Renewable Energy 274 (2026) 126181

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Framework for circular economy strategies in wind turbine end-of-life management

Pierre Doisy, Jagruti Thakur *

Department of Energy Technology, KTH Royal Institute of Technology, Stockholm, Sweden

ARTICLE INFO

Keywords:
Circularity framework
Wind turbine generator
Second-life
End-of-life management
Circular economy
9R framework

ABSTRACT

This study presents an integrated decision-support framework for evaluating circular economy strategies for end-of-life management in wind turbine generators (WTGs). The proposed framework combines economic, environmental, and circularity indicators to assess alternative pathways including repair, refurbishment, reuse, remanufacturing, recycling, and repowering. A circularity metric based on the 9R framework is developed to quantify the relative circular performance of different scenarios. Through scenario-based analysis, the framework evaluates the impacts of lifetime extension strategies on annual energy yield, greenhouse gas emissions savings, and economic performance. The results highlight the significant potential of second-hand WTG markets, particularly when turbines are relocated to sites with favourable wind conditions. The findings further demonstrate that increased circularity can simultaneously improve resource efficiency, reduce environmental impacts, and create additional economic value. The proposed framework provides a transparent and adaptable tool to support decision-making toward more sustainable and circular practices in the wind energy sector.

Abbreviations

Abbreviation	Full Form
AEY	Annual Energy Yield
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CE	Circular Economy
EIA	Economic Impact Assessments
EoL	End-of-Life
IEA	International Energy Agency
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NZE	Net Zero Emissions
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PPA	Power Purchase Agreement
ROI	Return on Investment
SDG	Sustainable Development Goal
WTG	Wind Turbine Generator
Nomenclature	
u	Wind speed
CP	Power coefficient
ρ	Density
A	Wind Turbine Generator rotor area
η_e	Electrical efficiency
η_m	Mechanical efficiency
$\overline{u}$	Location average wind speed
T_0	Initial design lifetime
i	Discount rate
n	Year n
$CAPEX_n$	Capital expenditure in year n
$OPEX_n$	Operation and maintenance expenditure in year n
B_n	Benefits year n
C_n	Costs year n
T	Effective lifetime
L_p	Product's average lifespan
L_avg	Average lifespan of a similar range of product
$mass_{product}$	Mass of the considered product
$mass_{average}$	Average mass of the considered product
$AEY_{product}$	Annual Energy Yield of the considered product
$AEY_{average}$	Average Annual Energy Yield of the considered product
M_p	Ratio mass electricity production for the considered product
M_{avg}	Average ratio mass electricity production for the considered product
Nb_{tot}	Total number of parts in the product

(continued on next column)

(continued on next page)

This article is part of a special issue entitled: SDEWES2025 - RENE published in Renewable Energy.

* Corresponding author.
E-mail address: jrthakur@kth.se (J. Thakur).

https://doi.org/10.1016/j.renene.2026.126181
Received 16 February 2026; Received in revised form 8 July 2026; Accepted 9 July 2026
Available online 10 July 2026

(*continued*)

Abbreviation	Full Form
Nb_{reuse}	Number of reused parts from the old product in a new one
$Nb_{repaired}$	Total number of repaired parts in the WTG
$Nb_{tot\_reparable}$	Total number of repairable parts in the WTG
$Nb_{reusable}$	Number of spare parts reusable from the considered WTG in a new one
$Nb_{repurposed}$	Number of spare parts repurposed from the considered WTG in new products
$N_{ass.sep}^{diff}$	number of dismantlable assembly points between two different materials
$N_{ass.non-sep}^{diff}$	number of non-separable assembly points between two different materials

1. Introduction

The global transition toward a sustainable and circular economy has become a key strategy to mitigate climate change and enhance long-term societal resilience. As electrification increasingly drives decarbonization strategies across multiple sectors, electricity generation from low-carbon sources has gained strategic importance. Within this context, wind energy has emerged as one of the most mature and rapidly expanding renewable technologies. However, as the first generations of wind turbine generators approach the end of their operational life, a significant challenge is becoming increasingly apparent: the sustainable management of wind turbine end-of-life processes. Current practices, dominated by recycling, recovery, or landfill, remain largely linear in nature and fail to fully realize the potential environmental and economic benefits offered by circular economy strategies.

