a more sustainable future.

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1 INTRODUCTION

1.1. THE BLADE WASTE PROBLEM

Wind energy is a promising source of renewable electricity generation in New Zealand. The country's geography provides favourable conditions for harnessing wind power. New Zealand already has several operational wind farms, and the potential for further development is significant. The shift to renewable green energy largely results from the Paris Agreement, which commits its 196 signatory countries to limit the increase in global average temperature rise (United Nations, 2015). The rapid deployment of onshore and offshore wind energy was made possible by supporting national and regional policies (Tazi et al., 2019). Unlike fossil fuels, wind energy generation does not produce harmful greenhouse gas emissions or air pollutants and is anticipated to significantly reduce environmental pollution.

Wind turbines are presently engineered to operate efficiently and reliably for 20–25 years, with the potential for further extensions beyond that period (Kolios & Martínez-Luengo, 2016). However, most wind turbines are decommissioned after the designed lifetime of around 20 years (Dolan & Heath, 2012). Wind farms around the globe are upgrading to larger turbine sizes as they offer higher efficiency and higher power generated. The upgrades for higher efficiency wind turbine blades often render the older wind turbines useless and discarded. The primary end-of-life (EoL) materials in wind energy projects include ferrous and non-ferrous metals, polymers, glass, and concrete (Tazi et al., 2019). The metal components from the wind turbine can be recycled or repurposed as spare components, promoting resource efficiency and reducing waste (Bradley, 2014), unlike the blades mostly made of carbon or fibreglass (Eligüzel & Özceylan, 2022). It is anticipated that by 2025, the world will be dealing with 100,000 tonnes of blade

waste annually, and by 2033 this figure is anticipated to be 200,000 tonnes per annum (Deeney et al., 2021). Some researchers have estimated the figures to be around 43,400,000 tonnes of blade waste by 2050 (Liu & Barlow, 2017). Dealing with the blades at the end of their 20-year design life is becoming increasingly challenging. Since decommissioning is the ultimate phase of any wind energy project, it is crucial to prioritise sustainability by maximising the repurposing or recycling of the extracted components (Spielmann et al., 2021).

1.2. WIND TURBINE BLADE WASTE HIERARCHIES

Waste hierarchies provide a construct for end-of-life options. Although there are various principles of waste management, such as 3R-7R (Balwan et al., 2022; Mohanty, 2011; Vermeulen et al., 2018), the general theme of the hierarchies is consistent – reduce and manage waste from the most environmentally preferential method. Some of the end-of-life wind turbine blade options observed from the literature are repurposing, recycling/recovery, refurbishment and reuse, and disposal. In priority order, the hierarchy is prevention, reuse, recycling, recovery, and disposal (European Union, 2008). The waste hierarchy of the end of service life options for wind turbine blades are shown in Figure 1.

The refurbishment or reuse of wind turbine blades is when the original product function of power generation is maintained. A wind turbine may be sold in its entirety, or undersized blades can be refurbished and sold to develop the wind energy market at a reduced cost (Andersen et al., 2014). This will be beneficial for farms that are upgrading their wind farms for higher energy generation. However, this option is feasible only when the wind turbine blades are not extremely deteriorated, and they match the specific requirements of the potential 'buyer'. Lifetime extension through refurbishment or remanufacturing

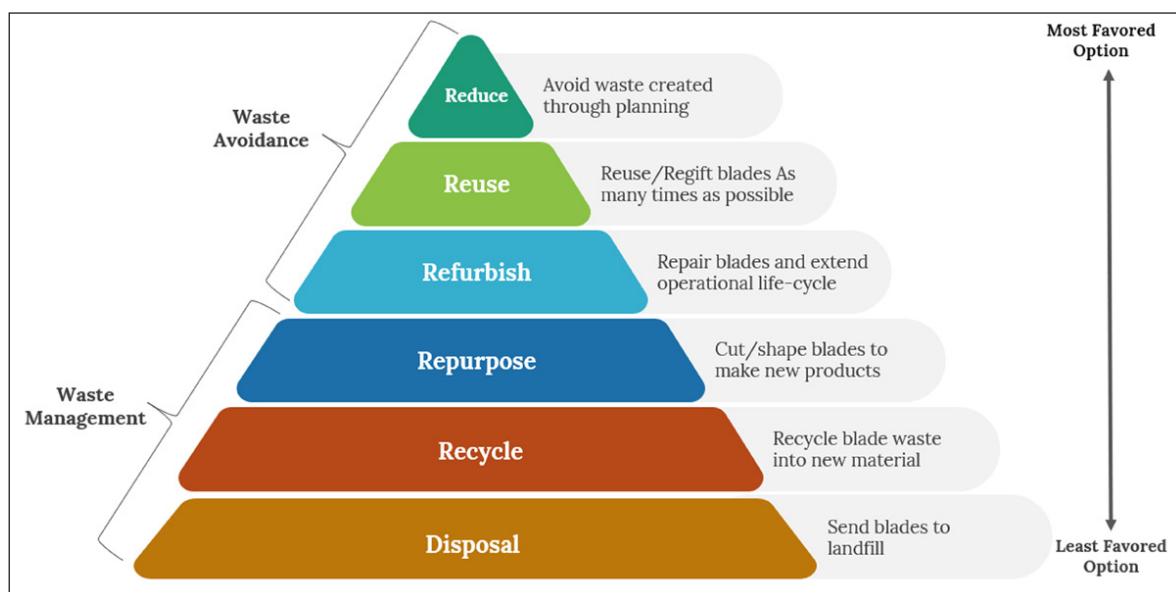


Figure 1 Wind turbine blade end-of-life waste hierarchy.

is the optimal solution for decommissioned blades. However, lifetime extension is still in its infancy (Jensen, 2018). Used wind turbine blades, decommissioned because of wind farm upgradation may still have a significant lifespan remaining. Such blades could be valuable for such smaller-scale applications. Countries with substantial experience in wind power, such as Denmark and Germany, have already been involved in this practice (Marsh, 2017).

