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Full length article

End-of-life wind turbine blade management across energy transition: A life cycle analysis

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A R T I C L E I N F O

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A B S T R A C T

The growing demand for renewable energy has led to a significant increase in the deployment of wind turbines globally. As these turbines reach the end of their operational lives, managing the waste generated from their composite blades presents environmental challenges. By employing life cycle analysis (LCA), the research assesses the environmental impacts of four major disposal scenarios - landfilling, mechanical recycling, pyrolysis, and solvolysis – in the context of Australia's ongoing energy transition from fossil fuels to renewables. This innovation provides a deeper insight into how shifting energy sources in the near future influence the environmental performance of recycling and disposal methods, offering guidance for more sustainable waste management strategies. According to the results, solvolysis shows the most positive impacts on the environment (single score factor ≈ -500 MPt) owing to the potential to produce recovered carbon fibre. Pyrolysis is the next environmentally friendly method, with a slight difference. Mechanical recycling appears to have comparable results to these methods, however the quality of recycled fibres has significant differences. Sensitivity analysis also underscores the critical role of electricity usage in the environmental impacts by 65 % and 86 % share of human health damage assessment in solvolysis and pyrolysis, advocating for its reduction or transition to renewable sources. Finally, the study shows that transitioning to renewable electricity in recycling processes revealed a potential reduction in the environmental impact by around 33–85 %, depending on the end-of-life treatment scenarios. There is also an opportunity to utilise both pyrolysis and solvolysis methods, as their environmental impacts are comparable when renewable resources are used. As we delve into innovative recycling approaches for wind turbine blades, there arises a hopeful prospect for a more sustainable future where conscientious material management contributes to environmental well-being.

1. Introduction

Over industrialisation, fossil fuel energy technologies played a key enabling role in revolutionising the world. Nevertheless, their consequential effluents and emissions have caused various damages to the biosphere (Khalid et al., 2023). In response to these undesirable environmental impacts, renewable energies including wind technologies are increasingly being employed in the global energy sector (Sacchi et al., 2019). From close to 17 GW in the year 2000, the global wind energy capacity reached 1017 GW by the end of 2023 (IRENA 2024). While wind technologies present a green energy option that aids in lowering carbon emissions, further benefits can be achieved with efforts to reduce the environmental impact across the whole life cycle, including at the end of life (Bonou et al., 2016). To guarantee the environmentally responsible implementation of wind energy, it is crucial to gain a deeper comprehension of the environmental impacts of wind turbine (WT) waste at the end of its life cycle.

Waste management encompasses a range of strategies aimed at minimising the environmental and health impacts of waste. Waste prevention has the highest priority in the waste management hierarchy. This implies the importance of design in wind manufacturing to build turbines with longer lifetimes and by considering disassembly and recycling at end-of-life. Components should be easily detachable and labelled for identification during the decommissioning phase. Such a

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design approach (aka "design for disassembly and recycling" (Norgren et al., 2020) can facilitate efficient dismantling and recycling processes. Refurbishing and remanufacturing wind turbine components, along with recycling materials, help retain their value within the economy, aligning with the principles of a circular economy (Bank et al., 2018). These approaches reduce waste and maximise resource utilisation (Spini and Bettini, 2024). Finally, if everything else fails, landfilling would be the only remained alternative.

Implementing effective strategies for material recycling of wind turbine components is a key factor for sustainable management. This involves separating and recycling materials like steel, copper, aluminium, composites and plastic. Efficient recycling demands proper dismantling, material separation, and tailored recycling methods, which are capable of handling diverse materials within wind turbines. Concrete, steel & iron and composite are the three main waste streams generated by discarded wind turbines (Alavi et al., 2024). Steel and iron are primarily managed through recycling as there are mature processes that enable their efficient reuse in new products (Vestas, 2006). For concrete, waste management primarily involves recycling and landfilling, as concrete can be crushed and reused as aggregate in construction, making recycling a common and viable option (Tam, 2009). In contrast, composite waste is addressed through a combination of landfilling, incineration, and recycling; however, many composites still end up in landfills due to the complexities of separating their materials. As a result, composite, primarily found in wind turbine blades, is the most challenging waste stream generated by wind turbines. The reason is carbon fibre-reinforced plastic (CFRP), or glass fibre-reinforced plastic (GFRP) consists of a matrix (usually a polymer resin) and composite fibres which separating these components during recycling without damaging the fibres is difficult (Liu et al., 2022), particularly because they are bonded tightly for structural strength.

According to the waste hierarchy, a design for recycling (DFR) that can reduce the generation of waste has the highest priority (Norgren et al., 2020). Therefore, some companies, such as Siemens Gamesa (Siemens-Gamesa) and General Electric (GE), have started producing 100 % recyclable blades using Arkema's Elium® resin, which is an acrylic-based polymer combined with a reactive monomer blend. According to the manufacturer's claims, the newly produced resin exhibits superior properties compared to similar materials (ARKEMA) and is cost-efficient during the decommissioning stage. Composite productions made with Elium resin can be treated at the end of their life through mechanical or chemical recycling, effectively separating the fibres and recovering virgin resin for reuse. It is a promising future for the world to reduce wind energy waste as a growing clean energy. The following levels of the waste hierarchy show the importance of reusing, recycling, and energy recovery in reducing energy usage, which is a paramount concern in the modern world (Gast et al., 2024). Although reusing blades can be greatly beneficial in terms of environmental and economic impacts, they can be used in extremely limited situations, for example, in the construction industry (André et al., 2020; Gentry et al., 2018; Tyurkay et al., 2024) and housing (Bank et al., 2018; Gentry et al., 2020). On the other hand, energy recovery by incineration used in some countries for EoL composite waste is at the lowest priority. However, this is not considered sustainable because it does support the objective of reducing CO_2 emissions based on the total targets (Ipswich, 2020). Hence, emphasising composite recycling offers a more viable pathway toward achieving a circular economy.

Recycling composites has been a highly challenging endeavour (Chen et al., 2023). Nevertheless, notable progress has been made in recent years, with certain companies implementing various recycling techniques on both industrial and laboratory scales (Mishnaevsky, 2023). Among different developing EoL treatment procedures, mechanical recycling by shredding and milling composite to powder and coarse fraction (Yazdanbakhsh et al., 2018; Li et al., 2016), thermal recycling like pyrolysis using high temperatures to burn the bonds and recycle the fibres (Jani et al., 2022; Yousef et al., 2024), and chemical recycling like solvolysis using chemical solvents in low temperatures and ambient pressure (La Rosa et al., 2021; Mattsson et al., 2020) or a combination of them (Wei and Hadigheh, 2023) are the most common ways, according to the literature (Rathore and Panwar, 2022). Each method has its own advantages and disadvantages. Therefore, it is essential to choose the best approach based on factors like material composition, economic viability, and environmental impact (Wei and Hadigheh, 2022). However, selecting the most favourable approach is always a trade-off between these factors.