The urgency of this challenge is reinforced by the broader international policy landscape. In 2015, the adoption of the 17 United Nations Sustainable Development Goals (SDGs) alongside the Paris Agreement marked a pivotal moment in global climate governance. The Paris Agreement, ratified by 196 Parties, aims to limit global temperature rise to well below 2°C, with efforts to remain within 1.5°C above pre-industrial levels, in line with Intergovernmental Panel on Climate Change (IPCC) recommendations [1]. This unprecedented international consensus has driven national commitments toward carbon neutrality. Despite these commitments, scientific evidence continues to highlight the severity of the climate crisis. Recent IPCC assessments have emphasized the narrowing window for effective action, while updates to the Planetary Boundaries framework indicate that six of nine critical thresholds have already been exceeded [2,3]. Current projections suggest that, under existing policy trajectories, global temperatures could rise by approximately 3°C by the end of the century [4], far exceeding the ambitions of international agreements. In this context, the focus has increasingly shifted from merely expanding renewable energy capacity to ensuring that energy systems are sustainable across their entire lifecycle.

Energy lies at the core of modern societies, underpinning activities ranging from heating and cooling buildings to powering transportation and digital technologies. Reflecting this central role, Sustainable Development Goal 7 aims to ensure access to “affordable, reliable, sustainable and modern energy for all” by 2030 [5]. Achieving this goal while simultaneously reaching carbon neutrality has led to the development of numerous energy transition scenarios. A common conclusion across these scenarios is that while overall energy consumption must decrease through efficiency improvements and demand reduction, electricity demand is expected to increase significantly as sectors electrify [6]. Consequently, renewable electricity generation, particularly from wind and solar, is expected to expand substantially [7].

Wind energy has already experienced remarkable growth over the past two decades. Global wind electricity generation increased from approximately 31 TWh in 2000 to nearly 2000 TWh in 2022 [8]. Installed wind capacity expanded from around 200 GW in 2011 to nearly 900 GW in 2021, representing a 4.5-fold increase in just ten years [9]. In 2022 alone, wind power generation grew by 265 TWh, corresponding to a 14% year-over-year increase [10]. However, achieving alignment with the International Energy Agency's Net Zero Emissions by 2050 scenario will require sustained annual growth of approximately 17% between 2024 and 2030 [10]. These figures underscore both the success of wind energy deployment and the magnitude of the effort still required.

At the European level, wind energy development is central to the European Green Deal and the objective of achieving climate neutrality by 2050. Initiatives such as the REPowerEU plan set ambitious targets for wind power deployment, with wind energy expected to provide 50% of the European electricity mix by 2050, up from 14% in 2018 [11]. Despite these ambitions, current deployment rates remain insufficient. In 2022, only 16 GW of wind capacity was installed across the European Union, far below the estimated 37 GW per year required to remain on track for 2030 targets aligned with the NZE scenario [12].

As wind capacity continues to expand, the issue of WTG end-of-life (EoL) management is becoming increasingly pressing. A growing body of literature has examined wind turbine performance, cost efficiency, and environmental impacts. Studies by Bhandari et al. [13] and Crawford [14] demonstrate how design and operational parameters, such as capacity factor, hub height, and rotor diameter, directly influence energy yield and carbon intensity. Higher turbine efficiency has also been shown to reduce the Levelized Cost of Energy (LCOE), strengthening the economic competitiveness of wind power [15]. Additionally, research on Global Warming Potential (GWP) highlights how increased turbine size and optimized operating conditions can reduce emissions per unit of electricity produced [13].

Beyond performance optimization, lifetime extension has emerged as a strategy to delay decommissioning and improve return on investment. Rubert et al. [16]propose methodologies for Lifetime Extension Analysis, which have been adopted in countries such as Germany and Denmark. However, regulatory uncertainty persists in other markets, including the United Kingdom [17], illustrating how national policy frameworks strongly influence the feasibility of circular economy (CE) strategies. This variability underscores the importance of localization when assessing CE options for WTG end-of-life management.