Repurposing is an option when reuse is not feasible. A blade is used whole or sectioned into parts, reshaped, and repurposed for other products for a new function (such as parts of temporary or inexpensive housing, office and home furniture, benches and playgrounds, pedestrian bridges, or powerline structures). This makes use of the structural and material properties of the blade (Jensen & Skelton, 2018). This approach extends the overall life of the blades, extending their life cycle.

Recovery or recycling requires energy and other resources and is preferred where recovery or repurposing is impossible. To convert the blade waste into something else, the blade is cut, shredded, or grounded into small pieces or granular material for use as a filler in concrete or other composites. Alternatively, some of the material may be subjected to thermochemical methods such as pyrolysis, solvolysis, and thermolysis to reclaim glass fibre component of the composite blade for subsequent use in other applications (Larsen, 2009). Some parts of the blade may be recovered, and the rest may be discarded. Some processes also focus on converting the composite using different temperatures and pressure into virgin materials (Jensen & Skelton, 2018).

Choosing to reuse and repurpose wind turbine blades at the end of their life is preferred over recycling because these options capitalise on the high-value engineered properties of the blades (Woo, 2020). This contrasts with recycling, which typically involves processing the blades into lower-value component materials, leading to downcycling. A blade can said to be downcycled when the wind turbine blades' initial structural value is not utilised to its original value (Woo & Whale, 2022). Due to differences in their application potential compared to their virgin counterparts, the recycled products cannot be explicitly considered identical or of equal value (Kalkanis et al., 2019). Research shows that wind turbine blade recycling renders a product of much lower quality (Jani et al., 2022; Jensen, 2019). Consequently, they may be regarded as having undergone downcycling. The damaging impact on the process of wind blade recycling since some blades contain fibreglass composites that can become hazardous dust and difficult to recycle. According to Andersen et al. (Andersen et al., 2014), there is high cost involved in the fibreglass recovery and recycling process. With accelerated research, the recovery of the whole composite materials from wind turbine blades individual components will become an

economical and viable option in future. However, it's important to note that these processes can also bring about unintended consequences such as increased carbon emissions, labour cost and energy use (Karavida & Peponi, 2023).

Disposal is when the blade is sent to the landfill and buried or when the blade is placed and left on the ground, the glass fibres and resin present in the wind turbine blade composites may take hundreds of years to degrade. There are a few methods available for end-of-life disposal of wind turbine blades, such as incineration with or without energy recovery, combustion, and landfill (Demuytere et al., 2024; Ramirez-Tejeda et al., 2016).

Discarding wind turbine waste is cheap and convenient in countries with an abundance of available land for disposal sites (Ramirez-Tejeda et al., 2016). Recently though, disposing of end-of-life blades in landfill is becoming increasingly passé. Landfills have become almost obsolete due to the significant restrictions placed on what material can be landfilled as part of the European Union Directive on Landfill Waste. For example, the Netherlands has banned composite materials from landfill, and France has banned any waste containing more than 30% plastic from landfills (Justine Beauson et al., 2022). Some European countries incinerate wind turbine waste as an alternative (Andersen et al., 2014; Grigaitienė et al., 2022; Overcash et al., 2018). However, in countries like Germany, Austria, Netherlands, and Finland, the landfill or incineration of composite waste is completely banned (Schmid et al., 2020). European Union Waste Framework Directive sets out waste management goals that each member must achieve (Justine Beauson et al., 2022), developing national waste legislation and policy. However, despite the increasingly stringent legislation and expense, the majority of blades still end up in landfills (Liu & Barlow, 2017). Where disposal in landfills remains an option, it is becoming increasingly expensive (Liu et al., 2022), and the bulk and composite nature of blades make them unattractive to landfill operators.

1.3. THE NEW ZEALAND CONTEXT

New Zealand, alongside the European Union and fourteen other nations, is a member of United Nations Environment Programme, 2023. "Aotearoa New Zealand's first emissions reduction plan" focuses on strategies, policies, and actions to achieve New Zealand's first emissions budget and outlines New Zealand's contributions to global efforts to limit warming (Ministry for the Environment, 2022). Late 2022 amendments to the New Zealand Building Code included the requirement for certain building and demolition work to have a waste minimisation plan and an amendment that made more explicit the importance of the building code in contributing to emissions reduction (Woods, 2022). These strategies emphasise the importance and drive