There has been an increasing academic and industrial interest in enhancing recycling treatment methods to improve yield and recycled fibre quality. Considerable attention has also been directed towards the environmental analysis of various disposal methods with a particular emphasis on adapting these methods to the specific characteristics of individual case studies. Such customisation is essential because life cycle assessments can yield different results depending on the specific environmental and contextual factors of each jurisdiction. For example, Alsaleh and Sattler (2019) assessed the life cycle of large onshore wind turbines in the USA that considered different aspects of the LCA as per the American regulatory standards. An example is the implementation of truck emission standards for road transportation. Also, Nagle et al. (2020) aimed to compare the environmental impacts of three possible disposal scenarios for wind turbine blade waste in Ireland, including landfilling and co-processing waste in Germany or Ireland (as a potential solution). In another case study, Teffera et al. (2021) presented their research about the life cycle assessment (cradle to grave) of the wind energy system in Ethiopia. In addition, Heng et al. (2021) forecast the future generation of wind turbine blade waste in Canada, covering all life cycle phases from production to disposal. The research evaluates greenhouse gas emissions and energy consumption for five approaches for handling this waste, including incineration and mechanical recycling. Li et al. (2016) evaluated both the environmental and financial feasibility of recycling carbon fibre composite waste using mechanical recycling in the UK. There are also environmental investigations from other jurisdictions, including China (Xu et al., 2022; Cong et al., 2023; Chen et al., 2023), Denmark (Besseau et al., 2019) and Italy (Brussa et al., 2023). The latest research conducted in Germany has estimated the quantity of blade waste (Johst et al., 2024) and investigated cost-effective decommissioning procedures utilising a new material flow projection model (Kramer et al., 2024) that is stronger than previous models considering a second life cycle for the wind turbines.

Thus, it can be concluded that while the environmental impacts associated with the end-of-life management of wind energy are addressed across the world, there remains a significant gap concerning the future energy sources for these systems. As most of the composite recycling infrastructures are planning to be established in the future, understanding the effect of energy sources on each scenario is crucial when selecting the most efficient recycling method for blade composite waste. This consideration ensures that the chosen recycling strategy minimises environmental impacts through a forward-looking perspective on future energy transition.

In our previous research, a new comprehensive methodology for considering different wind turbine technologies in waste estimation was developed, and it was applied to Australia as a case study (Alavi et al., 2024). Then, the amount of waste estimation attributed to the wind energy industry until 2060 has been estimated. This study now aims to provide a methodological approach for waste recycling analysis under various energy transition scenarios. More specifically, the study seeks to establish a robust life cycle assessment framework for diverse EoL treatment options for discarded wind turbine blades. Four treatment scenarios, including pyrolysis, mechanical recycling, solvolysis, and landfill, are defined. This leads to the evaluation of the environmental impacts and the potential changes in impact based on different energy sources used in blade composite treatment methods. Finally, a sensitivity analysis was conducted to systematically assess how variations in the key variables identified in the study affect the outcomes.

1.1. Case study region

For demonstration purposes, this study will use Australia as a case study; however, the methodology is generic and applicable to other contexts. While Australia has only 27 million population, it is ranked the 14th largest emitter worldwide (year 2023), accounting for slightly more than one percent of global emissions (CSIRO,2024). This is largely owing to electricity generation. According to the latest data on greenhouse gas emissions by the National Greenhouse and Energy Reporting (NGER) authority (NGER, 2022), nearly half of greenhouse gas emissions are linked to electricity generation, with coal playing a significant role. Electricity produced from brown coal accounts for 15.2 % of these emissions, while black coal (hard coal) is responsible for 46.8 %, highlighting the substantial environmental impact of coal-based power generation (NGER, 2022). According to the Paris Agreement 1.5 °C pathway, all countries are responsible for producing 90–100 % of electricity using renewable energy by 2050 (UNFCCC). Australia has reaffirmed its target of net zero emissions by 2050 leading to growing attention by the local industries to decarbonisation. As wind power is the most cost-effective form of large-scale renewable energy (Martinez-Marquez et al., 2022), The latest statistics (as of Apr 2024) show that Australia has around 150 operational wind farms with a total capacity of more than 11.5 GW (Rystad Energy 2024).

Fig. 1 illustrates the wind energy distribution and associated WT waste distribution in Australia based on our previous paper (Alavi et al., 2024). However, even with the Australian Government's initiatives to promote wind power development, there are currently no outlined plans for handling the EoL WT blades (Martinez-Marquez et al., 2022). As the wind energy sector continues to grow, Australia must formulate comprehensive strategies for the responsible management of end-of-life wind turbine blades, aligning with the broader goals of a sustainable energy future. It helps the government and related industries reduce both their immediate Scope 1 carbon emissions and, importantly, the Scope 3 embodied emissions of recycled material (Clean Energy Regulator, 2024).

Based on the author's calculations regarding wind turbine waste in Australia in 2024 (Alavi et al., 2024), it is projected that approximately 262,928 tonnes of composite waste will accumulate by 2060 from Australian wind farms. This volume of waste serves as the foundation for conducting a life cycle assessment to examine the environmental ramifications associated with its disposal.

2. Method

This section describes the life cycle assessment approach used to evaluate the EoL pathways for WT blade composites applied to the case study of Australia. Fig. 2 presents the flowchart outlining the overall strategy. In this paper, a wide array of data sources has been utilised to provide a thorough analysis of wind turbine waste management. This includes:

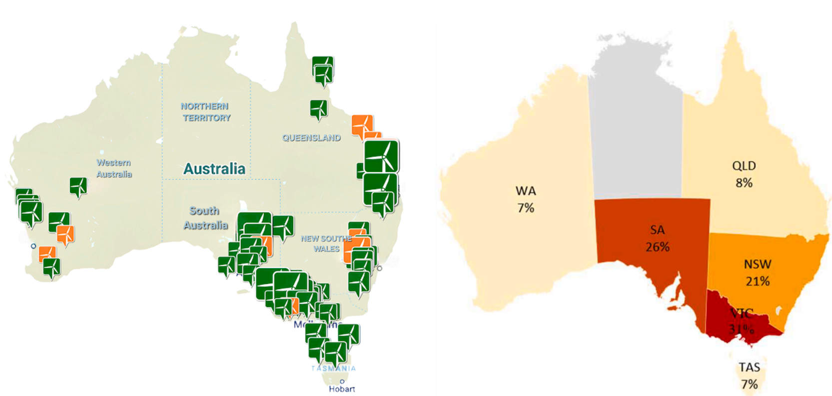
- Government reports (Clean Energy Council 2023; Clean Energy Council 2018; Clean Energy Council 2023) offer crucial insights into regulatory and policy contexts in Australia. These reports cover technological advancements, policy changes, and investment trends while also addressing the challenges and potential solutions for achieving Australia's clean energy objectives.
- Peer-reviewed papers (La Rosa et al., 2021; Mattsson et al., 2020; Nagle et al., 2020; Gennitsaris et al., 2023; Diez-Cañamero and Mendoza, 2023; Meng et al., 2018; Gharde and Kandasubramanian, 2019; Liu et al., 2020), which contribute academic research and theoretical perspectives about different EoL blade treatment scenarios. These will be examined in detail in Section 2.1.
- Manufacturer reports on wind turbines (Vestas, 2006; Garrett and Ronde, 2011), which provide practical and technical information related to wind turbines installed in Australia such as Vestas company.

By integrating these diverse sources, this paper evaluates the environmental impacts of the EoL wind turbines using LCA while also considering the implications of the transition in energy production. Additionally, it includes a sensitivity analysis of the key parameters contributing to the LCA and a detailed discussion to address various factors influencing the effectiveness of waste management strategies. The red blocks represent data collection, while the green blocks show the LCA analysis, which ultimately assesses the impact of the energy transition on the future of blade recycling.

2.1. EoL treatment scenarios

This paper analyses four distinct LCA scenarios, I, II, III, and IV, each evaluating the environmental impacts of a specific disposal method. A graphical overview of the four disposal scenarios along with the technical information, is provided in Fig. 3.

Scenario I examines the disposal of end-of-life wind turbine blades through landfilling. The LCA conducted in this research investigates the landfill scenario as a feasible yet less optimal option for treating EoL WT blade composites (Nagle et al., 2020; Gennitsaris et al., 2023). The study assumes that an initial sizing will be done for landfilling and then collected and transported to the nearest landfills in each state.



