

Energy-Transition-Sensitive Life Cycle Assessment of End-of-Life Wind Turbine Blade Recycling Pathways in India

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Abstract-- There has been a worldwide increase in the installation of wind turbines to capture renewable wind energy. As some of those turbines begin the removal phase of their life cycle, concerns about the disposal of their composite blades become increasingly important. This research takes a Life Cycle Assessment (LCA) to review the potential ecological implications of the last four end-of-life approaches—landfilling, mechanical recycling, pyrolysis, and solvolysis—within the context of ‘fossil-free’ India. These assessments capture the gradients of each energy shift to evaluate disposal sustainability, in turn aiding waste disposal planners in responsible decision-making. Solvolysis has the most positive impact (-500 MPt within the single score system) potentially as a consequence of recovering more valuable, high-quality carbon fibres. Pyrolysis follows and has a similarly positive impact as mechanical recycling, but with more lowgrade recycled fibres. Sensitivities point toward electricity as a key factor with 65% and 86% contributions to health impacts in solvolysis and pyrolysis respectively. This reinforces the need to optimize the energy used in these processes. Additionally, moving to renewable electricity for recycling operations can lessen overall environmental impacts by 30–86% depending on which disposal method is selected. Because of the similarities in environmental impacts, along with renewable energy, the combined use of pyrolysis and solvolysis can present a viable option. Finally, the growth of new, cutting-edge recovering techniques for wind turbine edges is the first step toward a more passively sustainable future in which the recovery of materials and the recycling of waste abiotic materials is achieved.

Keywords-- Wind turbine blades, Life cycle assessment (LCA), Composite recycling, Pyrolysis; Solvolysis, Circular economy, Renewable energy, India.

I. INTRODUCTION

Throughout the industrial revolution and many of the remarkable developments in human history, energy technologies that relied on fossil fuels were pivotal. Nonetheless, the destruction that these technologies brought about is grave, including emissions and pollutants that are extremely harmful (Khalid et al., 2023).

The energy sector is now turning towards renewables to replace these technologies and wind energy is positioned to be one of the most promising alternatives (Sacchi et al., 2019). The world’s installed capacity of wind energy has gone from about 17 GW in 2000 to 1,017 gigawatt by the finish of 2024 . Despite perceptions of wind energy being benign and eternally renewable, Bonou et al. (2016) maintain that all forms of energy, including wind, require a comprehensive life cycle and end-of-life (EoL) analysis. From a life cycle view, grasping and tackling the ecological issues associated with waste generated by wind turbines (WT) and the disposal of composite blades is essential to the sustainable utilization of wind technologies. As the waste demonstrates, the waste organization crisis highlights the issues with the health and environmental effect of waste.

Of the waste management options, prevention is the most sustainable (Whiteman et al., 2021). Therefore, clear disassembly and recycling designs become critical. Features that facilitate disassembly, marking, and material retrieval are important for effective end-of-life processing (Norgren et al., 2020). Additionally, the principles of circular economy predict the dissipation of eco-recycling and systematic waste managed disposal of products destined to waste landfilling, the least preferred alternative, and the disposal of eco waste through managed disposal (Spini & Bettini, 2024). Wind turbine components are prepared by a mix of materials such as steel, copper, aluminum, plastics, and composites. However, as noted by Alavi et al. (2024), most of the waste from the components consists primarily of steel, iron, concrete, and composites.

The closed-loop recycling of metals has been well established (Vestas, 2006). Also, construction grade recycled concrete is readily available (Tam, 2009). On the other hand, the recycling of composites, particularly turbine blade CFRP and GFRP, becomes nearly impossible because of the impregnated matrix (Liu et al., 2022).

Hence, DfR finds priority in the waste hierarchy (Norgren et al., 2020). Firms like General Electric (GE) and Siemens Gamesa are launching 100% biodegradable blades made from Arkema’s Elium® resin, a polymer with reactive monomer blends.

The resin enables mechanical or chemical recycling of the end-of-life turbine blades for the fibres and resin to be reclaimed and reused (ARKEMA). Such innovations are significant for the sustainable growth of wind energy. In addition to improvements in design, other options are blade reuse, recycling, and recovering energy. Reusing blades provides both ecological and economic advantages, especially in construction and housing, but low practicality curtails wide adoption. Recovery of energy through incineration is the least favorable option because of the extra CO₂ emissions generated (Ipswich, 2020). Thus, improving the recycling of the composites is the most feasible way to close the gap to a circular economy. New methods, both at the industrial level and laboratory scale, are being developed and have potential (Mishnaevsky, 2023) despite the intricate challenges in composite recycling (Chen et al., 2023). Typical EoL treatment methods include:

- Mechanical recycling refers to the process of shredding and milling composites into coarse and fine powders.
- In thermal recovering, or pyrolysis, huge temperatures are used to break polymer bonds and recover fibres.
- Involved in chemical recycling (solvolysis), we use diluents at small temperatures and pressures.
- Hybrid methods stem from the combination of multiple techniques (Wei and Hadigheh, 2023)

Every method has its pros and cons, and the best option relies on the makeup of the material, cost, and the consequences for the environment (Wei & Hadigheh, 2022). For that reason, some compromises will need to be made. More recent work focuses on how effective recycling is and how good the recovered fibre is. Some Life Cycle Assessment (LCA) studies have reviewed the environmental impacts associated with different disposal options in the USA (Alsaleh & Sattler, 2019), Ireland (Nagle et al., 2020), Ethiopia (Teffera et al., 2021), Canada (Heng et al., 2021), the UK, Denmark, China, Germany and Italy as well as Italy. While there has been significant research regarding EoL management, the effects of future Energy systems on the recycling value chain have yet to be studied in depth. As new recycling systems are developed, assessing the effect of energy change pathways on recovering systems' environmental outcomes becomes critical. This will help identify recycling methods for composite blade waste that are optimally sustainable and energy-efficient.

1.1 Overview of the Study Region:

To exemplify this study, India is used as a representative case training, although the method is universal and applies everywhere on the planet. India is the 14th largest emitter of greenhouse gases in the world and contributes slightly above 1% of the world's gases, as of the year 2023 (CSIRO, 2024). India has a relatively moderate population of 27 million people. Because of the poorly diversified population, the infrastructure in India is estimated to be responsible for a significant percentage of greenhouse gases. According to the National Greenhouse and Energy Reporting (NGER) authority, the electricity sector accounts for almost 50% of India's greenhouse gas emissions and coal is still a major contributor. Specifically, brown coal records for 16.3% of emissions and black coal (hard coal) contributes 47% which reveals the eco-friendly danger posed by coal-powered electricity (2022-NGER). India continues to hold its net-zero emissions goal by 2050 which has made decarbonisation strategies very exciting within its strategically positioned industries. Wind power is the most cost-effective and rapidly growing green energy source (2022- Martinez-Marquez et al). At 2024 April, India operates more than one fifty wind farms with a total capacity of over 12 GW (Rystad Energy, 2024). The geographical location of these wind farms and the anticipated wind turbine waste generation are shown in Figure 1 (from Alavi et al., 2024). Although India has made strides in the wind energy sector, the country still does not have a nationally coordinated plan for the end-of-life management of Wind Turbine (WT) blades (Martinez-Marquez et al., 2022). This is an urgent problem and, with further industry development, will remain unsolved and unresolved. The industry requires comprehensive end-of-life management to continue sustainably and meet objectives aligned with decarbonisation. This would also lower Direct emissions and embodied emissions from used material (Unspoiled Energy Regulator, 2024). Alavi et al. (2024) estimated that by 2060, India will have 262,930 tonnes of compound waste from the currently operational wind turbine generation. This estimated waste will form the basis of a Life Cycle Assessment (LCA) to determine the most environmentally sustainable option for EoL disposal. This will help to identify EoL disposal options that will improve recycling.

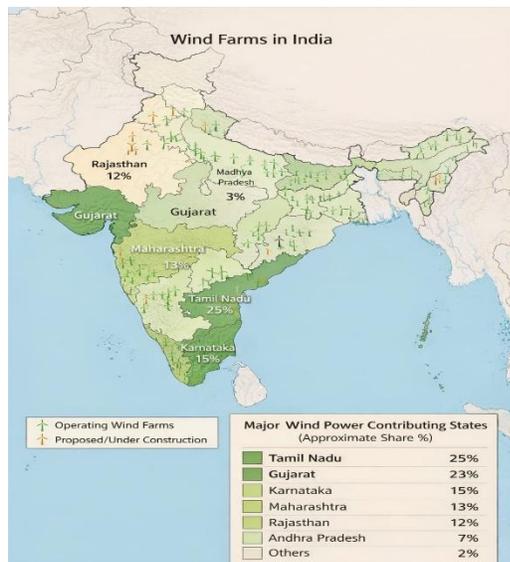


Figure 1. Installed wind power capacity across different states in India.