towards implementing circular economic practices, for which wind turbine blades will be a good example for New Zealand. Most significantly, taking responsibility for our waste”, a consultation document seeking feedback on proposals for a new national waste strategy and associated waste legislation. A dominant theme in the document is the need to shift to a low-waste, circular economy (Ministry for the Environment, 2021). The circular economy and its “make-use-return” mantra for resource expenditure is a conceptual shift from the existing predominant linear economy and its “take-make-dispose” philosophy (Gomis et al., 2023). Circular economy concepts optimise the use of resources in the world and improve sustainability (Gomis et al., 2023). The circular economy aims to remove waste and pollution, recirculate material in the economic system, and use regenerative resources (Blumhardt & Prince, 2022). To reduce natural material extraction, waste generation, and carbon emissions into the environment, circularity solutions aim at closing the circular economy loop through reuse, repurposing, recycling or remanufacturing (Arent et al., 2022). According to (Gharfalkar et al., 2015), prevention strategies should be taken before, a material or product turns into waste, aiming to stop or reduce waste generation.

1.4. RESEARCH PROBLEM

New Zealand has set a goal to reach net-zero greenhouse gas emissions by 2050 as outlined in the Climate Change Response Act (“Climate Change Response Act 2002,”). The country is progressively shifting towards renewable energy sources like wind farms for electricity generation (Walmsley et al., 2017; Zhang et al., 2023). This has led to the development of new wind farms in NZ for power generation (MacLean, 2023). Some wind farms are upgrading their wind turbines by replacing smaller blades with bigger blades to achieve this goal and improve efficiency (Meridian, 2023). The upgrading would lead to smaller wind turbine blades getting decommissioned.

Based on expert interviews and a meta-analysis of wind energy LCAs, identified the need for end-of-life scenarios for composite blade waste in sustainability assessments highlighting a significant challenge for the industry as waste disposal responsibilities shift towards manufacturers (Sakellariou, 2018). Research has been conducted globally to understand the end-of-life impact of wind turbine blades and to explore secondary uses for these materials (Nagle et al., 2020, 2022). Most studies are focused on America and Europe due to the mature wind industry in these regions and the urgent need for effective solid waste management in highly populated and limited land areas (Martini & Xydis, 2023; Sakellariou, 2018). Although there is some research on recycling of wind turbine blades in New Zealand, the recycling solutions are not feasible yet due to the high costs and the lack of a market for secondary materials (Pincelli et al.,

2024). However, there is a noticeable gap in the literature regarding the repurposing of wind turbine blades, with no identifiable scientific publications addressing this issue. The existing study pertaining to wind turbine repurposing in New Zealand has identified the drivers and challenges associated with the repurposing of wind turbine blades in built environment through a thematic analysis of interview data of subject matter experts (Meldrum et al., 2024).

This study explores the repurposing possibilities for wind turbine blade waste to avert decommissioned blade waste from going to landfills. This study aims to understand what repurposing solutions are available in the literature and how many are feasible. Thus, the sustainable use of wind turbine blade waste will be identified to close the material loop for circularity.

2 METHODOLOGY AND ANALYSIS

2.1. LITERATURE REVIEW

In-depth document analysis is conducted to determine possible solutions for end-of-life wind turbine blades in New Zealand (Joustra et al., 2021). A comprehensive literature review was performed for document analysis using a keyword search in Google Scholar as the main data repository. Regarded as a superset of major databases, including Scopus, Web of Science, EBSCOhost, JSTOR, Science Direct, Taylor and Francis, ProQuest, and Emerald. Google Scholar was primarily utilized for article identification, while relevant research papers were retrieved from specific databases (Saulick et al., 2023). The keywords used for the database search were “wind turbine blade”, “end of life”, “blade waste repurposing”, and “decommissioning”.

A snowball approach is then applied to overcome the limited outcomes from the relevant keyword search. A snowball literature review, also known as snowball sampling or snowballing, is a research method where relevant study sources or references or citations are identified within those sources to find additional relevant literature (Ghafoor et al., 2023; Wohlin, 2014). The iterative process of exploring the references in each new source creates a “snowball effect” of gathering information. This method was applied to identify potential repurposing solutions as the research aims to discover less known but relevant studies.

Publications and news articles on implemented repurposed solutions and webpages discussing the implementation of solutions, etc., are generally unavailable in academic literature from Google Scholar. Hence, a Google Search was conducted to identify proven concepts and implement repurposing solutions across the globe. Document analysis involved evaluating journal articles, public records, government policy documents, books, conference proceedings, news articles and web

material from around the world to identify all potential repurposing options.

Options falling under the downcycling and recycling category are excluded. In contrast, partial modification or reuse of end-of-life wind turbine blades as a whole is regarded as upcycling (Karavida & Peponi, 2023). Whereas partial modification or reuse of end-of-life wind turbine blades as whole can be considered as upcycling (Karavida & Peponi, 2023). After elimination, the identified repurposing options will be considered. All viable wind turbine blade waste repurposing solutions from the literature review are presented as images generated using Artificial Intelligence (AI) tools [Runwayml.com](https://runwayml.com) and [Dezgo.com](https://dezgo.com) by entering descriptive texts. Figure 2 shows the steps followed in this study for identifying the end-of-life repurposing solutions.

