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Life cycle environmental impact and disposal strategy selection of wind turbine blades based on uncertainty analysis

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ABSTRACT

The life cycle environmental impacts of wind turbine blades, crucial components of clean energy systems, require comprehensive assessment to guide sustainable waste management policies. Current evaluations often focus narrowly on disposal phases or single impact categories, leading to inconsistent conclusions due to divergent data sources and methodological approaches. Through an integrated life cycle assessment incorporating uncertainty analysis, this study establish that the manufacturing phase dominates the environmental footprint, contributing 44–99 % of total impacts across categories. Among end-of-life options, cement kiln co-processing yields the lowest climate impact, whereas pyrolysis and chemical recycling exhibit higher burdens. Sensitivity analysis identifies glass fiber and epoxy resin inputs as the dominant factors influencing environmental impacts across most scenarios, with benzyl alcohol consumption being the critical driver for chemical recycling. Threshold analysis further demonstrates that enhancing recyclate value can fundamentally shift environmental outcomes: certain technologies achieve net-negative impacts even under suboptimal conditions, while others require substantial yield or quality uplift to transition from environmentally detrimental to beneficial. Crucially, electricity decarbonization reshapes the relative performance landscape, with mechanical recycling and pyrolysis exhibiting heightened sensitivity due to their energy-intensive shredding and heating process. These findings underscore the necessity of prioritizing manufacturing innovations over end-of-life optimization alone. This study provides a robust, multi-criteria framework for policymakers and manufacturers to benchmark blade disposal technologies and strategically mitigate environmental impacts across the entire product life cycle.

1. Introduction

Achieving carbon neutrality requires a transformation of the power sector toward clean energy. Wind power, as a key solution, has received substantial policy support. Since 2005, when its cumulative capacity stood at just 1.3 GW (CWEA, 2010), China has seen explosive growth in wind power. It became the global leader in new installed capacity (13.8 GW, 36.8 % of the global total) in 2009 (CWEA, 2010; GWEC, 2010) and in cumulative installed capacity (44.7 GW) by 2010 (CWEA, 2011).

Although wind power is considered a clean energy source, the manufacturing, operation, and disposal of wind turbine equipment can still have significant environmental impacts. As the installed capacity of wind power grows, it is essential for the industry to continuously mitigate the environmental effects at each stage.

Blades are a crucial component of wind turbines, accounting for 20–30 % of the total system cost, second only to towers (Yang et al., 2023)0. The environmental impact of their production is substantial, particularly with epoxy resin, which contributes to nearly two-thirds of the global warming impact of this material (Diez-Cañamero and Mendoza, 2023). As wind turbines become larger, with rotor diameters increasing from under 100 m in 2015 to 136 m in 2020 (with the maximum reaching 166 m for onshore turbines), the materials used and

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environmental impact also grow.

The recycling of wind turbine blades (WTBs) is becoming an increasingly important issue as the first generation of turbines, installed around 2005, approaches decommissioning. By 2050, China is projected to generate 7.8 Mt. of blade waste (Yang et al., 2023)0. While recycling systems for materials like metals (copper, steel) are well-established, the composite materials in turbine blades, such as glass and carbon fiber composites, pose challenges because they cannot be easily melted, remolded, or degraded. Currently, a variety of end-of-life (EoL) strategies exist with distinct principles and outcomes: As traditional disposal methods, landfilling and incineration are subject to policy restrictions in regions such as China and the UK due to their consumption of land resources and greenhouse gas emissions (Hu et al., 2024). Cement kiln co-processing converts organic components into fuel for cement production through high-temperature treatment, while inorganic materials are incorporated into cement clinker (Ramos et al., 2025). Mechanical recycling has become the mainstream approach owing to its process adaptability; it primarily involves crushing blades for use in the construction materials sector (Revilla-Cuesta et al., 2024; Yazdanbakhsh et al., 2018a): transforming them into slender reinforcement fibers can enhance matrix toughness (Baturkin et al., 2021; Yazdanbakhsh et al., 2018b), and when combined with recycled construction aggregates, it demonstrates synergistic benefits by inhibiting shrinkage cracks in concrete (Trento et al., 2024; Baturkin et al., 2022). Pyrolysis and chemical recycling technologies recover fibers and organic products through anaerobic thermal decomposition and solvent dissolution, respectively. However, their large-scale application remains constrained by cost and efficiency limitations (Xu et al., 2025; Zhang et al., 2024).

The principles and outcomes of these technologies differ significantly, resulting in distinct environmental impact profiles. Therefore, comparing the environmental impacts of these recycling technologies is essential for identifying the most effective methods for reducing pollution and carbon emissions.

Research on the life cycle environmental impacts of wind turbine blade is rapidly advancing, focusing on several key areas. Cai et al. (2023) conducted a life cycle assessment (LCA) of nine common types of blades produced by Chinese companies, analyzing indicators such as acidification, eutrophication, greenhouse effects, and photochemical ozone formation. Similarly, Morini et al. (2021) found that using lower-impact epoxy resin and S-glass fiber instead of the standard materials could significantly reduce energy demand and carbon emissions. In terms of recycling, Diez-Cañamero and Mendoza (2023) assessed the circular economy performance and global warming potential of seven different recycling routes for Siemens Gamesa's blades, concluding that solvolysis, a chemical recycling process, had the highest circularity and lowest carbon footprint. Vo Dong et al. (2018) compared various recycling methods, finding that using recycled carbon fibers as substitutes for virgin fibers significantly reduced environmental impacts. Additionally, Yang et al. (2020) projected blade waste in China by 2050 and analyzed the environmental impacts of seven disposal methods in terms of energy consumption and greenhouse gas emissions. Heng et al. (2021) evaluated waste management strategies in Canada and found that cement kiln co-processing could achieve net-zero emissions by converting waste into energy and raw materials. Nagle et al. (2020) compared different disposal scenarios in Ireland and noted that the feasibility of co-processing increased with the volume of blade waste.

Despite the advancements in the field of life cycle environmental impacts (LCA) of wind turbine blades, existing research is constrained by several limitations.

The prevailing focus of LCA studies has been on the disposal phase, with a paucity of attention devoted to the production phase. The majority of existing studies have narrowly focused on carbon emissions and energy consumption, neglecting to address a comprehensive range of environmental impact categories. The findings and conclusions of disparate studies differ significantly, or even contradict each other, when comparing different recycling processes in the disposal stage. This underscores the crucial need for a more robust and integrated data framework, encompassing a diverse array of sources, to ensure the reliability of outcomes. Consequently, there is an imperative to synthesize diverse data sources to establish a reliable foundation for decision-making through multi-scenario and multi-data assessment employing uncertainty analysis.

To address these gaps, this study aims to provide a comprehensive and robust comparative life cycle assessment of multiple WTB EoL strategies. We compile an extensive inventory dataset by synthesizing multi-source data, explicitly incorporating uncertainty to reflect real-world variability. This foundation enables us to not only identify key contributors to environmental impacts across the entire lifecycle but also to reliably compare the environmental performance of different disposal processes under a unified framework. By further integrating sensitivity analysis on critical parameters and future energy trends, our work provides valuable insights for policymakers and industry stakeholders to formulate effective, evidence-based strategies for reducing pollution and carbon emissions throughout the blade's life cycle.

2. Methods

The methodological framework of this study is visually summarized in Fig. 1. The system boundary encompasses the entire life cycle of wind turbine blades, from manufacturing to final disposal. On the data collection side, multiple data sources were obtained through literature review and on-site collection, forming a life cycle inventory that explicitly incorporates uncertainty based on the distribution characteristics of the parameters.