II. METHOD

The life cycle assessment (LCA) approach examines the end-of-life (EoL) options for composite material wind turbine (WT) blades in India (AUS). This represents what is in Figure 2, which is a workflow diagram. A great deal of information from various sources was collected in order to understand wind turbine waste management. Government documents from the Clean Energy Council (2018 and 2023) describe various policies and regulations in India. These documents detail the policies' evolution, trends in investments, emerging technologies, and the country's clean energy objectives, along with the challenges and possible solutions. They also discuss the country's clean energy objectives. Section 2.1 provides a summary of the research studies from the various academic sources used. Information from turbine manufacturers, such as Vestas (2006) and Garrett and Ronde (2011), provides applied and practical information on the wind turbines in India and the newest models from Vestas and other relevant data. This research assesses the ecological effects of decommissioned wind turbines using Life Cycle Assessment (LCA) while incorporating changing trends in energy invention. It also performs a sympathy study on the key factors determining the LCA outcomes and elaborates on the drivers of the efficiency of the waste disposal management processes. The red and green blocks in Figure 2 indicate data acquisition and the analysis of LCA, respectively. They, in unison, evaluate the impacts of energy evolution on the prospective recycling of turbine blades.

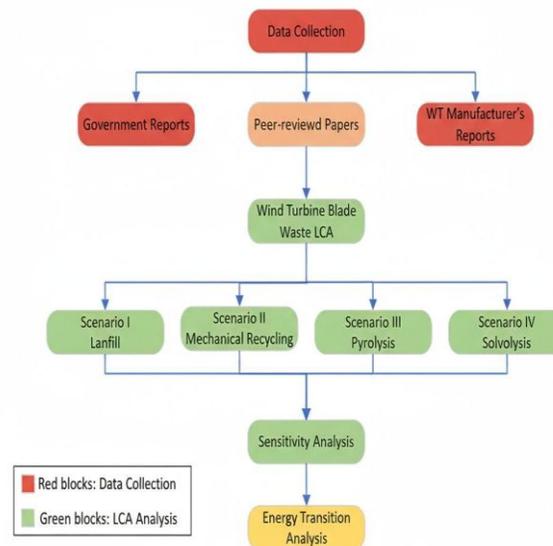


Fig. 2. The approach undertaken in this study.

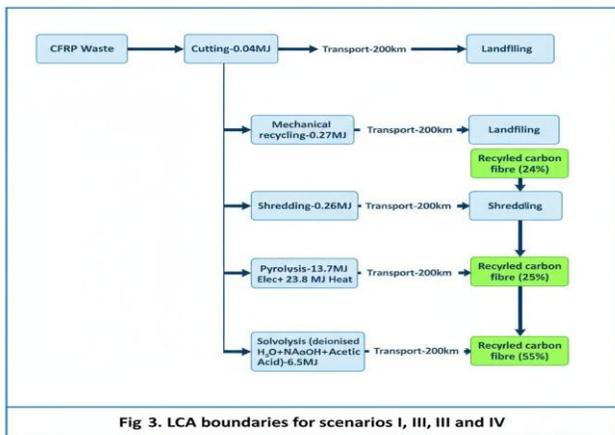
2.1. LCA-Based Scenarios for End-of-Life Wind Turbine Blade Disposal:

In India, the end-of-life (EoL) management of composite material wind turbine (WT) blades has been evaluated using the life cycle assessment (LCA) approach. This is summarized in a workflow diagram in Figure 2. Understanding wind turbine waste management required a significant amount of data, which was obtained through various channels. Government documents, such as those provided by the Clean Energy Council (2018 and 2023), outline the policies and regulations in India, and were helpful in this regard. These sources also look at how policies change, how investments are growing, new technologies, and India's goals for clean energy, including the problems they face and how to solve them.

Scholarly articles, such as those by 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), and Liu et al. (2020), were used to study end-of-life treatments for wind turbine blades, and they are discussed in detail in Section 2.1.

This can be researched through the company's archives, like in the case of Vestas (2006), or through more in-depth descriptions of the models the company has and is currently using and documents that describe, for instance, Garre and Ronde (2011), which examine the practical and technical aspects of the Indian wind turbines.

This research examines to what extent the transition to cleaner energy impacts the wind turbines that are at the end of their life cycle and the assessment of the end-of-life energy transition. It also analyzes the relation of waste management to the life cycle assessment, and the results of the sensitivity analysis regarding the life cycle and most critical factors. The red block in Figure 2 illustrates the data collection stage and the green blocks highlight the life cycle assessment process. Together, they demonstrate the effect of the energy evolution on future blade reprocessing.