2.2. A CASE STUDY

This research employed document analysis and a single case study method where a wind farm in the Palmerston North region of New Zealand was considered. One of the only seventeen in New Zealand, this wind farm will be called the New Zealand Wind Farm (NZWF). This wind farm has a capacity of 48.5 megawatts and is in the early stages of repowering the wind farm with larger turbines. As a result, the 196 blades of a total mass of 331 tonnes will soon need to be disposed of, recycled, or repurposed. The size of the blades extracted from the drawings provided by the wind farm. The wind turbine blades are 15 m long, 1 m wide at the widest point, and 0.55 m thick. The study of the repurposing of the 196 wind turbine blades provides an opportunity to conduct an in-depth study of a bounded system (Merriam & Tisdell, 2016).

This research utilised one case study for a more in-depth and comprehensive project analysis. Given the limited number of case studies available in New Zealand on the topic of wind blade repurposing, this approach

provides valuable exploratory insights into this emerging field. Moreover, previous research in related sustainability and wind turbine studies has successfully employed a single case study methodology (Feng et al., 2018; Hanes et al., 2021; Morini et al., 2021; Rahman & Wahid, 2021; Walzberg et al., 2023). The use of a qualitative single case study supports the intention of taking the next step towards viable, practical implementation of blade repurposing options while examining the existing New Zealand-specific tools could help with the repurposing and identify the benefits of each option for broader New Zealand-wide initiatives to improve the uptake of blade repurposing.

3 RESULTS

3.1. WIND TURBINE BLADE REPURPOSING SOLUTIONS

According to the wind farm owners, the total mass of the 196 NZWF wind turbine blades is 331 tonnes. Sixty repurposing options were identified from the literature, and most of them can be traced back to ideas presented by the Re-Wind consortium the Design Catalogue (Re-Wind, 2021). One organisation that spearheads the drive to investigate blade repurposing options is an international academic consortium called Re-wind (Bank et al., 2020; Network, 2021). The repurposing options described in the literature and suggested by industry sources were found to have been better articulated in either the Design Atlas or the Design Catalogue (Bank et al., 2020; Network, 2021). Re-wind has produced a design atlas and a design catalogue that conceptualises structures and products that can be constructed from repurposed wind turbine blades.

Although sixty potential repurposing options were identified from the literature, only solutions involving

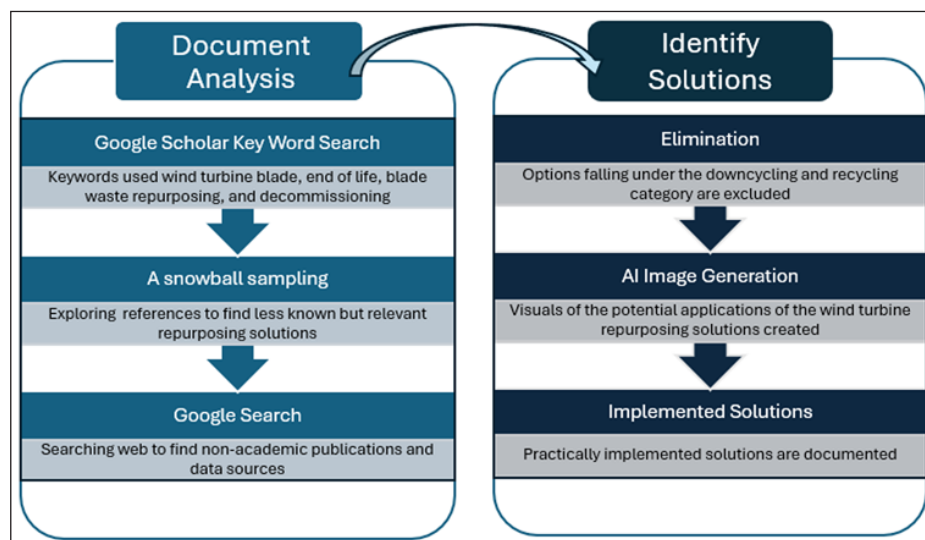


Figure 2 The process of the comprehensive literature review to identify end of life wind turbine blade repurposing solutions.

partial repurposing and full reuse were selected for further analysis. For instance, there exists commercial companies like Miljøskærm producing noise barriers using recycled blade material (Larsen, 2018). The noise barriers are created by shredding the blades and compressing the recycled fiberglass into sheets. Other options like fibres for fabric creation (Arabsolgar & Musumeci, 2020), Surf/skateboards (Jani et al., 2022), gummy bears (Khalid et al., 2023), railway sleepers (Wind-Recycling-Working-Group, 2023) were eliminated. These solutions were considered downcycling of the wind turbine material (Jani et al., 2022).

After elimination, 45 repurposing options were identified from 32 sources presented in Table 1. The images in the table were created using artificial intelligence (AI) image generators Runwayml.com and Dezgo.com by entering descriptive texts.

3.2. PRACTICALLY IMPLEMENTED SOLUTIONS

Most repurposing examples shown in the table are primarily demonstration projects and have not yet been implemented as practical solutions. However, a few countries have demonstrated the applicability of a few of these solutions. At the practical implementation level, Re-wind has been involved with designing and testing repurposed blades used as bridge girders for a footbridge constructed in County Cork, Ireland. The first was installed in late 2021 in Western Poland, while the County Cork Bridge was the second “blade bridge” to be constructed (Stone, 2022). K.Ruane et al. demonstrated that blade bridges can readily be constructed and have explained elaborately the design, testing, and construction processes of bridges while also presenting cost-related information for the structures (Ruane et al., 2023). Using wind turbine blades for bridges has seen cost reduction of 30% across the lifetime of the repurposed material bridge and has a high value in terms of the integrated sustainability indices (Deeney et al., 2021). In the United States, testing is being done for a blade bridge implementation by the Re-Wind team using 45 m long blades (Ruane et al., 2023). Similarly, prototyping for electrical transmission poles is also being performed in the USA (Alshannaq et al., 2021).