In recent years, researchers have increasingly advocated for integrating CE principles into the wind energy sector. They argue for a departure from linear “take-make-dispose” models toward approaches emphasizing design-for-disassembly, extended product lifetimes, and improved material recovery. Industry-led initiatives, including the Circular Wind Hub, promote collaboration, data transparency, and regulatory harmonization to enable system-wide circularity. Currently, it is estimated that 85% to 90% of a wind turbine's mass is recycled at the end of its life [18], with the remaining fraction managed through other disposal or energy recovery methods.

A substantial portion of CE research has focused on turbine blades, which remain one of the most challenging components to manage at end-of-life and are often cited as a major criticism of wind energy deployment. While blade reuse is environmentally preferable, structural constraints limit its applicability. Recycling options such as mechanical, thermal, and chemical methods are advancing, but each faces economic and technological barriers [19]. Advanced techniques such as pyrolysis and solvolysis show promise but remain costly and difficult to scale, while mechanical recycling typically yields lower-value outputs [20]. Despite ongoing research, industrial uptake remains limited.

As the first generation of wind farms begins to reach the end of their operational life, alternative strategies such as lifetime extension and repowering are gaining attention. Lifetime extension allows developers to continue operating existing infrastructure for a number of additional years, typically with some refurbishment, thus maximizing return on investment. Repowering, on the other hand, involves replacing older turbines with newer, more efficient models, often resulting in higher electricity output using either the same number of turbines or fewer units with greater capacity. Despite its potential, repowering remains underutilized, with less than 10% of decommissioned wind farms in Europe currently undergoing this process [21].

Manufacturers have begun embedding circularity into turbine design, aiming for fully recyclable components and reduced lifecycle emissions. While these initiatives represent important progress, they remain largely technology-focused and do not provide a comprehensive framework for evaluating and comparing different end-of-life strategies.

Several tools exist to assess the economic and environmental dimensions of wind energy projects. Economic metrics include Cost-Benefit Analysis, Return on Investment, Economic Impact Assessments, and LCOE, each offering distinct insights into project viability. On the environmental side, Life Cycle Assessment remains the most comprehensive method, complemented by carbon footprint and water use assessments. However, methods for assessing circularity are less mature. Tools such as Material Flow Analysis track resource inputs and outputs, while emerging circularity indicators lack standardization and integration into decision-making processes.

Notably, the potential for reuse and the development of a second-hand WTG market remain largely unexplored. Barriers include the absence of standardized certification schemes, unclear resale criteria, and limited tools for validating turbine performance post-decommissioning. Yet, establishing such a market could significantly enhance resource efficiency, reduce environmental burdens, and expand access to wind energy in emerging markets.

Although circular economy applications in the wind sector have received growing attention, the existing body of literature remains fragmented. Much of the research has concentrated on specific turbine components, particularly blades, which represent one of the most challenging waste streams from wind energy systems [22,23]. For example, Joustra et al. [24] examined how product design influences the recovery and reuse potential of composite materials, while Beauson et al. [25] provided a comprehensive review of sustainable end-of-life pathways for wind turbine blades, including reuse, recycling, landfill, and energy recovery options. Similarly, Türkay et al. [26] investigated circular economy opportunities for blade materials in the construction sector, and Deeney et al. [27] reviewed circular pathways for blade waste, highlighting the predominance of recycling-oriented approaches despite the higher value retention potential of reuse and repurposing strategies.

More recent studies have expanded the discussion beyond blades to address broader end-of-life management challenges. Reviews published in the literature emphasize the technical and economic uncertainties associated with recycling composite materials, recovering critical raw materials, and scaling circular business models for wind energy systems. Notably, recent syntheses of wind turbine end-of-life management have highlighted the need for decision-support approaches capable of evaluating trade-offs between competing circular strategies, particularly with respect to economic feasibility, environmental performance, and resource efficiency. Likewise, the Circular Economy Lifecycle Assessment and Visualization (CELAVI) framework developed by the National Renewable Energy Laboratory (NREL, now NRL) [28,29] represents an important advancement in modelling material flows and circular supply chains. However, its primary focus remains on lifecycle material management and supply-chain transitions rather than the comparative assessment of alternative end-of-life strategies from an integrated project-decision perspective.