2.2. LCA Methodology and Inventory Development:

I performed life cycle assessment using SimaPro version 9.4.0.2 and the Ecoinvent V3 database. The assessment method followed ReCiPe 2016 as the base method. ReCiPe employs center and termination methods to address characterisation aspects as depicted in Figure 4. The midpoint method assesses environmental impacts directly tied to an activity or process, such as assessing greenhouse gas productions, acidification, and resource depletion. The endpoint method assesses the cumulative longer-term impacts of the mid penalties on human health and the environment, as well as resource depletion (PRÉ-Sustainability, 2020). Thus, endpoint indicators reflect the total environmental impact of the midpoint impacts. The assessment avoided any offsetting benefits and focusing on the main process environmental burden (Corona et al., 2019).

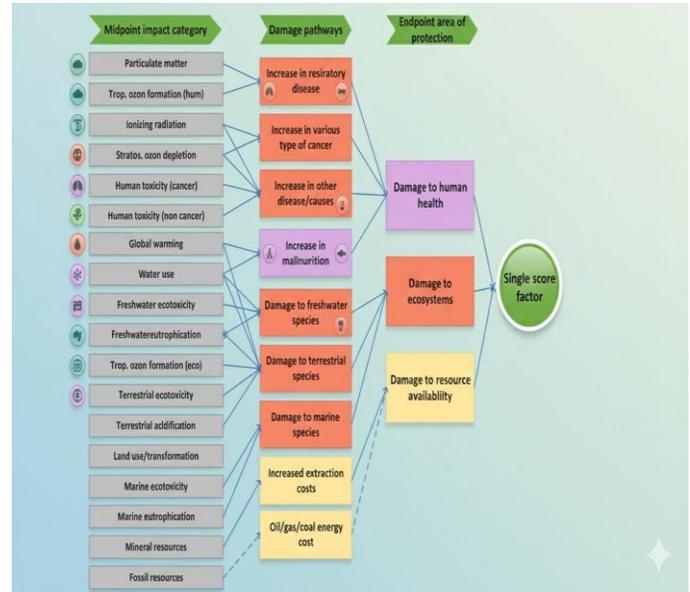


Figure:4: Framework outlining the associations across midpoint impact categories, damage pathways, endpoints of areas of protection, and their consolidation to a single environmental score.

2.3. Life Cycle Assessment (LCA) Framework and Assumptions:

Location can shape the assumptions made in a Life Cycle Assessment (LCA) study and therefore shape the results. In this research, LCA is focusing on the estimating ecological effects of Indian wind turbine (WT) blade waste (till 2060). The study based on predictions (Alavi et al., 2024) establishes a functional unit of managing 262,928 tonnes of end-of-life (EoL) blade composite waste in India by 2060. This provides an understanding of the waste burden and aids in future waste management analyses which can be beyond disposal and recycling. System boundary definitions shape the determination of relevant inputs and outputs, and the environmental interactions of the system. In this case bordering the environmental system ends with the life (EoL) stage of WT blades, meaning the study is cradle-to-grave. This culminates in the creation of recycled materials, which are produced in the various disposal and recycling methods. Taking into account previous research work and estimations (Alavi et al., 2024), 20 years was assumed for this study as within the literature, the average operational life of 15 to 25 years was also considered.

The analysis also did not account for waste produced during the production, operation and maintenance of WT blades, as this is substantially lower than waste created at the end of life blades. In India, an extra 95 % of wind energy is produced from turbines that are larger than 2 MW and mainly use carbon fibre to strengthen plastic blades. Consequently, this research is concerned solely with the treatment of CFRP at the end of life. It was assumed that all road transport accounted for among wind farms, landfills and recycling centers, and that all existing and prospective wind farms are sited within 200 km of these disposal or recycling operations. For subsequent research, these distances will be decreased to increase the waste logistics efficiency and sustainability. The initial approach to determining transport distances is to consider them as estimates and analyze them using the most significant factors. Analyzing the different quantities of recovered carbon fibre relative to different recycling methods is used as a basis. In this case, the LCA disregards the varying quality of the fibre and the differences in quality of the fibre that remain unmeasured, the latter of which will be discussed in Section 4. The research presumes that recycling methods and facilities operate without capacity limits. The absence of capacity limits makes it irrelevant how recycling blades are timed to 2060, and whether recycling is conducted in a sequence of batches or continuously, as both methods provide the same efficiency and net outcomes in terms of environmental effects.