On the analytical side, this inventory with uncertainty served as the basis for all subsequent calculations. First, the uncertainty in the impact assessment results was quantified using Monte Carlo simulation. Second, a comparative scenario analysis of different EoL strategies (S-1 to S-6) was conducted to evaluate their environmental trade-offs. Following this, a contribution analysis was performed for each scenario to identify the key life cycle stages, environmental impact categories, and processes. Finally, a sensitivity analysis was carried out to determine the critical parameters and their environmental impact turning points, as well as to explore the influence of evolving energy structures on the results. Detailed methodological descriptions are provided in the following sections.

2.1. Goal and scope definition

2.1.1. Function unit

A wind turbine blade is a cavity structure composed primarily of composite materials, which consist of two parts: the base material (resin) and the reinforcing material (glass or carbon fiber) (Joustra et al., 2021; Cooperman et al., 2021). This study focuses on the analysis of the most prevalent glass fiber and epoxy resin blades. 1 kg of blade is designated as the function unit to ensure the comparability of the research outcomes.

2.1.2. System boundary

The wind turbine blade life cycle begins with raw material acquisition and ends with disposal, following manufacturing, assembly, operation, and disassembly, as illustrated in Fig. 2. (Liu and Barlow, 2017). This study is performed from cradle to grave, and focuses on the phases during which the blade functions as an independent product. The disposal phase encompasses energy and material use, pollutant emissions, and potential recycling benefits. Transportation is excluded due to significant geographic variability and data uncertainty in blade production and recycling locations (Yang et al., 2020).

2.2. Uncertainty analysis

Given that the values of the same parameter vary across different

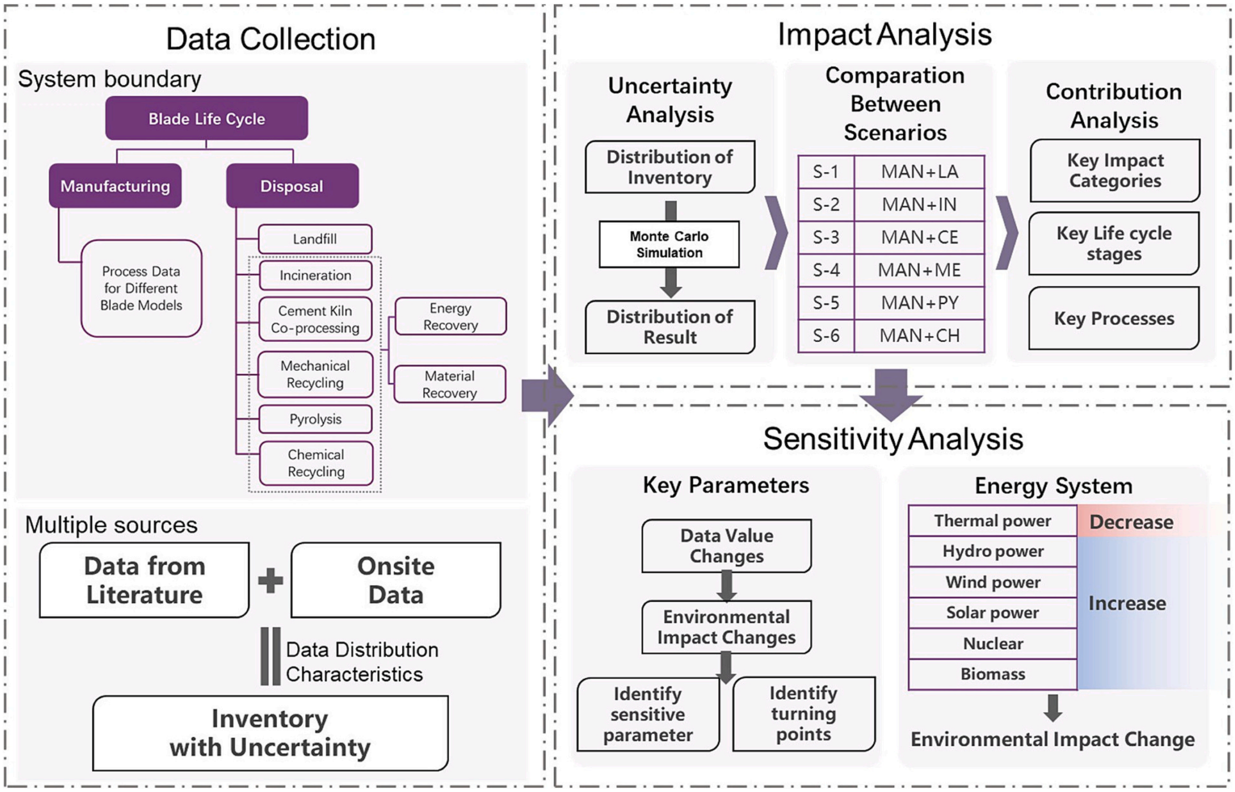

Fig. 1. Technology Roadmap.
Acronyms: MAN: manufacturing, LA: landfill, IN: incineration, CE: cement kiln co-processing, ME: mechanical recycling, PY: pyrolysis, CH: chemical recycling.

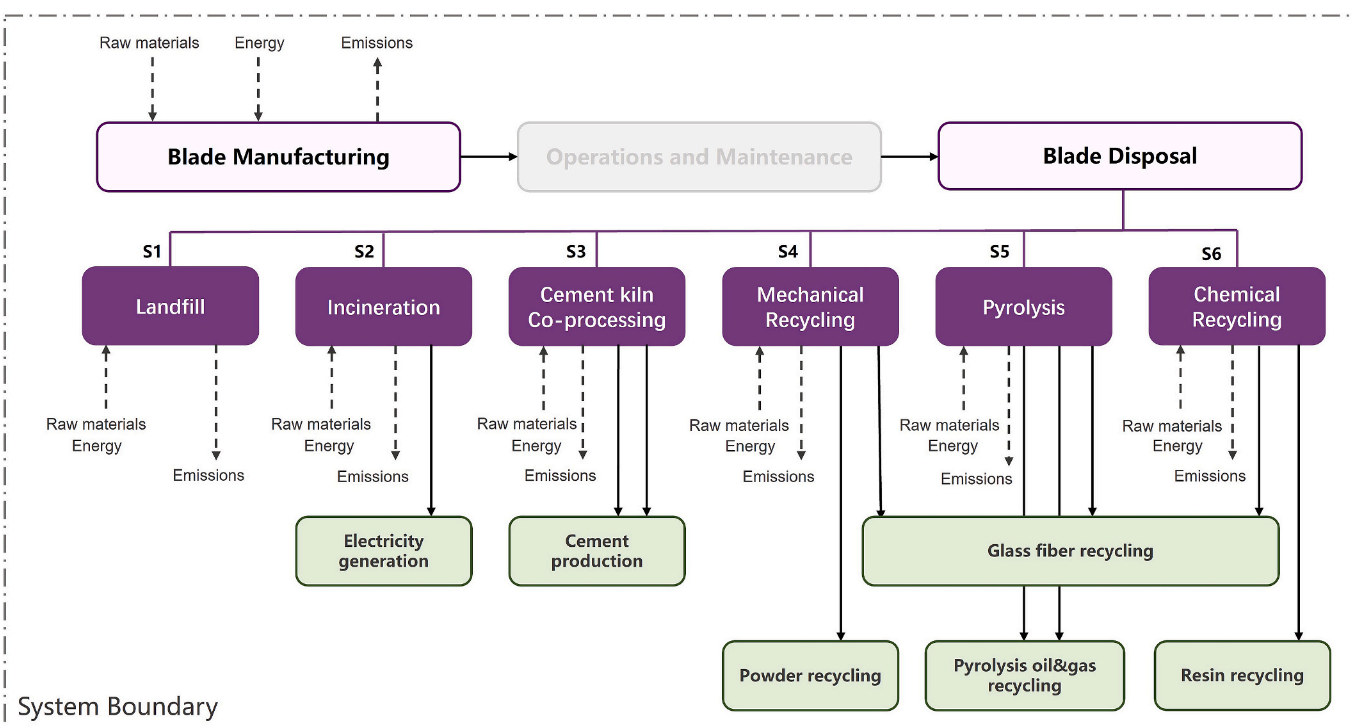

Fig. 2. System Boundary.