Other repurposing options that have progressed to the implementation stage are playgrounds and benches that have been designed by a Netherlands-based company (André et al., 2020). In Netherlands, architects have repurposed 27 blades to create playgrounds, urban furniture, place markers, and a bus shelter (Guzzo, 2019). Bike sheds, or shelters, have been built from discarded wind turbine blades and are being used in Denmark and Ireland. The project undertaken in Denmark is with the cooperation of the Danish Government (Ebert, 2021). Bike stands do not have any load considerations and have minimal design code requirements. The blades can be used entirely or in segments for the bike shelter. In the

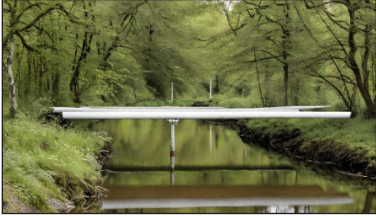
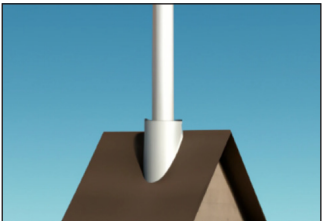
United States, several cities have begun incorporating the furnishings into their public spaces (Bennett, 2024). A similar initiative has been taken in China as well, where public seating is created from whole wind turbine blades (Guzzo, 2019). In the United Kingdom (UK), wind turbine blade sections have been implemented as reinforcing bars in concrete, replacing steel for the railway network infrastructure project (Djunisic, 2021). Other research, while not progressing with a specific solution to implementation, has shown that the material properties of repurposed blades are suitable for structural repurposing (Joustra et al., 2021) and that conventional structural analysis of repurposed blades is possible. The summary of the repurposed examples is shown in Table 2.

Wind turbine blades undergo varying dynamic loading or impact during their operational lifetime, such as lightning (Le Diagon et al., 2014). Before considering repurposing solutions, conducting a non-destructive damage analysis on the wind turbine blades is crucial to ensure their suitability for high-load applications (Luengo & Kolios, 2015). Testing is essential for ensuring safety and aiding in the planning of necessary repair activities if necessary (Colledani & Turri, 2022; Ruane et al., 2023). Existing studies provide methodologies to conceptualise and design end-of-life material (Le Diagon et al., 2014) and strategies for selecting appropriate wind turbine blades for repurposing solutions through frameworks (Johst et al., 2023). In their research, the authors created a manufacturing strategy and process for repurposed wind turbine blade climbing towers, playgrounds and photovoltaic floating pontoons (Johst et al., 2023). Further research around design and manufacturing processes is needed for all the repurposing solutions for real-life applications.

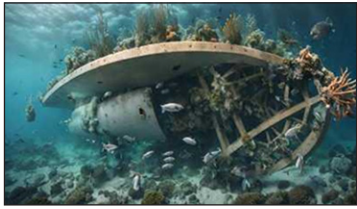
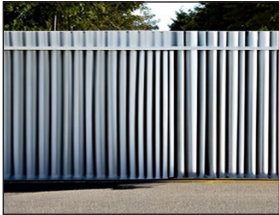
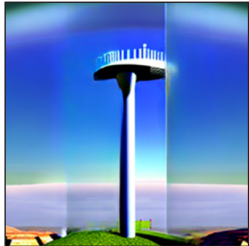
3.3. CIRCULARITY OF REPURPOSING SOLUTIONS

Ideally, all products should be created to avoid disposal in a landfill after use. Used materials should seamlessly integrate into the initiation of the subsequent production cycle. This concept is known as “cradle to cradle.” In the case of blades, the best outcome at the end of their lifespan is to be incorporated into creating new blades with equal or improved performance compared to the original, thereby upcycling the material (Martín et al., 2016). If recycled material is reused in developing new wind turbine blades, then the loop can be said to be closed. However, currently, no processes are available to upcycle the material economically. The materials that can be recovered from the composite are disproportionately low in value compared to the cost of extracting them (Jensen, 2018).

In the meantime, repurposing the end-of-life wind turbine material follows the strategy of slowing the loop. The slowing Loops concept is about prolonged use and reuse of material over time by product design or product

REPURPOSING OPTION	REPURPOSING OPTION	REPURPOSING OPTION
Shelters (Nagle et al., 2022; Ramirez-Tejeda et al., 2016)	Playground (L. C. Bank et al., 2018; Guzzo, 2019)	Public seating (Guzzo, 2019; Mishnaevsky Jr, 2021; Wass, January 2024)
		
Bike shelter (Bank et al., 2020; Ebert, November 2021)	Bridges (Jensen & Skelton, 2018; Leahy et al., 2021; Ruane et al., 2022; Zhang et al., 2022)	Place Markers (Guzzo, 2019)
		
Reinforcing bars (Djunisic, 2021; Gentry et al., 2018)	Transmission towers (Al-Haddad et al., 2022; Alshannaq et al., 2021; Martini & Xydis, 2023)	Furniture (Liu, 2023; Wings-for-Living)
		
Chimney Liners (Nagle et al., 2022)	Pedestal (Martini & Xydis, 2023)	Roofing material (Martini & Xydis, 2023)
		
Skate parks (Arabian & Shu, 2022)	Arched gateways (Nagle et al., 2022; Network, 2021)	Wind barriers (Bank et al., 2020)
		

(Contd.)