TABLE 1:

The reference point for calculations was the life cycle record for one kilogram of CFRP, using the methodologies outlined by La Rosa et al. (2021), Li et al. (2016), Nagle et al. (2020), Heng et al. (2021), Meng et al. (2018) and Nagle et al. (2020)

Process	Unit	Landfill	Mechanical recycling	Pyrolysis	Solvolysis
Acetic acid (production)	Kg	0.0	0.00	0.00	0.5
Industrial heat (natural gas)	MJ	0.0	0.00	24.0	0.00
Freight transport (lorry, 16–32 t, Euro 5)	Tkm	0.1	0.3	14	6.8
Deionised water	Kg	0.0	0.00	0.00	1.4
Sodium hydroxide (production)	Kg	0.0	0.0	0.0	0.1
Electricity (high voltage)	MJ	0.0	0.3	15	7.0
Inert waste for disposal [RoW]	Kg	1	0.6	0.5	0.4

III. RESULTS AND DISCUSSION:

3.1. Environmental Impact Assessment of EoL Scenarios:

Using ReCiPe 2016, this life cycle assessment studies 18 distinct environmental impacts associated with wind turbine blade composites. Table 2 illustrates the outcomes of the life cycle calculation, excluding any impacts for four different approaches regarding the materials' end-of-life management. There are positive impacts which mitigate negative impacts called credits. In this case, these credits resulted from recycling carbon fibre and other recycling activities such as energy recovery, reduced use of raw materials, and reduced overall environmental impacts. The study also appreciated the environmental merits of recycling working with a defined amount of recycled carbon fibre reinforced plastic (CFRP). The comparison indicated that mechanical recycling and landfilling are much more eco-friendly than pyrolysis and solvolysis. Out of all the methods, pyrolysis presents the most environmental impacts in most categories, while solvolysis is more damaging than mechanical recycling but less than pyrolysis. Section 2.2 discusses how impacts are evaluated and this was carried out for all four end-of-life treatment options. Results can be divided into three areas: human health, ecosystem quality, and resource use. As illustrated in Figure 5, the study assessed the environmental implications for each scenario by analysing factors such as transport, electricity consumption, waste disposal, heat from natural gas, and other materials. In every scenario, the largest concern was the adverse impact on human health, primarily driven by the consumption of electricity. For instance, in the case of the solvolysis scenario, over 65% of the health impact comes from electricity, while in pyrolysis, it is nearly 86%. More information is available in Table 3. In order for the analysis to be plausible, the damage assessment must be comprehensive. In the analysis, this is certainly the case. For the results to be plausible, sufficient detail must be provided, and as it stands, the damage assessment hits this target. The remaining analysis of the revised text continues to follow the logical flow of the claims, formulating pivotal queries on the key ideas of each segment. While the quality of recovered fibre is not completely represented in the LCA, it plays a major role in determining the value of the secondary market and in investment decisions. As mentioned by Sommer and Walther, the recovery quality data indicates that 50% of the carbon fibre is recovered through mechanical recycling, while pyrolysis and solvolysis offer 78% and 95% recovery, respectively. Given these results, it is clear that all recycling methods provide substantial environmental advantages. Such an impact is illustrated by the 10¹⁰ kg of CO₂ emissions that could be prevented by recycling all end-of-life wind turbine composites in India.

These emissions indicate an economic value of 2 million tonnes of oil that could be recovered, owing to reduced oil transportation and manufacturing processes, minus the oil required to produce new composites.

Table 2:
Comparative midpoint LCA results of treatment scenarios gross results

Impact Category	Unit	Mechanical	Pyrolysis	Solvolyis	Landfill
Climate change potential	kgCO ₂ eq	3.6×10 ⁻⁷	1.3×10 ⁻⁹	6.8×10 ⁻⁸	1.32×10 ⁻⁷
Water use	m ³	8.98×10 ⁻⁴	2.24×10 ⁻⁶	1.41×10 ⁻⁶	6.19×10 ⁻⁴
Stratospheric ozone impact	kgCFC11eq	2.7×10 ⁻¹	8.58×10 ⁻²	3.81×10 ⁻²	1.0×10 ⁻¹
Dependence on fossil fuels	kg oil eq	1.0×10 ⁻⁷	3.5×10 ⁻⁸	2.1×10 ⁻⁸	4.6×10 ⁻⁶
Exposure to ionising radiation	kBq Co-60 eq	2.8×10 ⁻⁵	2.7×10 ⁻⁷	1.1×10 ⁻⁶	1.8×10 ⁻⁵
Scarcity of mineral resources	kg Cu eq	3.48×10 ⁻⁴	3.40×10 ⁻⁵	1.31×10 ⁻⁵	2.16×10 ⁻⁴
Ozone precursor emissions (human health)	kg Nox eq	9.4×10 ⁻⁴	2.41×10 ⁻⁶	1.1×10 ⁻⁶	4.6×10 ⁻⁴
Land occupation potential	m ² a crop eq	7.27×10 ⁻⁵	6.96×10 ⁻⁶	2.82×10 ⁻⁶	2.9×10 ⁻⁵
Particulate matter formation	kg PM _{2.5} eq	4.1×10 ⁻⁴	1.13×10 ⁻⁶	1.1×10 ⁻⁶	1.66×10 ⁻⁴
Human toxicity (non-cancer effects)	kg 1,4-DCB	4.85×10 ⁻⁷	1.7×10 ⁻⁹	8.82×10 ⁻⁸	1.17×10 ⁻⁷
Ground-level ozone (ecosystem exposure)	kg Nox eq	9.62×10 ⁻⁴	2.57×10 ⁻⁶	1.19×10 ⁻⁶	4.77×10 ⁻⁴
Marine ecotoxicity potential	kg 1,4-DCB	4.77×10 ⁻⁴	6.09×10 ⁻⁷	3.01×10 ⁻⁷	5.16×10 ⁻⁵
Acidification of terrestrial environments	kg SO ₂ eq	1.08×10 ⁻⁵	3.33×10 ⁻⁶	3.62×10 ⁻⁶	3.9×10 ⁻⁴
Aquatic ecotoxicity (freshwater)	kg 1,4-DCB	1.24×10 ⁻⁶	4.4×10 ⁻⁷	2.18×10 ⁻⁷	3.19×10 ⁻⁵
Nutrient enrichment (freshwater)	kg P eq	3.88×10 ⁻⁴	1.62×10 ⁻⁶	7.89×10 ⁻⁵	6.88×10 ⁻³
Nutrient enrichment (marine systems)	kg N eq	2.27×10 ⁻³	9.87×10 ⁻⁴	5.02×10 ⁻⁴	3.51×10 ⁻²
Soil ecotoxicity (terrestrial)	kg 1,4-DCB	2.5×10 ⁻⁸	7.2×10 ⁻⁸	4.3×10 ⁻⁸	1.6×10 ⁻⁸