sources, this study proposes a probabilistic approach to calculate life cycle environmental impacts. Rather than relying on a single value, it defines a probability distribution for each input or output term based on data obtained from multiple sources. Then, it constructs random samples from the probability distributions defined for each parameter using Monte Carlo simulation. Repeated calculations are performed and summarized to obtain the uncertainty of the accounting results. For the sake of simplicity, the parameters were assumed to be independent of each other. The number of samples obtained and the characteristics of the data varied according to the parameters, and their distributions were assumed to be normal, lognormal, triangular, and uniform, respectively (Choudhary et al., 2014).

2.3. Life cycle inventory

The inventory data utilized for the calculations in this study are categorized into primary and secondary data. The direct energy consumption, material consumption, and pollutant generation of the blade manufacturing and disposal processes are primary data, which are derived from actual data from enterprises, and research and collection of literature and reports. These are listed in Section 1 of the supplementary Information. The production processes of the materials used in processes are secondary data from the ecoinvent 3.11 database.

2.3.1. Blade manufacturing

The blade manufacturing stage principally comprises material processing, component molding, and assembly. Initially, glass fiber and epoxy resin are amalgamated into a composite material, resin is poured into the fiber material and pressed into shape. Subsequently, the parts are bonded and assembled, and other accessories are installed. The inventory data for this process (see Table S1 in the Supplementary Information) is derived from the energy consumption, material consumption, and pollutant generation data of three distinct blade types (2 MW, 3 MW, and 5 MW) provided by CSSC Haizhuang Wind Power. This data set is supplemented with the blade material inventories of LM, Vestas, and Siemens Gamesa as disclosed in the DecomBlades project in Denmark (LM Wind Power, 2022; Vestas Wind Systems, 2022; SGRE, 2022).

2.3.2. Blade disposal

Six disposal methods were selected for this study: landfill, incineration, cement kiln co-processing, mechanical recycling, pyrolysis, and chemical recycling. Detailed descriptions and inventory data for the selected disposal methods are provided in the Supplementary Information (Table S2-S7), and are based on a wide range of published studies (Abbate et al., 2022; Hedlund-Åström, 2005; Kawajiri and Kobayashi, 2022; Khalil, 2018; Liu et al., 2019; Liu et al., 2021; Liu et al., 2022; Lefeuvre et al., 2017; Nunes et al., 2018; Pender et al., 2023; Pickering, 2012; Psomopoulos et al., 2019; Rathore and Panwar, 2023; Shuaib and Mativenga, 2016; Sproul et al., 2023; Vo Dong et al., 2015; Witik et al., 2013; Yousef et al., 2024; European Composites Industry Association (EuCIA), 2013).

2.3.3. Environmental credits of recycling wind turbine blades

The environmental credits associated with wind turbine blade waste management were calculated using the system expansion approach. In this approach, the recovered energy or materials from various recycling methods for blades were treated as substitutes for an equivalent amount of primary resources, based on the quantity and quality of the process outcomes. The materials or energy recovered from each EoL management method, how they are recycled, and the key parameters used to calculate the amount of primary materials substituted are listed in the Supplementary Information (Table S8), which compiles data, assumptions, and key parameters derived from previous studies (Liu and Barlow, 2017; Liu et al., 2022; Sproul et al., 2023; Vo Dong et al., 2018; Yousef et al., 2024).

2.4. Life cycle impact assessment and interpretation

In this study, life cycle modeling and impact assessment were performed using openLCA with the EF3.0 method. The Environmental Footprint (EF) method, proposed by the European Union, evaluates the environmental impacts of products, organizations, and services across 16 midpoint categories: Acidification, Climate change, Ecotoxicity: freshwater, Energy resources: non-renewable, Eutrophication: freshwater, Eutrophication: marine, Eutrophication: terrestrial, Human toxicity: carcinogenic, Human toxicity: non-carcinogenic, Ionizing radiation: human health, Land use, Material resources: metals/minerals, Ozone depletion, Particulate matter formation, Photochemical ozone formation: human health, Water use (Zampori and Pant, 2019).

To make the results more comparable, normalization and weighting were applied. Normalization compares the results to a reference value, such as annual environmental impacts in a region or globally. Weighting integrates the normalized results into a single assessment value by applying specific weights to each category. Normalization and weighting factors from EF3.0 were used for these calculations (Andreasi et al., 2023; Sala et al., 2018).

After obtaining life cycle impact results, interpretation is essential. In this study, "most relevant impact categories" refers to those with the greatest influence on overall environmental impact, as defined by the EU Product Environmental Footprint (PEF) methodology. These categories contribute at least 80 % to the total impact and must include at least three categories. The PEF also defines "most relevant life cycle stages" and "most relevant processes" as those that together account for 80 % of each relevant impact category.

Subsequently, a sensitivity analysis was performed to determine the parameters exerting the greatest influence on the results, and to assess how changes in the electricity mix affect the life cycle environmental impacts of the blades.

3. Results

3.1. Environmental impacts based on uncertainty

This study characterizes the probability distribution of inventory data based on data sources and employs Monte Carlo simulation to analyze result uncertainties. To illustrate the impact of individual process data distributions on outcomes, separate calculations are performed for manufacturing and disposal processes rather than presenting integrated results across the entire life cycle.

The results of climate change in Fig. 3 shows that the overall value of the manufacturing process is higher than that of the disposal process with less uncertainty, indicating that the manufacturing phase bears the main contribution to climate change in the life cycle of the blade and that the distribution of values of the inventory data for the manufacturing phase is more concentrated. Comparing different disposal processes reveals the following order of climate change impact from smallest to largest, based on median values: cement kiln co-

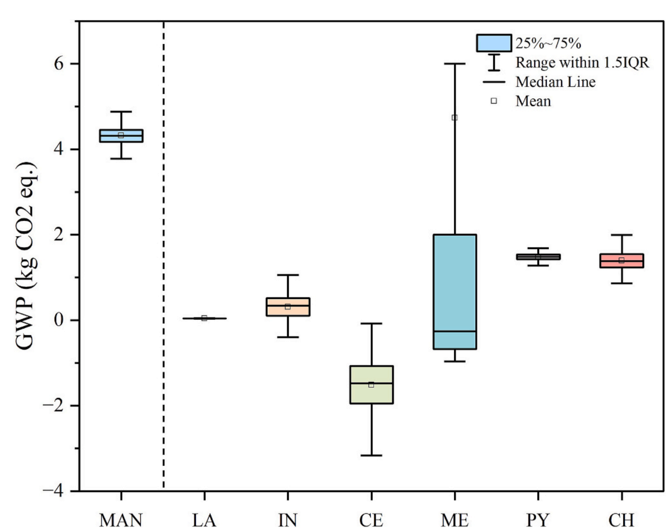

Fig. 3. Climate Change Impacts with Uncertainty in the Life Cycle Processes of Wind Turbine Blades.