REPURPOSING OPTION	REPURPOSING OPTION	REPURPOSING OPTION
Artificial reefs (Klain et al., 2020; Rahnama, 2011)	Culverts (Nagle et al., 2022)	Bleachers (Bank et al., 2020)
		
Liquid storage tanks (Nagle et al., 2022)	Pedestrian barriers (Arabian & Shu, 2022)	Impact attenuators (Arabian & Shu, 2022)
		
Photovoltaic plant (Joel H, 2020; Ratner et al., 2020)	Farming troughs (Network, 2021)	Cattle/grain partitions (Re-Wind, 2021)
		
Ventilation louvres (Arabian & Shu, 2022)	Fences (Nagle et al., 2022)	Urban Lighting (Guzzo, 2019)
		
Doors/Windows (L. C. Bank et al., 2018)	Noise barriers (Network, 2021)	Lookout tower (Guzzo, 2019)
		

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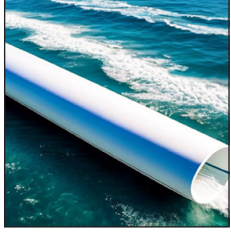
REPURPOSING OPTION	REPURPOSING OPTION	REPURPOSING OPTION
Evaporation cover (Deeney et al., 2021) 	Building façades (Nagle et al., 2022) 	Wave attenuator (Nagle et al., 2022) 
Piles (L. Bank et al., 2018) 	Retaining/strengthening wall (Anmet; Rorrer, 2021) 	Quiet pods (Nagle et al., 2022) 
Vertical landfills (Nagle et al., 2022) 	Glamping pods (Nagle et al., 2022) 	Aqueducts (Nagle et al., 2022) 
Promenade (Guzzo, 2019) 	Planter pots (Guzzo, 2019; Wings-for-Living) 	Climbing Tower (Johst et al., 2023) 
Animal Crossing (Anmet) 	EV charging station (Guzzo, 2019) 	Art (Anmet) 

Table 1 End-of-life wind turbine repurposing options from literature review.

life extension (Bocken et al., 2016). The cradle-to-cradle approach aims to close the loop by recycling materials infinitely, decoupling production from virgin material utilisation. The repurposing of the materials substitutes

the need for virgin material inflow for the proposed solutions. This strategy decelerates the pace at which raw materials are converted into products and subsequently consumed (Cooper, 2010). Where reuse is not possible,

REPURPOSING OPTIONS	COUNTRIES USED	REFERENCE
Bridges/bridge girders/Blade bridges	Ireland, Poland, USA, UK	(Stone, 2022), (Bennett, 2024; Ruane et al., 2023)
Playgrounds and benches/urban furniture/place markers/bus shelter/Bike stands	Netherlands, Denmark, Ireland, USA, China	(Guzzo, 2019; Ramirez-Tejeda et al., 2016) (Arent et al., 2022), (Bennett, 2024)
Structural reinforcing bars in concrete	UK	(Djunisic, 2021)
Railway infrastructure	UK	(Djunisic, 2021)

Table 2 Repurposing options progressed to the implementation stage around the world.

repurposing could be the solution to prevent wind blades from directly ending up in landfills and extend the wind turbine material life.

Repurposing wind turbines at the end of their life has proven to bring about positive outcomes for both the environment and the economy (Mamanpush et al., 2018). As an example of the amount of material that repurposing could divert away from landfill, it has been calculated that if 20% of all Irish wind turbine blade waste (90 blades per year) was repurposed, it would prevent 135 tonnes of blade waste entering landfill (Nagle et al., 2022). Thus, repurposing wind turbine blades is a contribution consistent with operating in the circular economy, aligning with the recirculate strategy (Blumhardt & Prince, 2022). To make a meaningful impact, however, the core principle of keeping products in use at the highest possible value needs to be adhered to, and the position of repurposing is above recycling in the waste hierarchy (Cole et al., 2019). “Most value is preserved when the [repurposed] product or material remains close to its original state” (Joustra et al., 2021). However, when a material becomes unused, it is better to use it in End-of-life repurposing applications rather than dispose of it. Repurposing options are simpler than recycling options as wind turbine waste can be collected directly or processed at a production site near the farm, negating the need for transportation to a recycling facility (Cooperman et al., 2021). Also, repurposing methods are composite blades, which are generally deemed safe with precautionary measures to prevent users from potential exposure to sharp glass fibres (Martinez-Marquez et al., 2022).