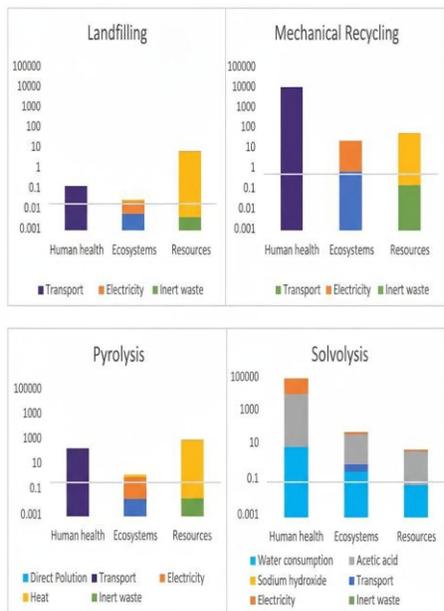


Fig. 5: Assessment of Disposal Treatment Scenarios: Influence of Various Limitations to Normalised Damage.

Table 3:
Assessment of Damage and Results for Composite Blade Waste Treatment

End-of-life treatment scenarios	Damage category	Total	Transport	Electricity	Inert waste	Heat	Direct pollution	Water consumption	Acetic acid	Sodium hydroxide
Pyrolysis	Human Health	109182	1030.14	94,217.61	64.26	12,766	1107.64	---	---	---
	Ecosystem	3960.00	39.51	3254.60	1.70	575	87.20	---	---	---
	Resources	2251.90	65.30	864.82	5.50	1315	0.00	---	---	---
Solvolyis	Human Health	70134.60	98950	45762.85	56.24	---	---	60.0	22095.80	1170.3
	Ecosystem	231990	38.10	1580.80	1.5	---	---	4.00	65740	38.21
	Resources	1601.80	63.01	420.10	5.0	---	---	0.40	1075.65	38.00
Landfilling	Human health	1162.90	733.0	269.2	161.00	---	---	---	---	---
	Ecosystem	42.03	28.21	9.00	4.23	---	---	---	---	---
	Resources	63.00	47.6	2.5	14.00	---	---	---	---	---
Mechanical recycling	Human Health	33290	1151.4	2086.23	92.0	---	---	---	---	---
	Ecosystem	119.00	44.28	72.1	2.40	---	---	---	---	---
	Resources	100.25	73.30	19.20	8.00	---	---	---	---	---

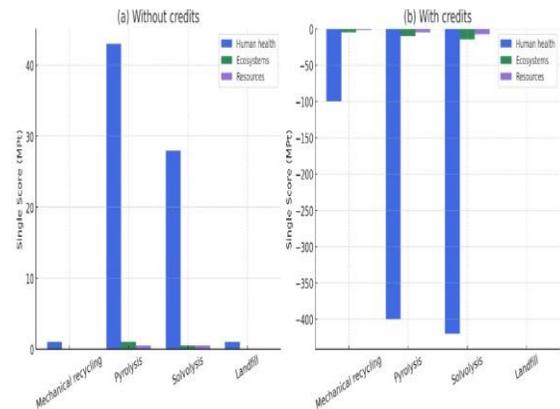


Fig. 6: Comparative solo score assessment of pyrolysis, solvolyis, and landfilling, mechanical recycling: a) without credit, b) with credit

3.2: State-by-State Assessment of Environmental Impacts:

In the context of the environmental impact of spent wind turbine blades across India, this section analyzes the single-score factor and the GWP, expressed in CO₂ equivalents. The environmental impact of composite waste is examined by state and by the location of the waste, as illustrated in Figure 1.