This limitation is also reflected in the broader circular economy literature. Several authors have noted that circularity assessments are often conducted independently from economic and environmental evaluations, limiting their usefulness for strategic decision-making. For instance, Saidani et al. [30] highlighted the lack of standardized approaches for measuring circularity and integrating circular indicators into decision-making processes. Similarly, Corona et al. [31] and Kristensen and Mosgaard [32] observed that existing circular economy indicators frequently focus on material loops while overlooking economic performance and environmental trade-offs. Consequently, despite significant advances in recycling technologies, life-cycle assessment methodologies, and circular business models, there remains a lack of integrated frameworks capable of simultaneously evaluating multiple end-of-life pathways according to circularity, environmental, and economic criteria.

The present study addresses this gap by moving beyond component-specific analyses and single-dimension assessments. Unlike previous studies, which typically focus on recycling technologies, blade management, material recovery, or environmental impacts in isolation, this work proposes a unified decision-support framework that combines Net Present Value (NPV), Levelized Cost of Energy (LCOE), avoided emissions, and a 9R-based circularity indicator within a single methodological structure. Furthermore, the framework enables the comparison of multiple end-of-life strategies, including repair, refurbishment, reuse, second-hand deployment, and recycling, thereby providing a more comprehensive basis for evaluating circular economy pathways in wind turbine generator management.

Despite substantial progress in understanding turbine performance, environmental impacts, and isolated CE strategies, a critical gap remains: the absence of an integrated framework capable of systematically assessing circular end-of-life strategies across environmental, economic, and circularity dimensions.

Although previous studies have investigated specific aspects of wind turbine end-of-life management, including blade recycling, lifetime extension, repowering, material recovery, and life-cycle environmental impacts, these approaches generally remain fragmented and focus on a single performance dimension. Consequently, there is still no integrated decision-support methodology that enables stakeholders to compare alternative circular economy strategies based on their economic, environmental, and circularity performance within a unified assessment framework.

This study addresses this gap by developing a comprehensive decision-support framework for evaluating circular economy strategies for WTG end-of-life management. The proposed framework integrates three complementary dimensions: (i) economic performance through Net Present Value (NPV) and Levelized Cost of Energy (LCOE), (ii) environmental performance through the quantification of potential avoided emissions, and (iii) circularity performance through an indicator derived from the 9R framework. This integrated approach enables the systematic comparison of multiple end-of-life pathways, including repair, refurbishment, reuse, and second-hand deployment.

The contributions of this paper are threefold. First, it proposes a novel multi-criteria framework that combines economic, environmental, and circularity assessments within a single methodological structure. Second, it provides a practical decision-support tool that allows stakeholders to evaluate trade-offs among alternative circular economy strategies for WTGs. Third, through a scenario-based application, it generates new insights into the feasibility and value creation potential of second-hand turbine markets, an area that remains largely underexplored in the literature.

2. Methodology

A substantial research gap exists within the current literature regarding the comprehensive assessment of WTG end-of-life management, the effective implementation of circularity processes in this context, and, more broadly, the evaluation of end-of-life scenarios and their associated impacts for renewable energy products. To address this gap, the methodology employed in this study is predicated on a detailed analysis of each stage within the product lifecycle. This approach facilitates a rigorous evaluation of the economic, environmental, and circularity impacts of various lifespan extension strategies.

2.1. Wind power project life cycle

This research seeks to develop a comprehensive framework to support decision making in managing WTG end-of-life with a circular perspective. While a product-centric approach could also be explored, it falls outside the scope of this research focusing on the project lifecycle. These two different perspectives are illustrated in Fig. 1.

The project lifecycle is depicted in Fig. 2, which outlines the main aspect of each project lifecycle steps. The framework adopts a cradle-to-grave perspective to support informed decision-making across the entire lifecycle of a wind power project.

All of these steps contribute to the capital expenditures of a wind power project. In particular, the early-stage engineering, environmental studies, legal agreements, and permitting processes represent a significant portion of the overall development budget. On average, these pre-construction development activities account for approximately 1.3% of total project costs [33].

Once all necessary construction permits are secured, the project proceeds with the construction phase, where the main costs are represented by the turbine, the connection to the grid and the installation costs.