(a) (b)

Fig. 1. a) Wind energy capacity and distribution in different states of Australia by Feb 2023 (RenewEconomy, 2024), orange colour for decommissioned windfarms and green colour for operational windfarms, b) Estimated WT waste distribution by 2060 in different states of Australia in our previous work (Alavi et al., 2024) (WA=Western Australia, SA= South Australia, QLD=Queensland, NSW= New South Wales, VIC= Victoria, TAS=Tasmania).

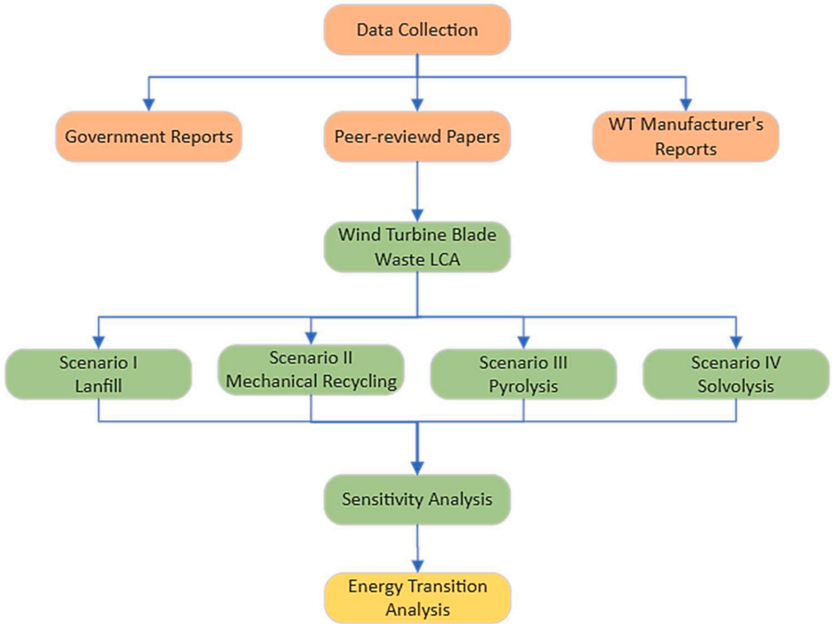


Fig. 2. The approach undertaken in this study.

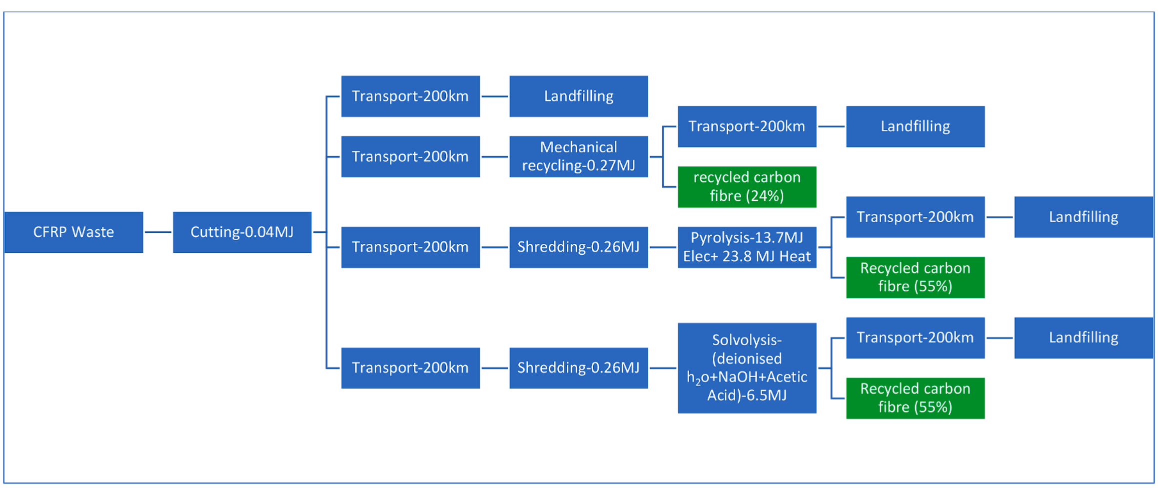


Fig. 3. LCA boundaries for scenarios I, II, III and IV.

Scenario II evaluates the mechanical recycling process of WT blade waste. After the initial reduction of composite waste size to 50–100 mm (Heng et al., 2021) by the shredding process, the composite components undergo grinding in a hammer mill and sorting into various lengths using sieves and cyclones (Li et al., 2016). Mechanically recycled carbon fibre typically serves as virgin glass fibre or fillers in less valuable products as the quality falls short of being on par with virgin composite materials (Meng et al., 2018), with the coarse fraction assumed to be sent to a landfill.

Scenario III evaluates the pyrolysis process of EoL WT blades. An initial sizing will be done, and then pyrolysis recycling involves breaking down organic materials (resin) through high temperatures in a range of 300 to 800 °C in the absence of or with limited levels of oxygen required for combustion (Diez-Cañamero and Mendoza, 2023) while the fibre remains. It is assumed that 55 % of the composite, made of carbon fibre, will be recovered, while the remaining 45 %, consisting of resin material, will be vaporised (Meng et al., 2018). In this process, the recovered carbon fibre has higher quality than mechanically recycled carbon fibre and can be used in some composite productions, for example, low-density polyethylene (Jani et al., 2022). Adjusting and controlling key parameters in the pyrolysis process (e.g., temperature and time) can significantly impact the yield and quality of the recycled carbon fibre (Spini and Bettini, 2024). As a result, efforts are being made to optimise conditions for the best possible outcome (Wei and Hadigheh, 2024).

Scenario IV explores the solvolysis for decommissioned WT blades. Chemical recycling methods involve various techniques to dissolve or break down the matrix polymers or resins that bind the fibres together using a solvent like supercritical N-butanol (Liu et al., 2020), subcritical water (Mattsson et al., 2020), Acetic acid and Sodium Hydroxide (La Rosa et al., 2021). Solvolysis at reduced temperatures is generally performed at temperatures near and under 200 °C at standard pressure (Gharde and Kandasubramanian, 2019). The fibres, after the initial size reduction, can be extracted through a chemical process and potentially reused to manufacture new materials or products. In this technique, similar to pyrolysis, 55 % of the composite, consisting of carbon fibre, is recycled, while the remaining material is disposed of in a landfill (Meng et al., 2018). Solvolysis is regarded as one of the most advanced emerging technologies as it can potentially yield higher-quality recovered fibres compared to other recycling methods (Sommer and Walther, 2021). However, the choice of solvents can affect both the duration and quality of the recycling process, which in turn impacts overall recycling efficiency. Additionally, the use of large quantities of solvents can be a disadvantage (Tyurkay et al., 2024).

Examining these scenarios provides valuable insights into the environmental performance of each treatment method. It aids in identifying more environmentally sustainable approaches for managing end-of-life wind turbine blade composites. However, there is often a trade-off between the efficiency of the recycling process and its environmental impact. For instance, while some methods may achieve high recovery rates, they might require significant amounts of solvents or energy, potentially offsetting their environmental benefits. Balancing these factors is crucial to optimising both the effectiveness and sustainability of the recycling process.