Although there is a framework for end-of-life wind turbine blade solutions such as reuse, recycle, and landfill (Ghosh et al., 2022), there is a deficiency in clearly defined circular design methodologies for repurposing solutions that effectively enhance the opportunities for re-purposing (Li et al., 2022). There are many models developed to achieve a circular economy, of which the butterfly diagram developed by the Ellen MacArthur Foundation clearly shows the circular economic processes that can be applied (Ellen-MacArthur-Foundation, 2022). The diagram shown in Figure 3 is based on McDonough and Braungart’s concept that aims to achieve zero waste, which was developed observing the evolution of material in natural ecological systems (“Peer Reviewed: Applying

the Principles of Green Engineering to Cradle-to-Cradle Design,” 2003). Since the wind turbine material is not biodegradable, only the technical cycle of the Butterfly Diagram is considered in Figure 3. Options in the butterfly diagram mainly focus on keeping the infinite material in the cycle by reducing resource leakage and negative external influences on the cycle.

All repurposing options suggested by this research are secondary uses, leading the wind turbine materials to secondary cycles. For example, when using wind turbine material in sheds, the composition of the wind turbine blade is not altered, and a new material is not developed. Instead, the suggested secondary usages only change the shape of the wind turbine blade, extending its life. When the material used from the repurposing ends reaches its end-of-life, it can be recycled, thus closing the loop and reducing resource leakage (Jensen, 2018). This is demonstrated by Figure 2 below, inspired by the Butterfly Diagram (Ellen-MacArthur-Foundation, 2022).

Incorporating upcycled blade waste aligns seamlessly with the circular economy ethos, creating a closed-loop system that promotes responsible resource management within urban regeneration initiatives (Karavida & Peponi, 2023). Beyond environmental considerations, integrating blade-made projects into the regeneration of critical urban spaces yields substantial social and economic benefits for local communities. The presented solutions present an interplay between environmental sustainability and circular economy principles with a holistic approach to fostering resilient and vibrant urban spaces. Utilising mechanical recycling has the potential to retain 69% or more of the mass of end-of-life turbine blades in circulation instead of ending up in landfills and reducing global warming by 7.1% (Hanes et al., 2021). According to R. Hanes et al. (Hanes et al., 2021), there are specific requirements for the circularity of end of solutions to be successful, such as incorporating uncertainties, stakeholder decisions, changing or growing scope and environmental, economic and social needs.

3.4. CHALLENGES WITH WIND TURBINE BLADE REPURPOSING

In Europe, the rise in used wind turbine blades, waste disposal laws, and developers’ permit concerns drive efforts to sustainably manage and dispose of composite

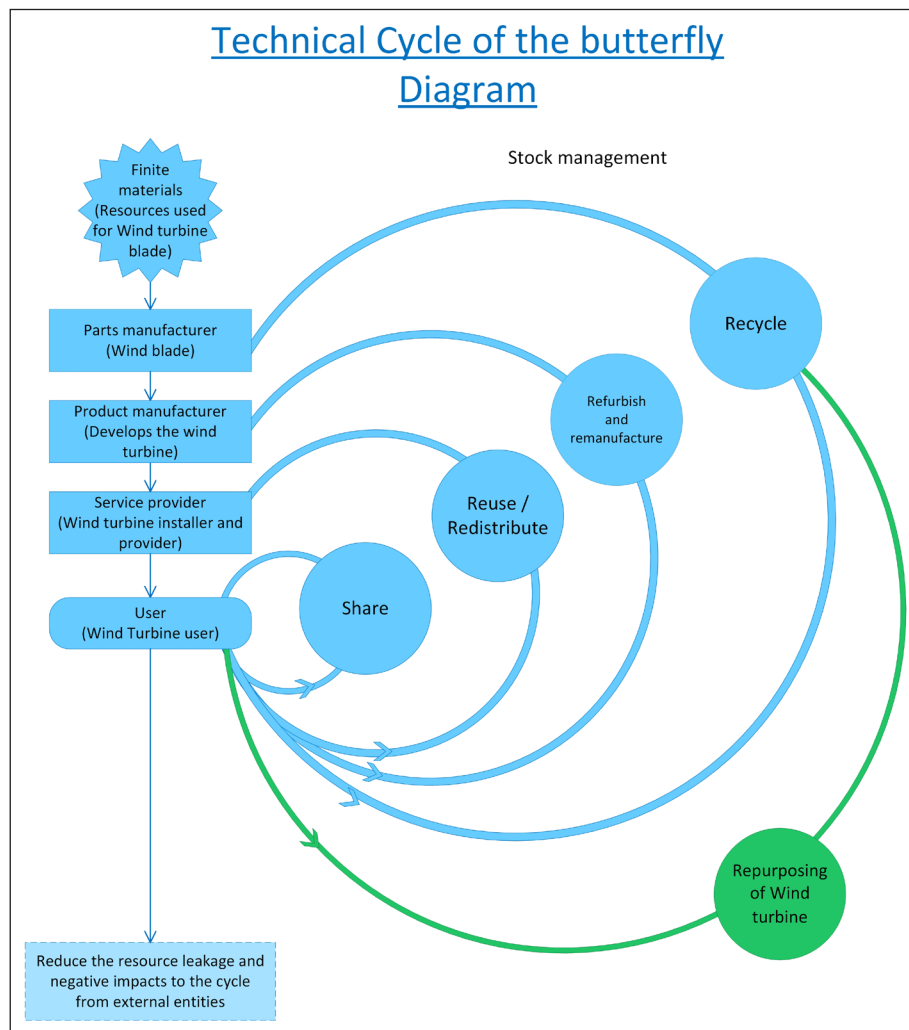


Figure 3 Circularity for end-of-life wind turbine blade repurposing.

blades (Sakellariou, 2018). Strong disposal laws and incentives for effective waste management would drive the windfarm owners towards effective wind turbine waste management.