From a wind power project developer's perspective, it is commonly estimated that the total development and CAPEX cost for 1 MW of installed capacity is approximately EUR 1.4 million [34].

During the operational phase, the wind farm actively produces electricity, thereby generating revenue and enabling the recovery of the initial investment.

Operational expenditure varies significantly depending on numerous factors, including turbine type, location, weather conditions, wind resource profiles, and site accessibility. As such, it is challenging to define a universal cost structure over the lifetime of a project. For the purposes of this study the OPEX value is fixed to an average value of USD 43/kW/year (approximately EUR 40/kW/year, 2024 conversion) [35]. This figure encompasses lease payments, insurance, transmission charges, maintenance, administrative costs, and taxes, providing a consolidated cost metric expressed as a price per kilowatt per year.

The WTG lifecycle ends with its end-of-life management, which involves decisions surrounding decommissioning, repowering, or extending the operational life of the wind turbines. Currently, end-of-life management is largely focused on decommissioning wind farms, with efforts to recover and recycle as much material as possible. Non-recyclable components are typically subject to energy recovery (e.g., incineration for heat generation) or, depending on regional regulations, landfilling.

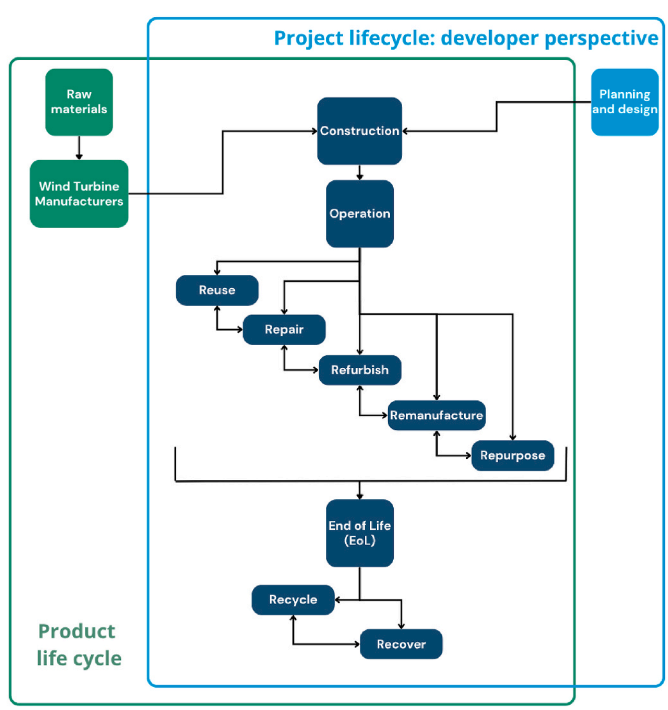

Fig. 1. Project-level and product-level lifecycle boundaries for wind turbine generators (WTGs).

2.2. Electricity production assessment

Numerous models exist for probabilistic wind power forecasting, includingprobabilistic assessment [36] using Weibull distribution [37], using selective ensemble of finite mixture Gaussian process regression models [38], using quantile regression with probabilistic forecasts. In this study, the Rayleigh distribution is employed due to its ability to provide a reliable and detailed representation of wind profiles, enabling an estimation of expected power production based on a chosen WTG type, at a given location.

$$h_R(u) = \frac{\pi}{2}\frac{u}{(\overline{u})^2} exp\left(-\frac{\pi}{4}\left(\frac{u}{\overline{u}}\right)^2\right) \quad (1)$$

The Rayleigh distribution is then used to calculate the Annual Energy Yield (AEY) to determine the value of the electricity produced by the decided WTG at a studied location, given by equation (2).

$$AEY = \sum_{u=u_{cut_{in}}}^{u=u_{cut_{off}}} P_{WT}(u)\cdot f(u).8760 \quad (2)$$

With

$f(u)$: the probability function from the Rayleigh distribution.

And $P_{WT}(u)$: the theoretical power for a given wind speed, following equation (3).

$$P_{WT}(u) = \frac{CP}{2}\rho A u^3 \eta_m \eta_e \quad (3)$$

The performance declining through the years, the WTG efficiency is assessed by a mathematical function in the model simulation [39].