2.2. Modelling and life cycle inventory

The LCA software used in this study was SimaPro version 9.4.0.2 (PRé-Sustainability 2023) with the Ecoinvent V3 database, and the methodology employed for this assessment was ReCiPe 2016, which employs damage assessment including midpoint and endpoint mainstream techniques to derive accurate characterisation factors (Fig. 4). The midpoint level focuses on specific environmental factors, such as greenhouse gas emissions, acidification, or resource depletion. These are the direct impacts or changes happening within the environment due to a certain activity or process. In contrast, the endpoint level is a broader, more holistic perspective that connects these specific environmental factors to broader, long-term effects on human health, ecosystems, and resources (PRé-Sustainability 2020). Endpoint impacts are the ultimate consequences that can occur due to the combined midpoint impacts. The outcomes of these indicators are multiplied by specific weights and combined in the single score factor for carbon fibre-reinforced plastic (CFRP). The contribution of each endpoint factor in the single score factor is 40 % for human health, 40 % for ecosystems, and 20 % for resources in the default ReCiPe 2016 method (PRé-Sustainability 2016). These factors play a significant role in quantifying and evaluating the environmental impact of wind turbine blades throughout their EoL. While endpoint or single-score indicators aid decision-making, midpoint indicators are valuable for pinpointing reduction goals and strategies tailored to specific environmental issues like climate change, acidification, and water scarcity (Kägi et al., 2015).

This paper also utilises "with credits" and "without credits" analysis, representing two different ways of accounting for the benefits or impacts associated with recycling and by-products. When using the "with credits" approach, the LCA includes positive adjustments for the benefits of recycling, by-products, or secondary products, reflecting the environmental savings or value gained from these processes. For example, recycling a material might lead to a credit for avoiding the need to produce new material. On the other hand, the "without credits" approach excludes such benefits, focusing solely on the direct environmental impacts of the primary process or product without accounting for the potential positive effects of recycling or by-products. This method provides a more conservative estimate of environmental impact, emphasising the direct impacts alone (Corona et al., 2019).

Table 1 displays the assumed quantities of materials and energy consumption associated with the end-of-life management scenarios.

2.3. Goal, functional unit, and system boundaries for the case study of Australia

Life Cycle Assessment (LCA) results may differ based on the location of the study, and assumptions are adjusted to fit unique geographical factors. In this study, the authors use LCA to compare the environmental impacts of composite waste treatment methods from Australian wind turbine blades until 2060. The functional unit is thus determined by the cumulative weight of blade composite waste by 2060 in Australia according to our previous work (Alavi et al., 2024) in 2024 and is defined as 'waste management of 262,928 tonnes of EoL blade composite'. It helps to sketch a vision of the future wind turbine waste management in Australia under various disposal options.

Defining the system boundary is crucial for understanding how the

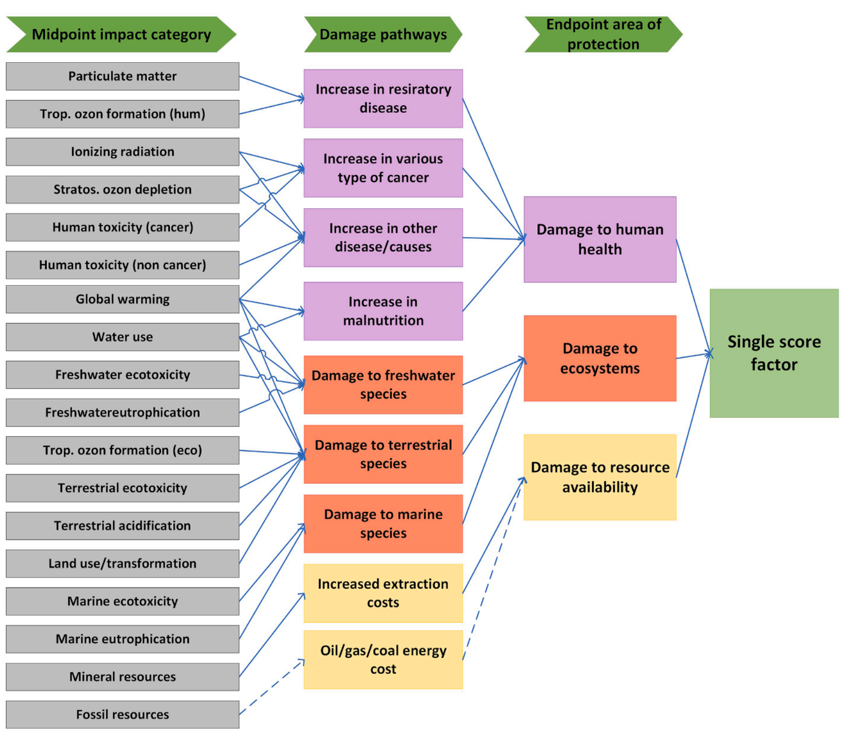


Fig. 4. Illustration of the connections between the inventory and midpoint categories (environmental impacts), damage assessments (endpoint levels), and single score factor. (Adopted from (PRé-Sustainability 2020) with some modification).

Table 1
Life cycle inventory for 1 kg of CFRP as the base of calculations according to (Li et al., 2016; La Rosa et al., 2021; Nagle et al., 2020; Heng et al., 2021; Meng et al., 2018).

Process	Unit	Landfill	Mechanical recycling	Pyrolysis	Solvolysis
Transport, freight, lorry 16–32 metric-ton, euro5 [RoW]	tkm	0.2	0.31	0.28	0.27
Electricity, High voltage [AU]*	MJ	0.04	0.31	14.00	6.80
Heat, district or industrial, natural gas [GLO]	MJ	0.00	0.00	23.80	0.00
Inert waste for disposal [RoW]	kg	1.00	0.57	0.4	0.35
Water, deionised [RoW]	kg	0.00	0.00	0.00	1.35
Acetic acid, qt plant/kg/RNA	kg	0.00	0.00	0.00	0.45
Sodium hydroxide, production mix, at plant/RNA	kg	0.00	0.00	0.00	0.04

* : Potential electricity sources include Brown coal (Lignite), Black Coal (Hard coal), Natural gas, Solar energy and Wind energy. They have been utilised in Section 3.3 to assess the impact of the energy transition on the recycling scenarios with the help of ecoinvent database in SimaPro.

system functions, what inputs and outputs are relevant, and how the system interacts with the environment. In this analysis, the system boundary commences once the blade has been detached from the hub and disassembled. This assessment examines wind turbine blades at the end of their useful life, which means a "grave-to-cradle" life cycle is assessed, where the system boundary concludes with the production of recovered materials.

The assumptions are as follows:

Assumption 1: The lifetime of wind turbines ranges from 15 to 25 in the literature (Heng et al., 2021; Gennitsaris et al., 2023; Ghosh et al., 2022; Fonte and Xydis, 2021). For the purpose of this study and according to our estimation in the previous publication (Alavi et al., 2024), an average lifespan of 20 years was used.

Assumption 2: The waste flow generated during the production, operation, and maintenance of WT's blade is not considered in the life cycle assessment. This is justified because of the relatively small volume, in contrast to the waste generated at the end-of-life of wind turbines (Chen et al., 2021; Liu and Barlow, 2017; Cooperman et al., 2021).

Assumption 3: According to the data collected in this study, more than 90 % of wind energy capacity in Australia is generated from wind turbines with a capacity > 2 MW. Wind turbines of this size likely have carbon fibre-reinforced plastic (CFRP) blades (Lefeuvre et al., 2019). Hence, the study is focused on CFRP EoL treatment.

Assumption 4: All road transport between wind farms, landfill sites, and recycling infrastructures are included. It is assumed that all wind farms, both current and future, are located within 200 km of landfill or recycling infrastructure. In our future work, we are planning to optimise the transport distance and disposal infrastructure locations to enhance the efficiency and sustainability of the recycling process.

Assumption 5: Transport distances have been approximated as a preliminary assessment, taking into account all relevant contributing factors.

Assumption 6: The analysis considered different yields of recovered materials (carbon fibre) for the different recycling methods; however, any possible variability in the quality of recovered carbon fibres cannot be considered in LCA. We will discuss the quality of recovered carbon fibres in Section 4.