processing, mechanical recycling, landfill, incineration, chemical recycling, and pyrolysis. The uncertainty in results, ranked from highest to lowest, is: mechanical recycling, cement kiln co-processing, manufacturing, incineration, chemical recycling, pyrolysis, and landfill. The results for mechanical recycling exhibit extremely high uncertainty, with values spanning from the lowest to the highest. Additionally, mechanical recycling exhibits a longer tail distribution at the high-value end. This stems from the process's energy consumption being highly dependent on specific equipment models, cutting precision, and shredding fineness, with reported energy consumption data in the literature exhibiting an extremely wide range. Cement kiln co-processing ranks second in uncertainty magnitude, primarily due to significant variations in thermal energy recovery and application methods across different studies. Notably, when evaluation metrics shift from climate change to other impact categories (see Figs. S1–S15 in Section 2 of the Supplementary Information), the uncertainty rankings of treatment options undergo substantial alterations. For instance, chemical recycling demonstrates moderate uncertainty regarding climate change impacts but exhibits the highest uncertainty in freshwater ecotoxicity potential. This underscores the importance of multi-criteria assessment and suggests that decision-makers should select EoL treatment options based on specific environmental priorities. These uncertainty characteristics, particularly the extreme spread in mechanical recycling, highlight the critical need for more robust and standardized data for emerging recycling technologies, a point we will further discuss in Section 3.4.

3.2. Environmental impact contribution analysis

The median life cycle environmental impacts of the wind turbine blades across the six EoL scenarios (S-1: landfill; S-2: incineration; S-3: cement kiln co-processing; S-4: mechanical recycling; S-5: pyrolysis; S-6: chemical recycling) are summarized in Table S9 (see Section 2 of Supplementary Information for the complete dataset). To enable comparison and aggregation across different impact categories, the results were normalized and weighted. The aggregated total environmental impacts are presented in Fig. 4.

Relative to landfill (S-1) as the baseline, cement kiln co-processing (S-3) and mechanical recycling (S-4) yield the lowest overall environmental impacts, reducing the total life cycle result to 75 % and 76 % of the baseline, respectively. Incineration (S-2) follows, reducing impacts to 96 % of the baseline. In contrast, pyrolysis (S-5) and chemical recycling (S-6) show no net reduction, with environmental impact values equivalent to 100 % and 119 % of the landfill scenario, respectively. This suggests that, under current assumptions, these advanced recycling methods do not yet offer environmental advantages over conventional landfill disposal for the overall impact score.

The contribution analysis, decomposed into three components—manufacturing (blue), disposal impacts (gray), and recycling benefits (green)—reveals that the manufacturing stage dominates the total environmental impact across all scenarios (Fig. 4). This is particularly evident for landfill and incineration (S-1 and S-2), where manufacturing accounts for nearly the entire impact, indicating that the choice of disposal method offers little benefit offset when recycling benefits are absent or minimal. The consistent prominence of the manufacturing phase underscores that reducing upstream impacts—through material substitution, energy efficiency, or process redesign—would yield greater environmental benefits than optimizing EoL treatment alone.

Building upon these aggregated results, a more granular analysis was conducted following the PEF methodology by first identifying the most relevant impact categories for each scenario and then drilling down into the specific processes that contribute the most within each key category.

The analysis of these most relevant categories—visually highlighted in red bars in Fig. 5 for clear identification—reveals a consistent pattern across scenarios S-1 to S-5, where metal and mineral resource depletion dominates, followed by climate change, non-renewable energy depletion, and freshwater ecotoxicity. This pattern underscores that the environmental profile is fundamentally governed by resource-intensive material production and energy consumption. A significant deviation

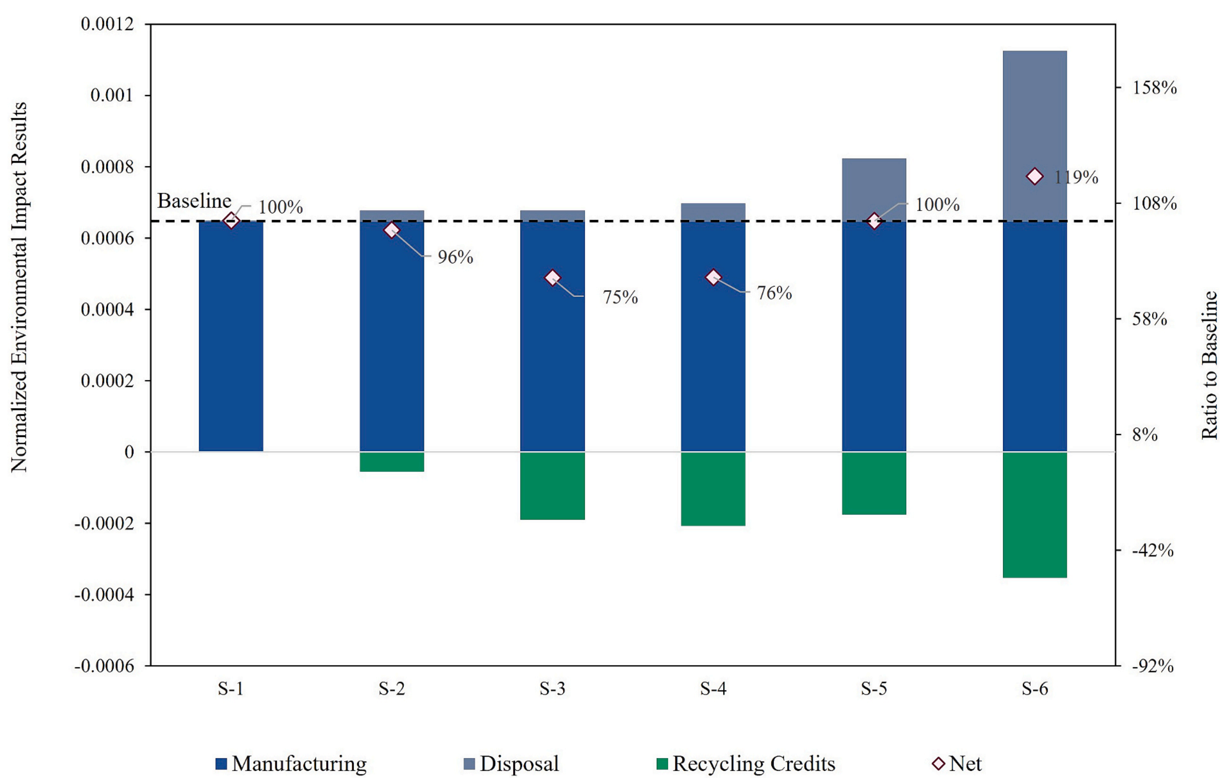

Fig. 4. Total environmental impact of different scenarios.