2.3. Economic indicator

This study uses two economic indicators: the LCOE and the Net Present Value (NPV).

LCOE provides stakeholders with a clear understanding of the average cost per megawatt-hour (MWh) of electricity generated over the entire project lifespan, serving as a useful benchmark for comparing energy production costs. NPV offers insight into the overall financial return of a project, enabling assessment of its economic viability by accounting for both revenues and expenditures over time.

The LCOE are calculated following equation (4).

$$LCOE = \frac{NPV_{TotalCosts}}{NPV_{Yield}} \quad (4)$$

With:

$$NPV(TotalCosts) = \sum_{n=1}^{T} \frac{CAPEX_n + OPEX_n}{(1+i)^n} \quad (5)$$

$$NPV(Yield) = \sum_{n=1}^{T} \frac{AEP_n}{(1+i)^n} \quad (6)$$

It is important to note that the LCOE is highly dependent on the underlying assumptions used in its calculation. For comparisons between technologies to be valid, these assumptions must be standardized and reflect a consistent scope and basis. As an example, CAPEX can be estimated using a variety of methodologies, such as those provided by the NRL [40], the UK Department of Energy and Climate Change [41], or

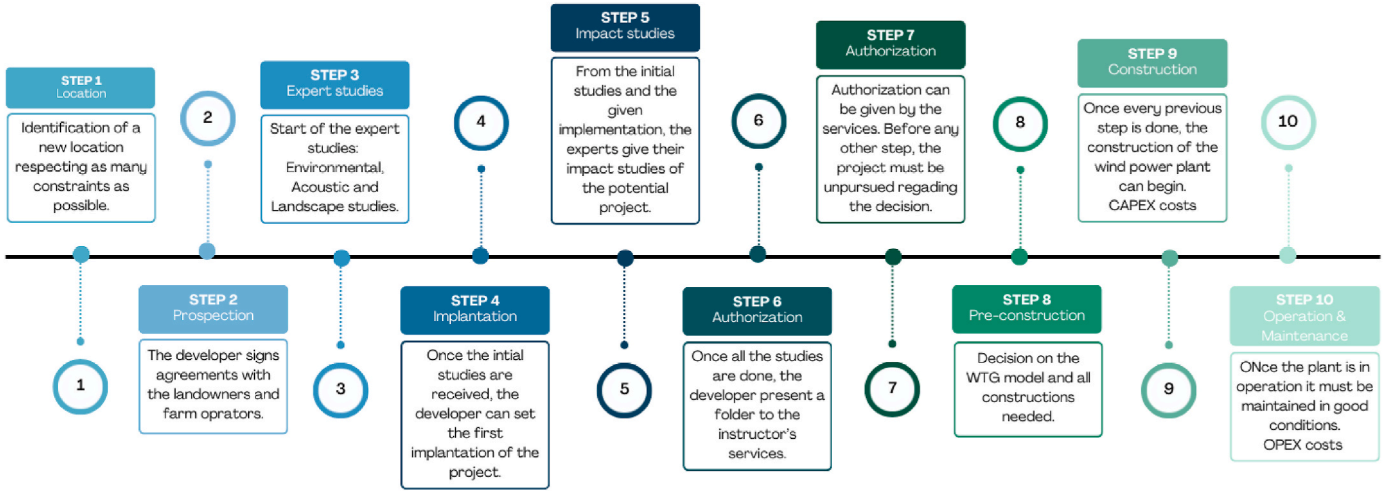

Fig. 2. Details of the WTG lifecycle from cradle to before the end-of-life management.

the probabilistic engineering cost model developed by researchers at the University of Tokyo [42].

The Net Present Value (NPV) is a fundamental economic metric used to assess the financial viability of a project, computed using equation (7).

$$NPV = \sum_{n=1}^{T} \frac{B_n - C_n}{(1+i)^n} \quad (7)$$

By incorporating the time value of money, the NPV provides project developers with insights into the long-term profitability of their investment. It is important to recognize that NPV relies on forecasted values and assumptions about future financial performance, introducing a degree of uncertainty into the analysis. Despite this limitation, NPV remains a widely adopted tool in project finance and investment decision-making, particularly in the renewable energy sector.