Assumption 7: Given the assumptions that there are no capacity constraints on the recycling process and no limitations on the number of recycling facilities, the approach to handling decommissioned blades—whether stockpiling them until 2060 or recycling them incrementally each year—would not affect the overall results. This is because, with an ample and unrestricted recycling infrastructure, both strategies would ultimately achieve the same recycling outcomes in terms of efficiency and environmental impact. Thus, stockpiling blades until 2060 or recycling them continuously throughout the years would yield equivalent results under these conditions.

3. Results analysis

3.1. Direct environmental impacts

According to the ReCiPe2016, 18 environmental impacts of the wind turbine blade composites are assessed in this LCA. The results of the quantitative life cycle assessment for four treatment scenarios without considering credits are presented in Table 2. "Credits" in this context refer to any positive contributions or benefits that offset negative impacts. These credits include factors related to recovered carbon fibre due to recycling procedures, including energy recovery, raw material conservation, and other environmentally friendly practices that reduce the overall environmental impact. In this study, we accounted for a specific percentage of recycled CFRP as avoided burdens, capturing the benefits of recycling. This comparison illustrates that mechanical recycling and landfilling generally have lower environmental impacts compared to pyrolysis and solvolysis. Pyrolysis tends to have the highest quantities in most categories evaluated. Solvolysis has a higher impact than mechanical recycling but a lower impact than pyrolysis (Table 2).

A damage assessment (explained in Section 2.2) has been carried out considering four EoL treatment scenarios. The results were categorised into three important factors: human health, ecosystem, and resources. Fig. 5 presents the contribution of various parameters encompassing transport, electricity usage, inert waste disposal, heat generation by natural gas, and material consumption, defining the environmental impacts of these four disposal scenarios. Across all scenarios, 'human health' has the highest impact score. This is mainly due to electricity consumption, as can be seen in the logarithmic charts. For example, for the solvolysis treatment scenario, electricity consumption accounts for over 65 % of the impact on human health, while for the pyrolysis scenario, electricity consumption contributes to 86 % of the impact on human health. A detailed table of results has been provided for the damage assessment analysis (Table 3).

The results show considerable variation when recycling credits for recovered composite materials are taken into account. Recycling credits refer to the avoided burdens originating from the primary production of the composite waste that can be applied as a credit for the full recovery of the composite, for example, the beneficial environmental outcomes associated with recycling materials compared to disposing them in landfill, such as energy savings, reduced emissions, and decreased resource extraction. This is because creating new components like composites from raw materials often requires substantial energy (more than two times (Gennitsaris et al., 2023) and resources. Then, Recycling composites means fewer raw materials are required, preserving natural resources and reducing the environmental impact related to extracting and processing these resources, like lowering the associated CO_2 emissions. Therefore, recycling is assumed to decrease the need to produce composite from virgin material.

Fig. 6 shows the overall impact assessment (single score), highlighting the comparison between scenarios with and without credits. Here, a lower negative score correlates with greater beneficial outcomes.

Table 2
Quantitative midpoint LCA results of four treatment scenarios (without credits).

Impact category	Unit	Mechanical recycling	Pyrolysis	Solvolysis	Landfill
Global warming	kg CO_2 eq	3.6E+07	1.3E+09	6.8E+08	1.32E+07
Stratospheric ozone depletion	kg CFC11 eq	2.7E+01	8.58E+02	3.81E+02	1.0E+01
Ionising radiation	kBq Co-60 eq	2.8E+05	2.7E+07	1.1E+06	1.8E+05
Ozone formation, Human health	kg NO_x eq	9.4E+04	2.41E+06	1.1E+06	4.6E+04
Fine particulate matter formation	kg PM2.5 eq	4.1E+04	1.13E+06	1.1E+06	1.66E+04
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.62E+04	2.57E+06	1.19E+06	4.77E+04
Terrestrial acidification	kg SO_2 eq	1.08E+05	3.33E+06	3.62E+06	3.9E+04
Freshwater eutrophication	kg P eq	3.88E+04	1.62E+06	7.89E+05	6.88E+03
Marine eutrophication	kg N eq	2.27E+03	9.87E+04	5.02E+04	3.51E+02
Terrestrial ecotoxicity	kg 1,4-DCB	2.5E+08	7.2E+08	4.3E+08	1.6E+08
Freshwater ecotoxicity	kg 1,4-DCB	1.24E+06	4.4E+07	2.18E+07	3.19E+05
Marine ecotoxicity	kg 1,4-DCB	1.82E+06	6.09E+07	3.01E+07	5.16E+05
Human carcinogenic toxicity	kg 1,4-DCB	2.56E+06	9.09E+07	4.34E+07	6.8E+05
Human non-carcinogenic toxicity	kg 1,4-DCB	4.85E+07	1.7E+09	8.82E+08	1.17E+07
Land use	m^2a crop eq	7.27E+05	6.96E+06	2.82E+06	2.9E+05
Mineral resource scarcity	kg Cu eq	3.48E+04	3.40E+05	1.31E+05	2.16E+04
Fossil resource scarcity	kg oil eq	1.0E+07	3.5E+08	2.1E+08	4.6E+06
Water consumption	m^3	8.98E+04	2.24E+06	1.41E+06	6.19E+04

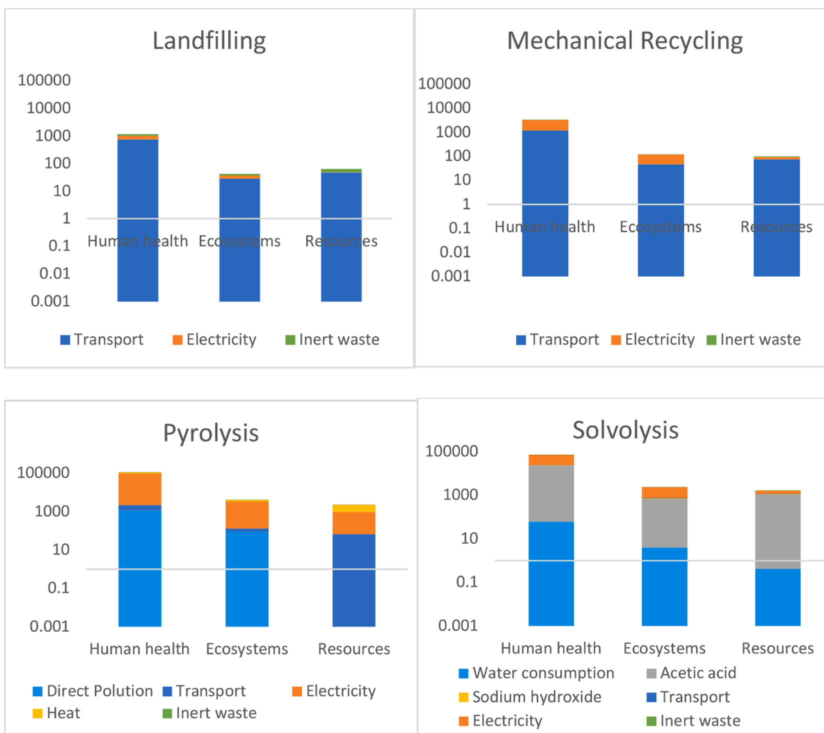
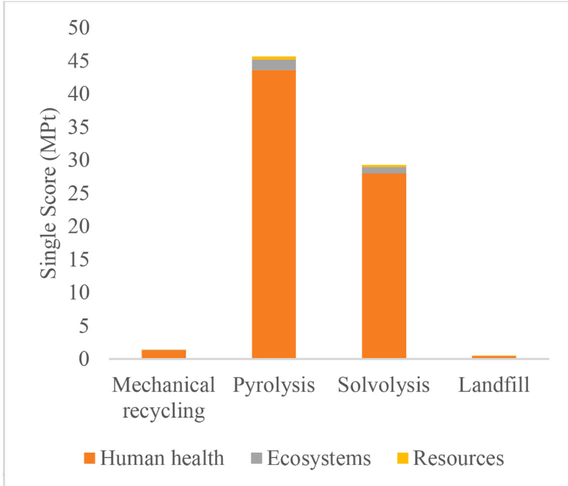


Fig. 5. Contribution of the various parameters to the normalised damage assessment of disposal treatment scenarios.