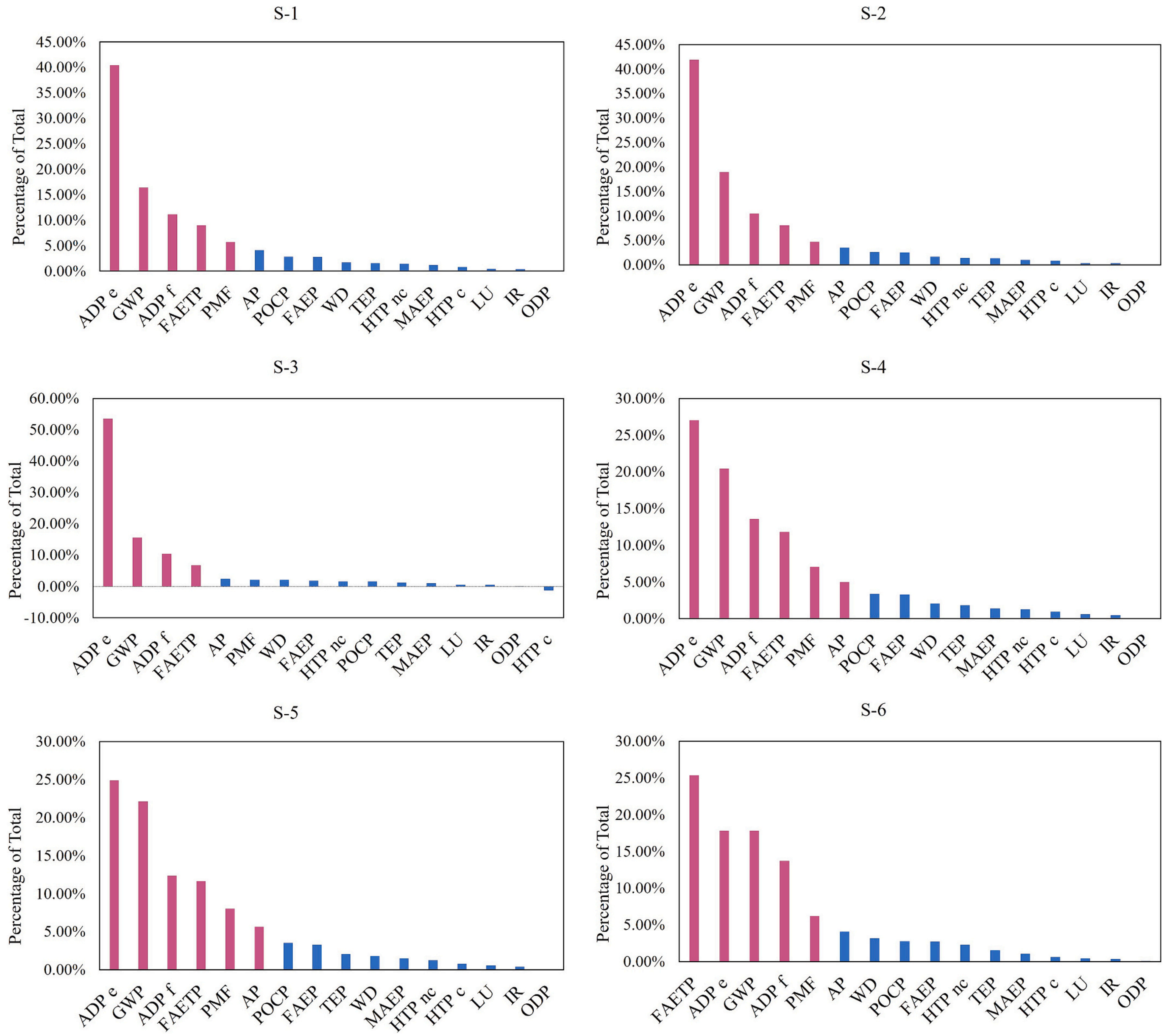

Fig. 5. Contribution of different impact categories to the total environmental impact of different scenarios.

from this pattern occurs in the chemical recycling scenario (S-6), where freshwater ecotoxicity emerges as the single largest contributor, surpassing resource depletion. This shift is directly attributable to the chemical inputs required for the process (e.g., benzyl alcohol and potassium hydroxide), highlighting a critical trade-off where advanced recycling may avoid resource depletion but introduce higher toxicity burdens.

Further analysis of the processes contributing to these key impact categories reaffirms that glass fiber production and epoxy resin production are the universal environmental hotspots across all scenarios. Beyond these common processes, the choice of EoL technology introduces distinct secondary contributors: heat or energy recovery becomes a major factor in incineration (S-2) and cement co-processing (S-3); the production of chemical inputs, notably benzyl alcohol and potassium hydroxide, emerges as the most relevant process for multiple categories in chemical recycling (S-6); and the environmental benefits from recovered materials, such as glass fibers and recycled resins, constitute significant positive contributions in mechanical (S-4), pyrolysis (S-5), and chemical (S-6) recycling, as visually evidenced by the taller bars in corresponding categories of Fig. 6. This analysis demonstrates that while material production dominates the overall impact, the selection of an EoL pathway determines the secondary hotspots, influencing whether the primary trade-off involves energy recovery, chemical consumption, or recycling operations.

3.3. Sensitivity analysis

The specific scenarios and corresponding input variables considered in this section, as well as the detailed calculation results, can be found in the Excel file provided in the Supplementary Information.

3.3.1. Sensitivity to key parameters and recyclate value

A one-way sensitivity analysis (Fig. 7) was conducted by increasing key inputs by 10 % to identify the parameters with the greatest influence on the total environmental impact. The specific parameters selected for this analysis are detailed in Section 3 of the Supplementary Information (Table S10).