The allocations are 7% Western India (WA), 26% Southern India (SA), 8% Queensland (QLD), 21% New South Wales (NSW), 31% Victoria (VIC), and 7% Tasmania (TAS). Figure 7 demonstrates that recycling credits are of the greatest benefit in terms of environmental impact in Victoria, New South Wales, and Southern India. These recycling credits are also the basis of the CO₂ emissions trend illustrated in Figure 8, where emissions are lower across all four end-of-life treatment options. In particular, the recycling of composite waste by pyrolysis or solvolysis in Victoria (3.5 million tonnes), Southern India (3 million tonnes), and New South Wales (2.5 million tonnes) contributes substantially to emission reduction as it circumvents the highly carbon-intensive process of virgin carbon fibre reinforced plastic (CFRP) production.

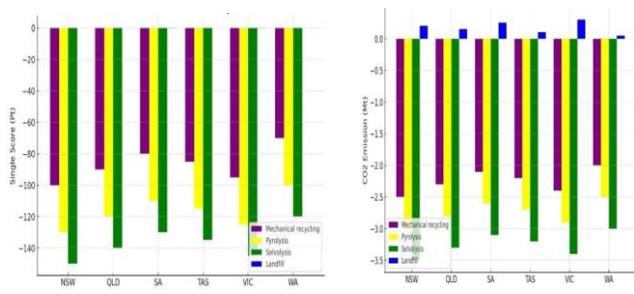


Fig:7

Figure 7 represents the Statewise Comparison of Single Score Factors for Four Treatments, and Figure 8 represents the Projected Global Warming Impact of Wind Turbine Blade Waste Treatment Across Indian States by 2060.

3.3: Impact Analysis of Electricity Consumption and Transport on Environmental Performance of Recycling Methods:

Figure 5 illustrates that the use of electric power and the means of transport have the greatest impact on the environment. To gain further insight, a sensitivity analysis focusing on a single factor was conducted to assess the impact of each factor on the model's outcomes (Groen et al. 2014). The impact of a dimensionless parameter illustrated in 10 shows the effect of a 50% increase or decrease in baseline electricity use and transport factors. Regarding landfilling, a change in electricity use has a small effect, while a shorter distance to transport the waste has a greater effect, since the energy demand is low. In the case of mechanical recycling, the energy escalates, thus the impact of transport distance becomes more drastic compared to other factors.

In pyrolysis and solvolysis, large amounts of electric power are required; thus changes in transport factors have a small effect, while changes in electricity use have the greatest impact, with pyrolysis exhibiting nearly a 50% impact. In conclusion, for all recycling and disposal, the greatest impact on the environment is from electricity use. To enhance the eco-friendliness of recycling technologies, it is essential to minimize electricity use and switch to other power sources.