Table 3
Damage assessment results for blades composite waste treatment scenarios.

End-of-life treatment scenarios	Damage category	Total	Transport	Electricity	Inert waste	Heat	Direct Pollution	Water consumption	Acetic acid	Sodium hydroxide
Landfilling	Human health	1162.82	732.95	269.19	160.67	—	—	—	—	—
	Ecosystems	41.73	28.20	9.30	4.22	—	—	—	—	—
	Resources	62.87	46.66	2.47	13.73	—	—	—	—	—
Mechanical recycling	Human health	3328.57	1150.74	2086.24	91.58	—	—	—	—	—
	Ecosystems	118.75	44.28	72.06	2.41	—	—	—	—	—
	Resources	100.24	73.26	19.15	7.83	—	—	—	—	—
Pyrolysis	Human health	109,182.2	1026.14	94,217.61	64.26	12,766	1107.64	—	—	—
	Ecosystems	3957.02	39.48	3254.58	1.69	574	87.17	—	—	—
	Resources	2251.88	65.33	864.83	5.49	1316	0.000	—	—	—
Solvolysis	Human health	70,134.57	989.49	45,762.84	56.23	—	—	59.93	22,095.76	1170.30
	Ecosystems	2319.92	38.07	1580.79	1.48	—	—	3.99	657.36	38.20
	Resources	1601.81	63.00	420.06	4.80	—	—	0.41	1075.64	37.88



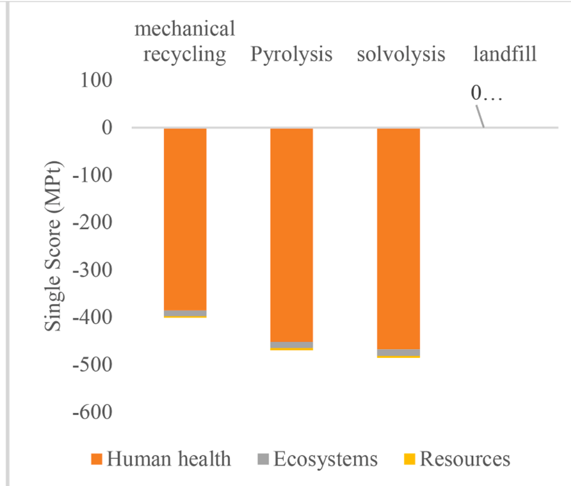


Fig. 6. Single score factor for mechanical recycling, pyrolysis, landfilling and solvolysis: a) without credits and b) with credits.

Notably, recycling quality and yield rates differ depending on each treatment method (Sommer and Walther, 2021). It is clear that, although mechanical recycling has the lowest negative environmental impacts after landfilling in Fig. 6(a), the single score factor in Fig. 6(b) with credits indicates that pyrolysis and solvolysis have greater positive impacts because of higher recycling rates (Fig. 3). Conversely, despite the pyrolysis procedure yielding the most unfavourable environmental impacts among all scenarios, its advantages due to carbon fibre recycling yield outweigh this drawback. It should be noted that the quality of recycling cannot be considered in the LCA procedure; however, it can be very influential in terms of the potential value of the recovered materials in secondary markets and decision-making on future investment. According to the research carried out by Sommer and Walther (2021), the quality of recovered carbon fibre is 50 %, 78 % and 95 % for Mechanical recycling, pyrolysis and solvolysis, respectively.

These results clearly show that recycling by any method significantly reduces the environmental impact of wind turbines. Recycling all EoL wind turbine composite materials in Australia could reduce about 1010 kg of CO_2 emissions (Table 4). Reusing these materials in secondary markets reduces the need for new production from virgin resources, contributing to decreased emissions. For example, it helps reduce fossil fuel resource consumption by around 2 million tonnes of oil due to reducing energy consumption for manufacturing processes or transportation.

3.2. State-wise environmental impacts

To compare the environmental impacts of wind turbine blade waste in Australia, this section focuses on the single score factor and global warming potential (CO_2 emissions). The overall environmental impacts of composite waste have been distributed across Australian states according to their contributions to the generation of this waste shown in Fig. 1 (WA=Western Australia by 7 %, SA= South Australia by 26 %, QLD=Queensland by 8 %, NSW= New South Wales by 21 %, VIC= Victoria by 31 %, TAS=Tasmania by 7 %).

Specifically, in Fig. 7, VIC, NSW, and SA demonstrate the most pronounced desirable environmental effects while considering recycling credits, respectively. The CO_2 emission chart (Fig. 8) also depicts similar results across all four treatment scenarios. Recycling composites through pyrolysis or solvolysis can reduce CO_2 emissions by approximately 3.5 Mt in Victoria, 3 Mt in South Australia, and 2.5 Mt in New South Wales, primarily by eliminating the need to produce new carbon fibre-reinforced plastic (CFRP).

Table 4
Quantitative LCA results of four treatment scenarios (with credits).

Impact category	Unit	Mechanical recycling	Pyrolysis	Solvolysis	Landfill
Global warming	kg CO_2 eq	-9.57E+09	-1.10E+10	-1.16E+10	1.33E+07
Stratospheric ozone depletion	kg CFC11 eq	-2.64E+03	-2.55E+03	-3.03E+03	9.81E+00
Ionising radiation	kBq Co-60 eq	-6.21E+08	-7.92E+08	-7.93E+08	1.86E+05
Ozone formation, Human health	kg NO_x eq	-2.02E+07	-2.36E+07	-2.49E+07	4.67E+04
Fine particulate matter formation	kg PM2.5 eq	-1.84E+07	-2.24E+07	-2.24E+07	1.66E+04
Ozone formation, Terrestrial ecosystems	kg NO_x eq	-2.06E+07	-2.38E+07	-2.52E+07	4.78E+04
Terrestrial acidification	kg SO_2 eq	-3.70E+07	-4.41E+07	-4.38E+07	3.94E+04
Freshwater eutrophication	kg P eq	-3.71E+06	-3.17E+06	-4.01E+06	6.89E+03
Marine eutrophication	kg N eq	-2.43E+05	-2.15E+05	-2.63E+05	3.52E+02
Terrestrial ecotoxicity	kg 1,4-DCB	-1.19E+10	-1.48E+10	-1.51E+10	1.62E+08
Freshwater ecotoxicity	kg 1,4-DCB	-3.26E+08	-3.75E+08	-3.97E+08	3.19E+05
Marine ecotoxicity	kg 1,4-DCB	-4.19E+08	-4.78E+08	-5.09E+08	5.17E+05
Human carcinogenic toxicity	kg 1,4-DCB	-3.32E+08	-3.37E+08	-3.85E+08	6.84E+05
Human non-carcinogenic toxicity	kg 1,4-DCB	-6.64E+09	-6.79E+09	-7.67E+09	1.17E+07
Land use	m^2a crop eq	-2.67E+08	-3.35E+08	-3.40E+08	2.91E+05
Mineral resource scarcity	kg Cu eq	-6.47E+06	-7.97E+06	-8.18E+06	2.16E+04
Fossil resource scarcity	kg oil eq	-2.35E+09	-2.67E+09	-2.81E+09	4.66E+06
Water consumption	m^3	-5.81E+07	-7.21E+07	-7.30E+07	6.20E+04