In a regulatory sense, the repurposed product must meet all the conditions of the New Zealand regulatory environment. These will include compliance with the New Zealand Building Code. The New Zealand Building Code is performance-based, meaning it states how a building must perform instead of describing how it must be designed and constructed. There are two ways of demonstrating compliance with the code: presenting a “deemed to comply” solution or an “alternative solution”. The alternative solution allows the use of innovative products if they can demonstrate compliance with the Building Code (Ministry of Business Innovation and Employment, 2023a). This would include providing some or all fact-based technical information, independent assessments, assessments against industry requirements, independent appraisals, and product certification to the regulator (Ministry of Business Innovation and Employment, 2023b). The time and cost of demonstrating compliance under the

alternative solution pathway will likely be significant. The government has the most significant role in the uptake of these solutions by creating better policies and providing incentives for the circularity of wind turbine blade waste (Martinez-Marquez et al., 2022).

Repurposing all 196 NZWF blades would require a large-scale civil construction project. While small-scale projects may utilise some of the blades, the aim is to repurpose all the blades, and the most efficient way for that to occur is through large projects. Several factors contribute to the complexity of repurposing wind turbine blades. These include existing decommissioning contracts, the waste status of the blades, the transfer of ownership, proprietary blade data, the sales price (if not donated), transportation considerations, installation costs, labour and potential liability issues (Arent et al., 2022). Each aspect adds layers of intricacy to the decision-making and implementation processes associated with repurposing these blades (Ruane et al., 2023). The outgoing costs, which would vary with each repurposing option, must be considered against the likely target markets. The commercial realities of implementing and committing to a repurposing program start with

being able to repurpose the blades as cost-efficiently as possible. Sequencing the project demand for the repurposed blades to their availability and establishing an end market could be challenging (Hopkinson et al., 2018). The challenge of upscaling the solution to large-scale production is still unsolved (Amodeo, 2022; Ruane et al., 2023).

Some repurposing might require adaptation and/or modification of the blade geometry before its use (J Beauson et al., 2022). The repurposing of the wind turbine blades is influenced by factors such as the blade's design, material makeup, recycling technology accessibility, legal considerations, necessary infrastructure, transportation logistics and dismantling procedures, and the economic aspects of the entire process (Sakellariou, 2018). Additional concerns include the high energy intensity needed for the repurposing process, the potential loss of the original structure of the blades during the transformation (Wind-Recycling-Working-Group, 2023), availability of blade geometry and design data, constructability of proposed design and user experience (Ruane et al., 2023). Further investigation and analyses are required to determine the environmental impact of repurposing compared to other options (Nagle et al., 2022). Businesses can benefit from the results of the SWOT (Strengths, Weakness, Opportunities and Threats) analysis of wind turbine blade waste repurposing in New Zealand was presented from content analysis of the literature.

3.5. LIMITATIONS AND FUTURE WORK

This study on the repurposing of wind turbine blades in New Zealand has several limitations. Focusing on a single wind farm, the findings may not be generalisable to all wind farms in New Zealand or globally due to variations in blade types, sizes, and local regulations. Data availability from the literature review and document analysis may limit the comprehensiveness of the study, as some repurposing solutions might not be well-documented or accessible. Additionally, many identified repurposing options are still in the conceptual or demonstration stages, making it difficult to assess their practical viability, economic feasibility, and long-term sustainability. The need for compliance with New Zealand's regulatory frameworks, including the Building Code, presents significant time and cost barriers to implementing repurposed materials.

Future studies could focus on an economic feasibility analysis for individual proposed solutions and a comprehensive environmental impact assessment to validate the proposed solutions' benefits. They could also delve deeper into stakeholder perspectives, which are crucial for successful implementation. Further applied research could also explore legislative levers, market models, and life cycle assessments to enhance understanding and feasibility.

4 CONCLUSION

This research identified viable repurposing options through a comprehensive literature review for the New Zealand wind farm wind turbine blades using a single case study approach. This research is the first New Zealand-specific exploration of the repurposing of wind turbine blades. This study identified theoretical ideas and proposed practical solutions for decommissioned wind turbine blades considered in a case study. The paper provides alternative solutions to the traditional linear resource and waste management system of the take-make-dispose approach for better circularity. Repurposing the NZWF blades in any of these manners would divert 331 tonnes of material from landfills. It presents an opportunity for the wind industry to take notice and prepare for the changing waste landscape. Avoiding the low end of the waste hierarchy will be the expectation and potentially a requirement. The industry now has the opportunity to influence future legislation and concurrently prepare itself for its arrival.

For academics, the research introduces significant scope for further applied research. Broadly, future research could focus on areas that would benefit the wind energy sector's transition to a circular economy. Specifically, the following areas present opportunities: understanding what legislative levers could benefit the transition to a circular economy and exploring market models for collecting and repurposing blades in New Zealand. To establish the best solutions for the wind turbine blades, structural analysis, cost analysis, and life cycle assessments need to be performed across multiple case studies to determine the viability of these solutions for different blade types, which is the limitation of this study.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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