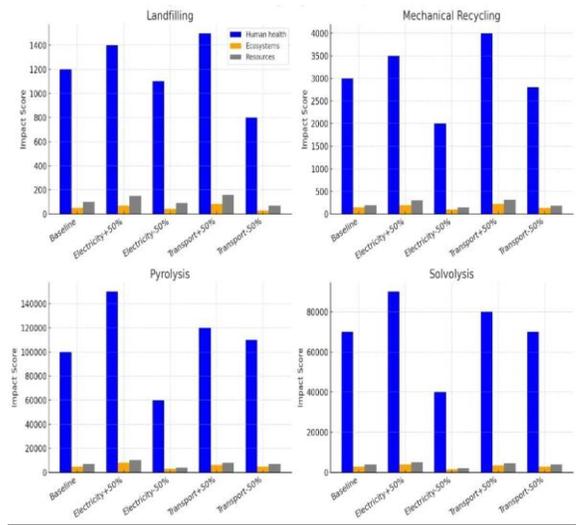


Figure 9: Sensitivity of Environmental Outcomes Across Four Disposal Methods

IV. DISCUSSION AND POLICY RECOMMENDATIONS:

Getting to know the impact throughout the life cycle of the environmental management of wind turbine blades composites gives important insights that further deepen understanding. The most important factors in the study were human health, ecosystems, and finally, the depletion of natural resources. Out of those factors, human health was the most important in every situation especially in the end stages, indicating its vital importance. The increase in CO₂ emissions during transport and recycling was caused by the burning of fossil fuels. Electrical fossil fuel usage is highly problematic for solvolysis and pyrolysis, processes for which more than 70% and 90% of the negative impacts to human health occur, respectively. Thus, a meaningful difference could be made by reducing electricity consumption and replacing fossil fuels. The impact of energy type is significant on recycling methods. For coal, the impact of pyrolysis was far worse than that of solvolysis. The negative impacts were greatly diminished by the use of wind and solar energy, which highlighted the importance of recycling and the use of renewable energy in waste disposal.



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The study also highlighted the variation in the amount of materials recycled and recovered. After landfilling, mechanical recycling carried the lowest environmental impact, but that score improved when lower recovery rates were factored in. The limitation of Life Cycle Assessments (LCAs) is they cannot appraise the value of recycled materials which is driven by the specific recycling process and the economic worth (Fonte and Xydis, 2021). This makes it challenging to analyze the environmental pros and cons of different recycling variations (Delaney et al., 2021). The market for secondary recycled composites has been expanding, particularly within sectors seeking recycled materials to replace newly minted ones. The techniques called Mechanical recycling yield composites of inferior quality that can only be used with cement and concrete, while advanced techniques like pyrolysis and solvolysis offer materials of higher quality (Sommer and Walther, 2021) which can be used for non-structural and even structural applications like automobiles, ships, and aircraft (Zhang et al., 2020; Pimenta and Pinho, 2011). Collaboration with stakeholders like wind turbine producers, waste administrative corporations, policy makers, and scholars is a must (Jensen et al., 2020). Encouraging innovation and improving disposal techniques is a multidisciplinary approach that must be undertaken. For the wind energy sector to be truly sustainable, it must operate within a managed sustainable circular economy and be complemented by the appropriate policies. Design for recyclability, holding manufacturers accountable, developing standards for safe disposals, and guaranteeing transparency within the circular economy are also imperative. Compared to the other attributes, the lack of project funds and the intricate task of formulating and implementing state and federal regulations continue to pose challenges (CEC, 2023). The addition of social and environmental requirements is linked to an increase in project time and costs. The contribution of the industry to the climate of the wind turbine has to be acknowledged, and the teaching of industry professionals and the general public proper recycling and turbine life cycle handling at each phase is of utmost importance. Achieving sustainability, lowering the environmental impact of wind energy, and recovering resources will promote the formation of a circular economy in the wind energy sector.

V. CONCLUSION

With the expansion of the wind energy sector in India, it is imperative to understand the ecological consequences of decommissioned wind turbine blades.

This research focuses on the four primary approaches of addressing old turbine blades which are mechanical recycling, landfilling, solvolysis and pyrolysis. It also explores the impact of substituting the type of electricity on the efficiency of waste management. A complete life cycle assessment, from cradle to grave, has been conducted on almost 262,930 tonnes of projected blade waste to be generated by the year 2060.

Core results include:

- Of all the recycling methods for FRP, pyrolysis and solvolysis have the most positive effect on the atmosphere.
- The effect of electrical energy consumptions on the environment is most pronounced in pyrolysis and solvolysis because they use large amounts of electricity.
- The use of less electricity, or a shift to renewable energy, can greatly increase the waste management eco-efficiency.
- However, the use of brown or hard coal during pyrolysis will suffer approximately 60% more negative environmental impact than solvolysis.
- The shift to renewable energy improves the eco-efficiency of both pyrolysis and solvolysis.
- Replacing fossil fuels with pyrolysis will have an 85% and 33% carbon footprint reduction for pyrolysis and solvolysis, respectively.
- The recycling of CO₂ by pyrolysis or solvolysis in the respective Indian states is almost 3.6 Mount in Victoria, 3.1 Mount in South India, and 2.7 Mount in New South Wales.

Limitation:

- Not having specific details on the types and amounts of carbon fiber vs. glass fiber used poses potential issues with the estimation of the environmental impacts of the study's assumed generic composite types.
- Due to the absence of recycling infrastructure for composites in India, the distance of EoL blade transport had to be guessed.
- Future studies will use reverse logistics optimization to improve impact assessments related to transport. This will address the current shortcomings in the study.

This study examines the environmental impacts of various end-of-life (EoL) options for wind turbine blade composites. It also emphasizes how the energy source chosen impacts the results.

This should aid decision-making in the prioritization of energy use and optimizing for human health and the overall environmental impact in the context of renewables and the future of energy.

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