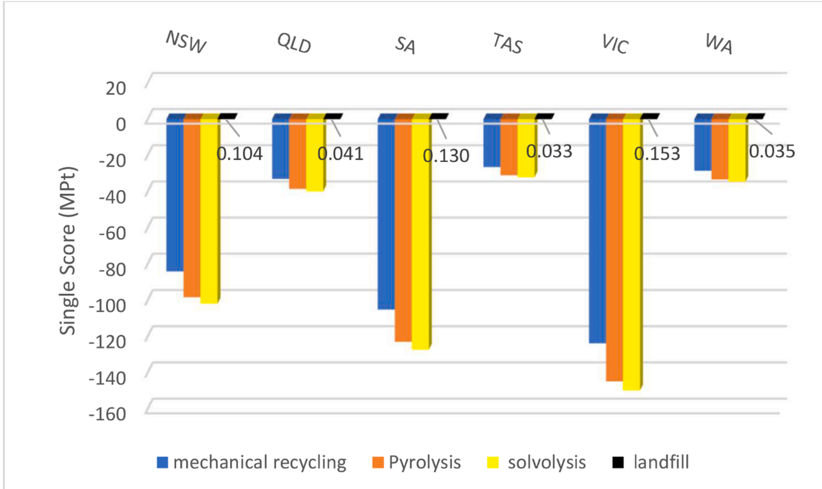


Fig. 7. Quantitative comparison of single score factor for four treatment scenarios by different states.

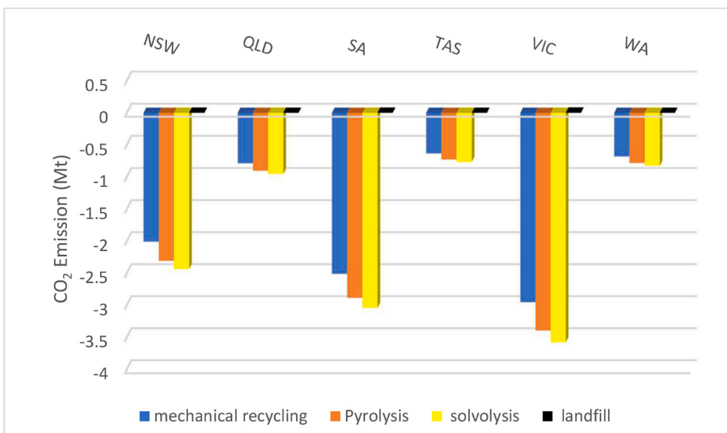


Fig. 8. Global Warming Impact (GWI) contribution estimated in Australian states for the treatment of 262,928 tonnes WT blades composite waste generated by 2060.

3.3. *Transitioning to renewable energy*

Comparing single score factors and carbon footprints for different recycling methods (without credits) and considering the transition of energy generation from fossil fuels to renewable energies assists in better long-term decision-making. In Fig. 9, the energy sources for producing electricity will change from 100 % using coal and natural gas to 100 % using solar and wind energies.

The charts illustrate that the mechanical recycling method is less impacted by changes in energy sources when compared to the other methods. This is because it has the lowest energy consumption. When Brown coal and hard coal are used as energy sources, the single score

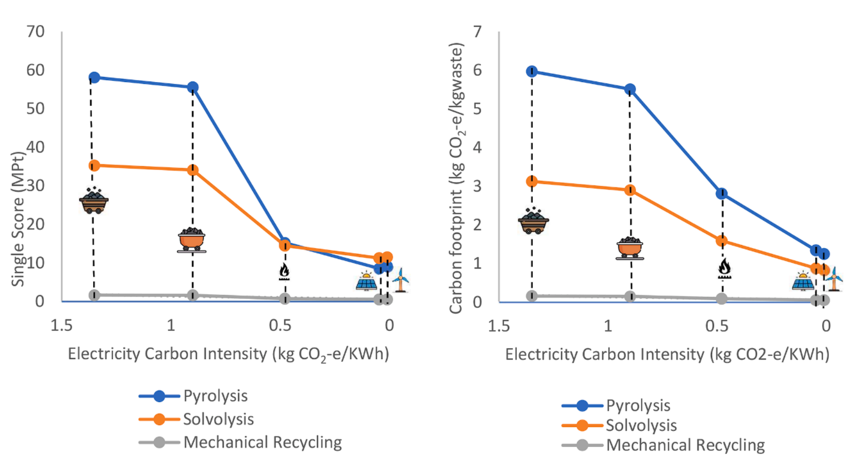


Fig. 9. Comparison of single score factor and carbon footprint derived from LCA outcomes for three EoL treatment approaches employing diverse energy sources (Brown coal (Lignite), Black Coal (Hard coal), Natural gas, Solar energy, Wind energy).

factor for pyrolysis is significantly higher than solvolysis, with the difference being around 60 %. This indicates that pyrolysis has a higher undesired environmental impact when these coal-based energy sources are employed. Using natural gas as the energy source, the single score factor for pyrolysis is approximately similar to that of solvolysis (14.5 MPt). Then, if wind and solar energies are utilised, solvolysis has a slightly higher single score factor than pyrolysis (11.5 and 8.5 MPt), meaning slightly higher negative environmental impacts. This can be explained by the impacts associated with the use of the solvents. Regardless of the energy sources employed, the carbon footprint of pyrolysis consistently surpasses that of solvolysis due to the higher energy consumption associated with pyrolysis. However, the disparity between the two methods narrows when renewable energy sources replace fossil fuels. Substituting fossil fuels with renewable energy leads to a reduction in carbon footprint by approximately 85 % for pyrolysis and 33 % for solvolysis. This data suggests that solvolysis is a more environmentally friendly recycling method than pyrolysis when fossil fuels are used in the recycling industries. However, with a transition to renewable energies, both pyrolysis and solvolysis can be environmentally viable options. Therefore, future research should further explore other aspects of the recycling process, such as the quality of recovered CFRP and the economic feasibility of different recycling methods.

3.4. Sensitivity analysis

According to Fig. 5, transport factors and electricity consumption have the most effect on the environment. Therefore, a sensitivity analysis has been performed, tackling one-factor-at-a-time, to evaluate how each specific factor influences the modelling outcomes (Groen et al., 2014). Fig. 10 shows the impact of dimensionless parameters on results when electricity consumption and transportation factors are increased or decreased by 50 % from the baseline. It is evident that in landfilling, altering electricity consumption is not particularly critical due to its low energy requirement. On the other hand, the transport distance has a more significant impact. In mechanical recycling, there is greater electricity usage compared to landfilling. This leads to a more pronounced impact compared to the transport factor.

It is evident that altering the transport factor has minimal impact compared to adjusting the electricity factor in both pyrolysis and solvolysis methods, given their higher electricity requirements than other disposal methods. However, varying electricity has the highest impact

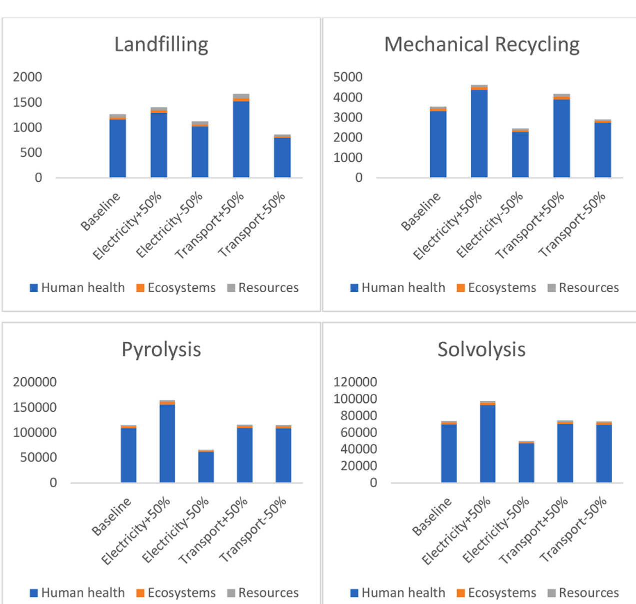


Fig. 10. Normalised sensitivity analysis on four disposal scenarios.

on pyrolysis (around 50 %). In summary, the level of electricity consumption significantly influences environmental impacts. Therefore, minimising electricity usage or transitioning to renewable energy sources will have the greatest impact on the environmental sustainability of any recycling technology.