The results unequivocally identify glass fiber and epoxy resin

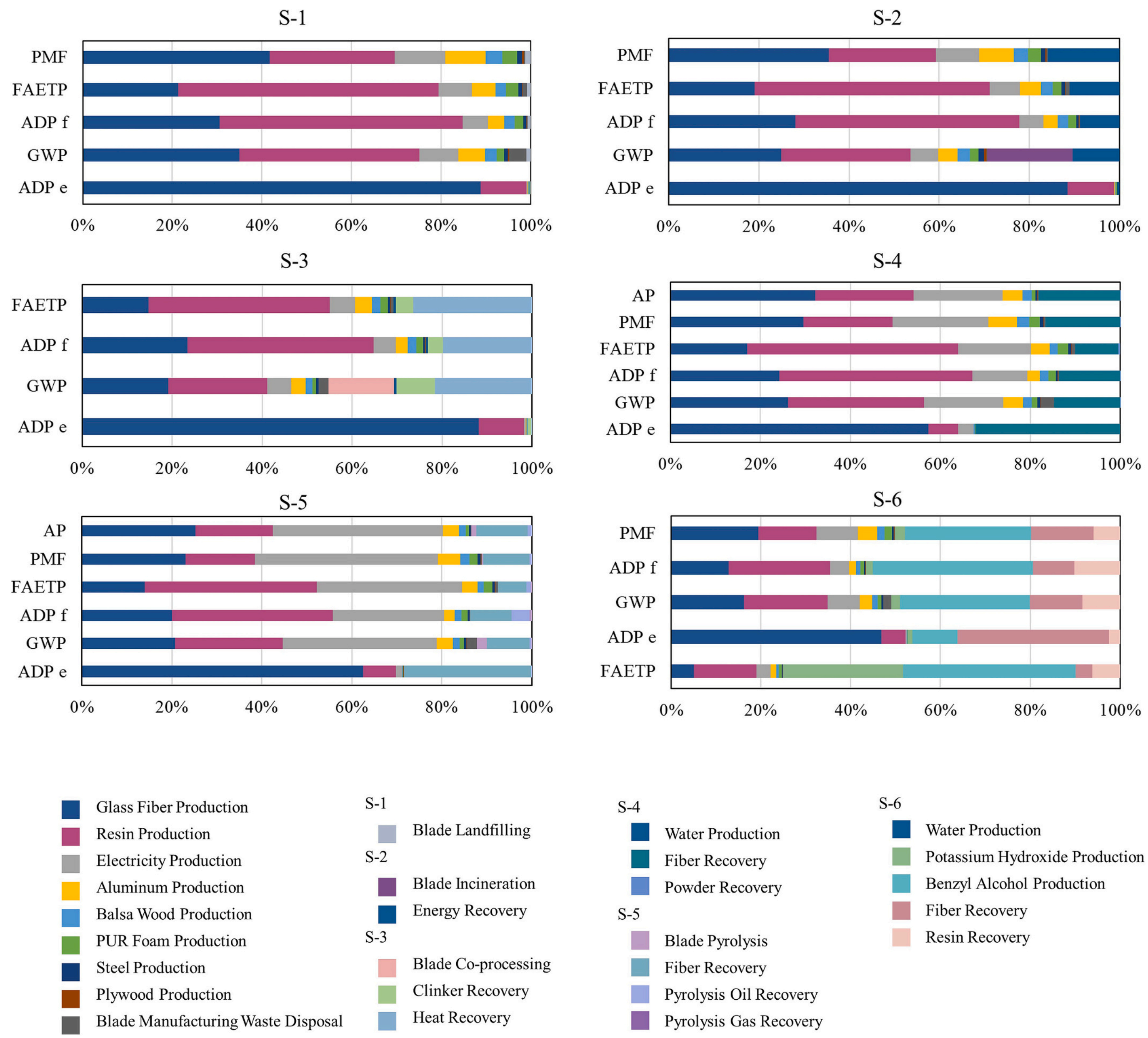

Fig. 6. Contribution of different processes to the total environmental impact of different scenarios.

consumption as the two most sensitive parameters across all EoL scenarios, reinforcing their role as the primary environmental hotspots. This underscores that efforts to reduce the life cycle impact must prioritize material efficiency and alternative material development.

Beyond these common hotspots, process-specific sensitivities were identified:

- For chemical recycling (S-6), the consumption of benzyl alcohol emerged as the most sensitive parameter, even exceeding the impact of glass fiber.
- For pyrolysis (S-5), the electricity consumed during the process was the third most sensitive factor.
- Crucially, for all recycling methods (S-3 to S-6), the amount of recyclate recovered was a key sensitive parameter, ranking just behind the primary material inputs. This highlights that the efficiency and output of the recycling process itself are critical determinants of its overall environmental performance.

This finding directly motivates a threshold analysis to determine the critical recyclate value required for each EoL technology to achieve a net environmental benefit (i.e., Global Warming Potential $\leq$0). As shown in Fig. 8, a stark contrast is observed:

- Inherently Beneficial Technologies: Cement kiln co-processing (CE) and mechanical recycling (ME) already demonstrate a net benefit under baseline conditions. Their breakeven points occur at negative recyclate value variations, indicating high robustness and a lower risk of net environmental harm.
- Efficiency-Dependent Technologies: Incineration (IN) and chemical recycling (CH) require significant improvements in recyclate yield and quality (positive value variation) to reach breakeven, highlighting their potential contingent on technological advancement.
- Energy-Limited Technology: Pyrolysis (PY) did not cross the breakeven point within the assessed range, suggesting its high energy consumption presents a fundamental challenge to achieving carbon neutrality with current technology.

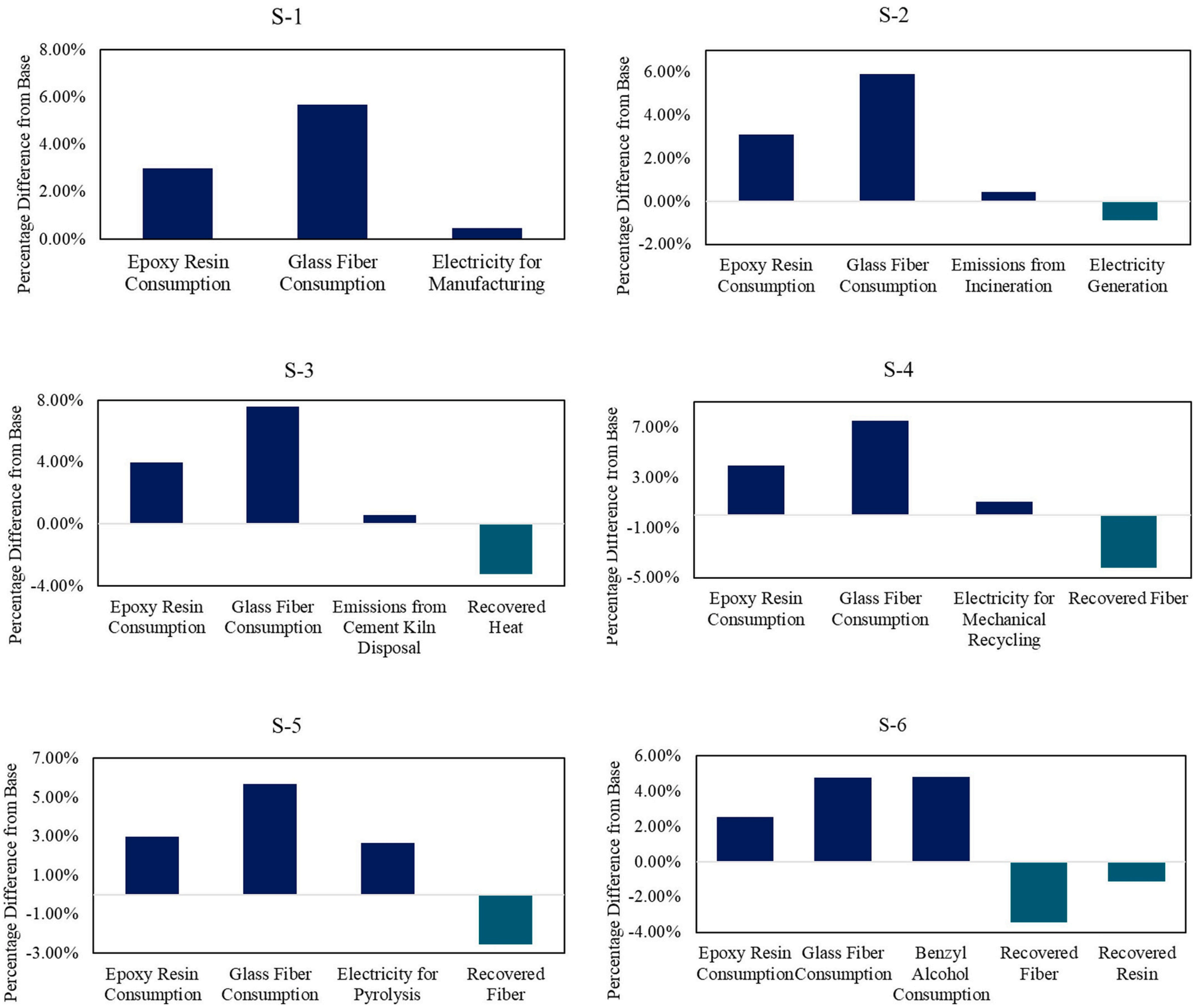

Fig. 7. Results of sensitivity analysis of total environmental impacts.