2.4. Environmental indicator

The environmental metric employed in this work is the Potential Saved Emissions, expressed in CO_2-equivalent emissions. This metric allows for the calculation of emissions avoided through the use of wind energy instead of conventional electricity sources, when extending the operational life of WTGs. It is calculated using the equation (8), calculating the saved emissions due to the extended lifetime electricity production compared to the electricity production with the French electricity production emission average (as France will be used for the case study).

$$Potential\ Saved\ Emissions = \sum_{i=T_0}^{i=T} AEY(i)*(C0_2\ eq\ emissions\ avg - C0_2\ eq\ emissions\ wind\ elec) \quad (8)$$

This comparison is made with the French electricity production average, 39g of CO2 eq/kWh, in 2023 [43]. The amount of one kWh of wind electricity has a value between 8 and 20 gCO2 eq/kWh [44], and is set to 10 g CO2eq/kWh in this study.

2.5. Circularity indicator

To structure the development of the circularity indicator, the 9R framework is used as a foundation for evaluating end-of-life pathways [45]. This indicator enables a comparative assessment of different end-of-life strategies in terms of their alignment with circular economy principles.

2.5.1. Refuse (R0)

The refuse indicator aims to "make a product redundant by abandoning its function or offering the same function with a radically different product" [45]. In this end-of-life circular indicator no metric assesses the refuse strategy.

2.5.2. Rethink (R1)

The rethink indicator aims to "Make product use more intensive" [45].

Let L_p denote the actual lifespan of a WTG and L_{avg} represent the average expected lifespan for products within the same category. Extending the operational lifespan of a WTG beyond the average enables additional electricity generation, thereby intensifying the use of the existing asset. This strategy can be evaluated by quantifying the additional energy produced during the extended period, specifically, from the end of the average lifespan to the actual extended lifespan.

To contextualize this value, a reference for the maximum possible electricity production is established. This maximum is defined as the cumulative energy output a WTG could theoretically produce if operating at 100% efficiency throughout its service life, up to a technical upper limit of 60 years. This limit reflects increasing operational risks associated with excessive aging, even when refurbishment, repairs, or reuse are applied. The reference production value is based on the WTG's original installation site.

$$theoretical\ elec\ prod\ MAX = AEY\_initial*60 \quad (9)$$

The score for R1 is the following:

$$w_{R1} = \begin{cases} \dfrac{\sum_{i=0}^{i=L_p} AEY(i)}{theoretical\ elec\ prod\ MAX}, & if\ L_p > L_{avg} \\ O, if\ L_p = L_{avg} or\ L_p < L_{avg} \end{cases} \quad (10)$$

2.5.3. Reduce (R2)

As the reduce strategy aims to "increase the efficiency in product manufacture or use by consuming fewer natural resources and materials" [45]. This metric is adapted to consider the resource needs to produce an amount of electricity, as for the end-of-life WTG, the product is already created.

$$M_p = \frac{mass_{product}}{AEY_{product}} \quad (11)$$

$$M_{avg} = \frac{mass_{average}}{AEY_{average}} \quad (12)$$

Equations (11) and (12) depict the two-ratios related to the needed mass to produce a single kWh on the overall product life cycle, for the considered product scenario and the average product's one.

The Reduce score corresponds to the ratio between the two previous equations, normalised to one. The less material is needed to produce a single kWh of electricity, compared to the usual amount of material needed, the closest the score is to 1. The metric could also be negative if the product gets many operations leading to higher material usage per kWh in overall.

The score is written as follow:

$$w_{R2} = 1 - \left(\frac{M_p}{M_{avg}}\right) \tag{13}$$

2.5.4. Reuse (R3)

The Reuse strategy aims to "Reuse by another consumer of discarded product which is still in good condition and fulfils its original function" [45].