4. Discussion and policy implications

The comprehensive life cycle analysis on various end-of-life treatment scenarios for wind turbine blade composites offers valuable insights into their environmental impacts. The assessment considered factors crucial to human health, ecosystem, and resource preservation. Across all scenarios, 'human health' emerged as the dominant factor, highlighting its paramount importance in decision-making. CO_2 emission is one of the critical parameters affecting human health. A large amount of CO_2 emission results from burning fuels to produce energy required for recycling processes as well as transport.

Notably, electricity consumption played a critical role, particularly in the solvolysis and pyrolysis scenarios, accounting for over 65 % and 86 % of the impact on human health, respectively, because of using fossil fuels. This underscores the significance of reducing and transitioning to renewables in these treatment processes to mitigate their environmental footprint. Furthermore, the choice of energy sources substantially influenced the environmental impact of treatment methods. When brown coal and hard coal were employed, pyrolysis exhibited a significantly higher environmental impact compared to solvolysis. This emphasises the importance of considering the energy mix when evaluating the sustainability of recycling processes. Transitioning to renewable energy sources, such as wind and solar energy, narrowed the gap between the environmental impacts of pyrolysis and solvolysis. This suggests that using renewable energy in recycling infrastructures is very advantageous.

The analysis also sheds light on the varying effects of recycling yield rates among different treatment methods. While mechanical recycling showed the lowest negative environmental impacts after landfilling without considering credits, its single score factor decreased due to the lower percentage of recovered composites when considering credits for recycling.

However, a constraint lies in the inability to factor in the quality of recovered composites in various recycling methods within the LCA. The economic viability of recovered carbon fibres can be affected by variations in their strength and other mechanical and chemical properties (overall quality), which are contingent on the specific recycling method used (Fonte and Xydis, 2021). Consequently, it proves challenges to directly compare the environmental efficacy of these diverse recycling technologies and identify the most advantageous option (Delaney et al., 2021). Additionally, economic considerations regarding the recycling process and the recovered value of CFRP play a significant role in determining the optimal approach for managing CFRP at the end of its life cycle.

The secondary market for recycled composite materials is currently growing and developing. Efforts to create viable markets for recycled composites have gained traction, especially in industries seeking sustainable alternatives to virgin materials (Mamanpush et al., 2018; Nagle et al., 2022). Mechanical recycling produces low-level quality recycled composites that can be used in the cement and concrete industry (Oliveira et al., 2020; Bhandari and Nam, 2024). Pyrolysis and solvolysis can recycle composite waste with a higher quality and yield rate (Sommer and Walther, 2021). Therefore, the researchers are attempting to develop the infrastructures to utilise them again as composites in different applications, including non-structural and structural components in marine, automotive and aeronautics according to the quality (Zhang et al., 2020). As an example, automotive semi-structural parts like car dashboards, carburettor housing, and car rear wings are potential applications for recovering CFRP through pyrolysis and solvolysis (Pimenta and Pinho, 2011).

Stakeholder engagement and collaboration should always be the case and be seriously considered (Jensen et al., 2020). It covers engaging stakeholders throughout the value chain, including wind turbine manufacturers, waste management companies, policymakers, and research institutions. Researchers are always dedicated to advancing end-of-life disposal techniques for composites, potentially revolutionising their future management. Using these potentials by fostering collaboration and knowledge sharing between related parties will help to develop innovative solutions for sustainable waste treatment and circular economy practices.

Effective policies and regulations are essential for a seamless transition to sustainable management and a circular economy in the wind energy sector. They play a crucial role in advocating and incentivising sustainable waste treatment practices while promoting the principles of a circular economy (Ortegon et al., 2013; Ferrell and DeVuyst, 2013). This can include incentivising manufacturers to design for recyclability, extended manufacturer responsibility requirements, standards for environmentally sound disposal practices, and transparency for effective circular economy business and operational plans. However, some scholars believe that the expenses and intricacies associated with project development are already experiencing substantial growth, primarily attributed to state and federal mandates (CEC 2023). Additionally, a mounting emphasis is on meeting social and environmental standards for renewable energy technologies that may result in heightened expenses and extended timelines for reaching decisions and obtaining approvals (CEC 2023).

Last but not least, raising awareness among industry professionals, employees, and the public about the importance of sustainable end-of-life treatment for wind turbines is a proactive and future approach that paves the way to reach a more sustainable outcome. It includes promoting education and training programs to ensure proper handling and recycling practices are followed at every turbine's life cycle stage.

By focusing on these areas, the wind energy industry can effectively address end-of-life treatment challenges, minimise environmental impact, and foster a circular economy approach promoting resource conservation and sustainability.

5. Conclusion

As the wind energy sector expands in Australia, addressing the environmental repercussions of retiring wind turbine blades is imperative. This research compares the environmental impacts of four main EoL treatment methods, including landfilling, mechanical recycling, pyrolysis, and solvolysis, and how modifying electricity resources shapes waste management outcomes. For this purpose, life cycle assessment -grave to cradle- has been applied to the case study of Australia by 262,928 tonnes of WT blade composite waste until 2060. The key findings are:

- Amongst existing FRP recycling methods, pyrolysis and solvolysis showed the most positive impacts on the environment.
- This study highlights the significance of electricity consumption on the environmental impacts, particularly in pyrolysis and solvolysis, as they need more electricity supply.
- Transitioning to renewable energy sources or minimising electricity usage can significantly contribute to a more sustainable waste management process.
- When using brown or hard coal, pyrolysis shows a significantly higher negative environmental impact than solvolysis, with a difference of approximately 60 %.
- As the energy landscape shifts towards renewables, both pyrolysis and solvolysis emerge as viable options, with solvolysis generally being more environmentally friendly. Substituting fossil fuels with renewables results in an 85 % reduction in the carbon footprint for pyrolysis, while solvolysis achieves a 33 % decrease.
- Utilising pyrolysis or solvolysis for composite recycling could lead to a reduction in CO_2 emissions of about 3.5 Mt in Victoria, 3 Mt in South Australia, and 2.5 Mt in New South Wales.

This study faces several limitations. While data on the weights of wind turbine blades is available, the specific type of composite material—whether carbon fibre or glass fibre—remains unknown. This lack of clarity necessitated the use of assumptions that may not fully capture the material's environmental impacts. Additionally, the absence of an established composite recycling infrastructure in Australia led to rough estimates of transport distances for EoL blades. Future research plans to implement reverse logistics optimisation will enhance understanding of these distances, potentially leading to more accurate assessments of environmental impacts associated with transport.

In conclusion, this study comprehensively assesses the environmental implications of different EoL methods for wind turbine blade composites in the context of energy source transition which is a key parameter influencing the recycling process. These findings offer valuable guidance for decision-making processes, emphasising the need for strategies that prioritise human health, optimise energy consumption, and consider the broader environmental impact of recycling processes considering the future renewable energy development.

CRediT authorship contribution statement

Zahraossadat Alavi: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Kaveh Khalilpour:** Writing – review & editing, Supervision. **Nick Florin:** Writing – review & editing, Supervision. **Ali Hadigheh:** Writing – review & editing. **Andrew Hoadley:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is available in the manuscript.

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