3.3.2. Changes in the electricity mix

Future electricity mix scenarios were constructed based on the projected evolution of China's power grid, as forecasted in the report "China's Energy and Power Development Plan for 2030 and Outlook for 2060", released by Global Energy Interconnection Development and Cooperation Organization in 2021. The baseline scenario reflects the current structure from the China Energy Statistics Yearbook 2022, while future scenarios model the increasing share of clean energy (wind, solar, hydro, nuclear, and biomass) and the corresponding decline of thermal power at four time points: 2025, 2030, 2050, and 2060 (see Table S11 in Section 3 of the Supplementary Information for detailed shares).

The decarbonization of the electricity mix significantly reduces the life cycle environmental impact across almost all impact categories and scenarios, as the environmental burden of electricity consumption decreases (Fig. 9). Several distinct trends and exceptions to this overall reduction were identified:

1. Differential improvement among EoL scenarios: Although a cleaner grid improves the environmental performance of all EoL options, the magnitude of improvement varies significantly due to their differential electricity consumption. This variation alters the relative ranking of EoL scenarios in certain impact categories. For example, in acidification potential (AP), mechanical recycling and pyrolysis—which initially exhibited the highest impacts—are projected to become the second and third most environmentally friendly options by 2060 as the grid decarbonizes. This shift occurs because these processes are highly electricity-intensive: mechanical recycling requires substantial power for shredding and crushing retired blades, while pyrolysis depends heavily on external energy for high-temperature heating.
2. Increased impact of incineration: The net environmental impact of incineration (IN) increases as the grid decarbonizes. This occurs because the environmental credit from incineration is derived from displacing grid electricity; as the grid becomes cleaner, the marginal benefit of displacing a unit of electricity diminishes.
3. Increased ionizing radiation and land use impacts: The impacts for ionizing radiation (IR) and land use (LU) increase over time. This is directly attributable to the rising shares of nuclear power (which contributes to IR through the nuclear fuel cycle) and photovoltaic (PV) power (which has a relatively high land use footprint per unit of electricity generated), respectively, in the future energy mix.

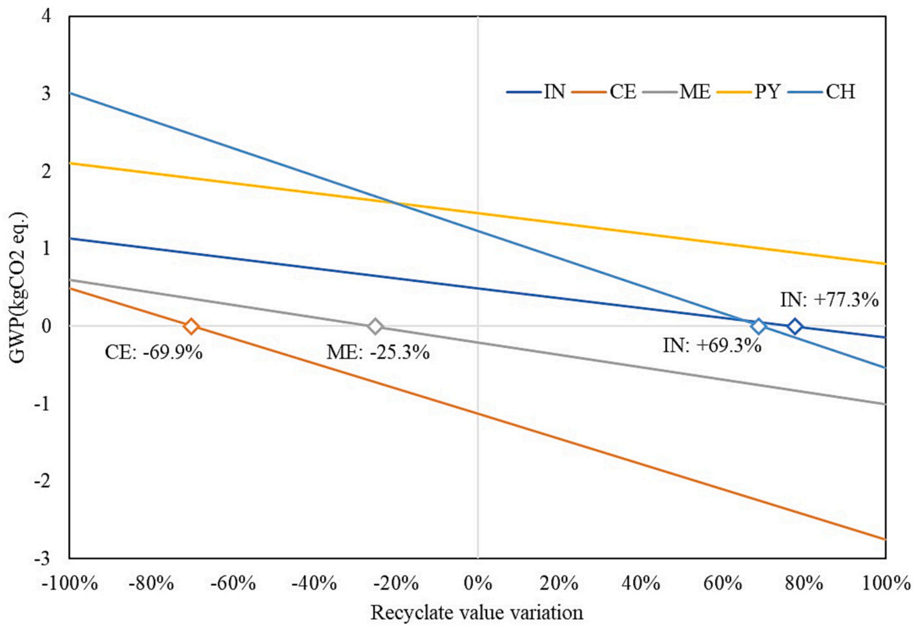

Fig. 8. Sensitivity of GWP impact of blade as a function of the recyclate benefit.

To facilitate clearer observation of these changes, Fig. 9 provides magnified views of several impact categories that exhibit pronounced trends.

3.4. Discussion

Many LCA studies on wind turbine blade disposal rely on singular or inconsistent data sources, leading to significant variability in results and hindering cross-study comparability. As illustrated in Fig. 10, the global warming potential (GWP) values reported in literature (Cong et al., 2023; Deeney et al., 2021; Diez-Cañamero and Mendoza, 2023; Heng et al., 2021; Korey et al., 2023; Liu et al., 2019; Pender et al., 2023; Sproul et al., 2023; Yang et al., 2023; and Yousef et al., 2024) vary considerably—for instance, landfill results span an order of magnitude, while incineration and cement co-processing are sometimes credited with net-negative emissions and elsewhere with net-positive impacts. These discrepancies stem not only from differences in data sources but also from variations in system boundaries, allocation methods, and technological assumptions across studies. For example, the outlier conclusion by Diez-Cañamero and Mendoza (2023)—that chemical recycling yields the lowest GWP—likely arises from a narrow scoping that omits chemical production impacts, focusing solely on energy use. In contrast, the present study explicitly accounts for uncertainty and variability through probability distributions in the life cycle inventory, offering a more nuanced and statistically informed basis for decision-making. While our results for landfill and incineration show broad agreement with literature, the lower impact estimated for cement co-processing can be attributed to our assumption of 100 % clinker substitution efficiency. Similarly, the long upper tail in mechanical recycling reflects the high uncertainty in electricity consumption data, modelled log-normally to better represent real-world variability.

Most published studies focus exclusively on climate change, with limited attention to other environmental indicators. Yet, as demonstrated in Table S12 and S13 (see Section 4 of the Supplementary Information), which compile literature values for GWP and abiotic resource depletion (ADP), the relative performance of disposal options can shift dramatically even between these two commonly reported categories. This divergence underscores a critical limitation of single-criterion comparisons: a method leading in GWP reduction may perform poorly in ADP, as these tables clearly illustrate. If such inconsistencies arise between just two indicators, the integration of a broader set of impact categories—such as ecotoxicity or land use—would inevitably reveal even more complex trade-offs. These findings compellingly argue against oversimplified environmental rankings and highlight the necessity of multi-criteria decision frameworks that reflect diverse environmental priorities—particularly within policy and industrial contexts where trade-offs are inevitable.

When evaluating EoL technologies from an integrated perspective, it becomes evident that no single disposal method outperforms others across all environmental and technical dimensions. Mechanical recycling and cement co-processing currently represent the most environmentally favorable options based on median impacts, owing to their relatively mature processes and favorable energy/material recovery balances (Yazdanbakhsh et al., 2018a, 2018b; Baturkin et al., 2021). However, pyrolysis and chemical recycling—though presently exhibiting higher life cycle impacts—offer unique advantages: they enable recovery of high-value materials, reduce downcycling, and align with circular economy principles. Their current environmental burdens largely reflect their developmental status; most studies rely on pilot-scale or theoretical data, where energy efficiency has not yet been optimized. From a technical standpoint, chemical recycling shows promise in regenerating virgin-quality fibers and resins, while pyrolysis can yield reusable fibers and fuels—but both remain energy-intensive and costly compared to conventional options (Xu et al., 2024). Significant investment in process scaling, catalyst development, and solvent recovery is needed to reduce their costs and environmental footprints.

Ultimately, the greatest share of environmental impacts arises not from the EoL stage, but from the manufacturing phase—dominated by glass fiber and epoxy resin production. These processes are energy- and emission-intensive, involving high-temperature melting, chemical synthesis, and substantial fossil fuel-derived inputs. Therefore, while optimizing disposal pathways is relevant, the most impactful reductions in life cycle emissions would be achieved through material innovation—such as bio-based resins, recycled fiber feedstocks (Beauson et al., 2025), or low-curing matrices (Pender et al., 2024)—coupled with industrial decarbonization measures like renewable energy integration, heat recovery, and catalytic efficiency improvements (Furszyfer Del Rio et al., 2022; Sogancioglu et al., 2019; Pizza et al., 2014; Mu and Vaughan, 2020; Hermansson et al., 2022).

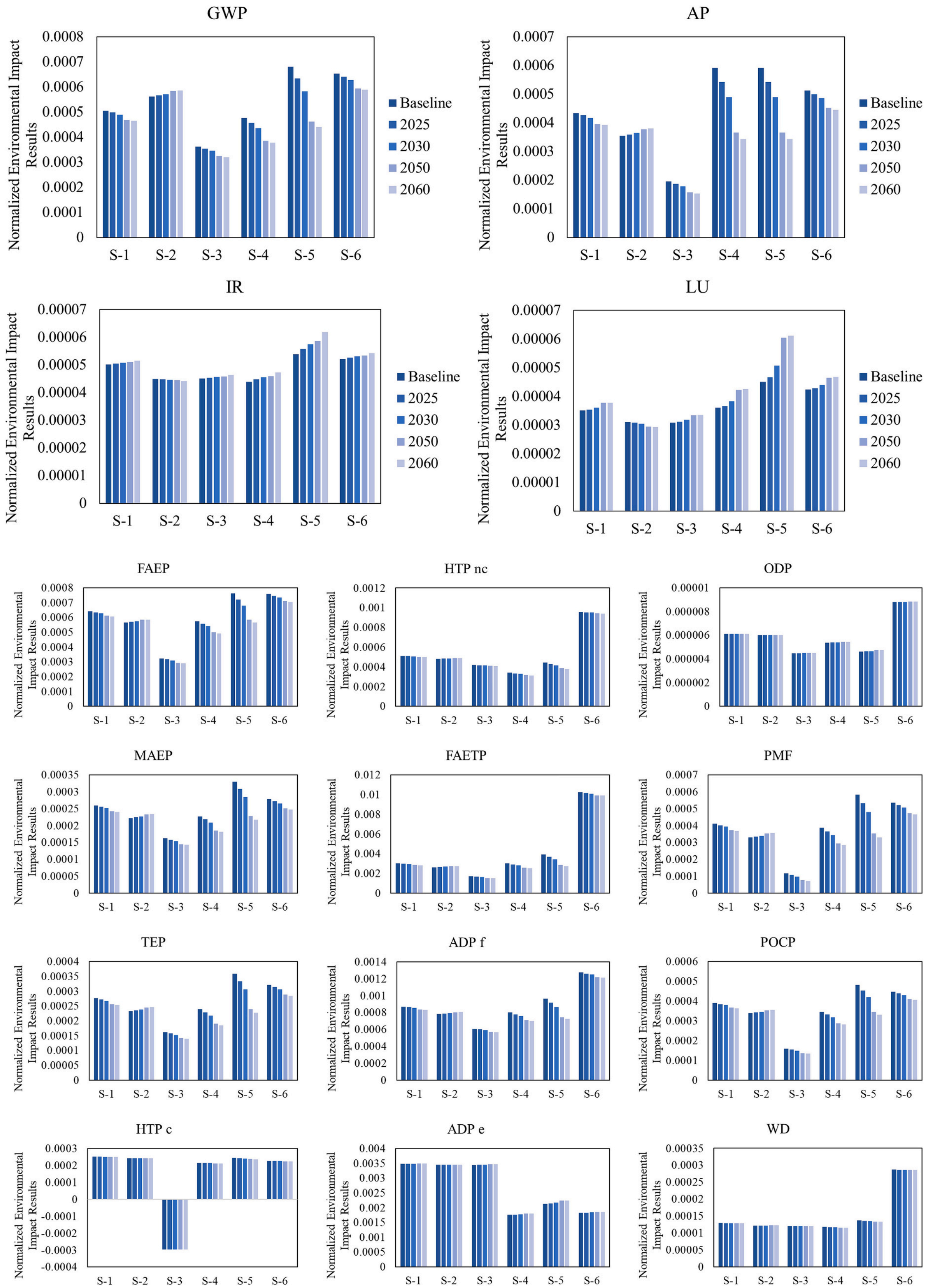

Fig. 9. Changes in environmental impacts under different energy mixes.

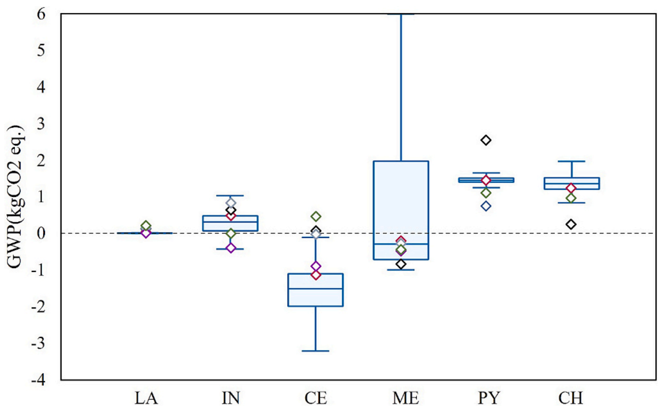

Fig. 10. Distribution of GWP result values for different recycling processes in this and other studies. Notes: Scatter points denoting environmental impacts of different EoL options as reported in prior literature, the box plots depict the results derived in this study.

4. Conclusion and future research direction

This study compared the life cycle environmental impacts of six EoL options for wind turbine blades through a comprehensive assessment incorporating uncertainty analysis. The key findings are:

- Cement kiln co-processing and mechanical recycling were identified as the environmentally preferable options, exhibiting the lowest overall environmental impacts.
- In contrast, chemical recycling and pyrolysis were associated with the highest environmental burdens under current technological assumptions.
- The manufacturing stage, dominated by glass fiber and epoxy resin production, was confirmed as the largest contributor to the life cycle environmental impacts across all scenarios.
- Sensitivity analysis revealed that glass fiber and epoxy resin quantities were the most influential parameters overall; however, benzyl alcohol consumption was the dominant factor for chemical recycling.
- Threshold analysis suggests that improving recyclate value is critical for enhancing the performance of incineration and chemical recycling, while maintaining high recyclate quality is essential for cement kiln co-processing and mechanical recycling. For pyrolysis, enhancing energy efficiency and emission control is the primary opportunity for impact reduction.
- The decarbonization of the electricity mix generally reduces the environmental impacts across scenarios, except for incineration, where the benefit is offset by a reduction in credited avoided electricity production.

This study provides a robust decision-support framework that quantifies the environmental trade-offs between various blade EoL strategies under uncertainty. Based on our analytical approach and results, cement kiln co-processing and mechanical recycling emerge as the most promising options within the environmental dimension assessed. It should be noted, however, that environmental impact is only one of the many aspects to consider when selecting EoL treatment options for wind turbine blades. A comprehensive evaluation including economic costs, processing efficiency, and technological maturity is necessary for practical implementation. Furthermore, since the manufacturing stage dominates the environmental impacts, future research should expand the assessment to blades made of different materials, especially carbon fiber-reinforced polymers, which are expected to be used in next-generation larger turbines. Such studies will be crucial for guiding the sustainable management of composite waste in line with evolving industry practices.

Declaration of competing interest

We confirm that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.108214.

Data availability

Data will be made available on request.

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