In this case, the indicator focuses on quantifying the proportion of a WTG that is reused in a subsequent life cycle. The metric is presented in two complementary forms: as a percentage of total mass and as the number of reused components. This dual approach is essential, as individual parts can differ significantly in scale, mass, and material density. A mass-based percentage alone may obscure meaningful insights, particularly when heavier components dominate the overall mass, even if a greater number of smaller parts are reused. Conversely, analysing the reuse from a component-count perspective provides clearer visibility into which specific elements are being repurposed, offering a more detailed understanding of reuse patterns.

$$w_{R3,1} = \%\ of\ mass_{reused},\ at\ the\ End\ of\ Life \tag{14}$$

$$w_{R3,2} = 1 - \frac{Nb_{tot} - Nb_{reuse}}{Nb_{tot}} \tag{15}$$

2.5.5. Repair (R4)

The repair strategy aims to "Repair and maintenance of defective product so it can be used with its original function" [45].

This step can be developed through the following metric:

$$w_{R4,1} = \frac{Nb_{repaired}}{Nb_{tot\_reparable}} \tag{16}$$

>

$$w_{R4,2} = \left[\sum_{i=year\_repair}^{i=T}\left(AEY_{with_{improved_{efficiency(i)}}} - AEY_{without_{the_{improved_{efficiency(i)}}}}\right)\right] \Big/ AEY_{without_{the_{improved_{efficiency(i)}}}} \tag{17}$$

This metric permits to calculate the extra avoided emissions from the product that got reparation compared to the evolution of the electricity production of the product without reparation.

2.5.6. Refurbish (R5)

The goal of this strategy is to assess the impact of a possible important operation towards the refurbishment of the product. This strategy, for the end-of-life of a WTG may be done through the change of the rotor or the rotor and nacelle which allows the refurbished WTG to be more productive, but also leads to extra costs and emissions due to the dismantling and construction of the shifted parts.

This indicator is considering only those two different ways of refurbishment, as depicted as today's main operation for refurbishment for WTG, and consequently it is written as follow:

$$w_{R5} = \begin{cases} 100\%,\ if\ rotor\ and\ nacelle\ update \\ 50\%,\ if\ rotor\ update \\ 0\%,\ if\ no\ update \end{cases} \tag{18}$$

The efficiency impact depends on the year when the refurbishment process is applied, as the more year the WTG operate, the more the efficiency decreases, though, the newly installed, either, rotor, or rotor and nacelle, they have their capacities, characteristics, abilities. The WTG efficiency decreasing can be modelled through a simple linear function, with an efficiency considered to be 100% at year 0 [39]:

$$E_{ff}[i] = E_{ff}[i-1] - 0,005 \tag{19}$$

As modelled through a simple linear function, the efficiency increasing due to the refurbishment process can be modelled as highlighted in Table 1, considered to be possible after 15 years.

2.5.7. Remanufacture (R6)

This strategy aims to study the possibility of either using spare parts of old products in a new one, or on the other side, to assess the possibility to obtain spare parts from an existing product, coming to its end-of-life.

In the WTG sector, what is difficult to consider is that the spare parts come with lower mechanic abilities, that would be needed to be assessed and highlighted regarding their implication in the possible efficiency performance of the resulted WTG. In this paper, we assume that the spare parts have their initial performances.

The indicator for R6 is the following:

$$w_{R6,1} = \frac{Nb_{reusable}}{Nb_{tot}} \tag{22}$$

$$w_{R6,2} = \%\ of\ the\ new\ WTG\ coming\ from\ old\ WTG \tag{23}$$

This process leads to decrease the raw materials usage and decreases the overall emissions of the new made products. It will be calculated and considered for the old product, as it is our concern, and therefore will be considered as decreasing the old product emissions.

2.5.8. Repurpose (R7)

This strategy aims to quantify the number of repurposed parts or percentage of a product during its end-of-life process. Product part's can then be reused in another context, other product, that are not related to the first and initial usage, but that extend the usage of a produce product.

This strategy is analysed through the following indicator, considering the percentage of repurposed parts and the number of repurposed parts, regarding the general amount of the WTG mass or number of parts.

$$w_{R7,1} = \%\ of\ mass\_repurposed \tag{24}$$

$$w_{R7,2} = 1 - \frac{Nb_{tot} - Nb_{repurposed}}{Nb_{tot}} \tag{25}$$

2.5.9. Recycle (R8)

The Recycle strategy aims to develop processes to "Process materials to obtain the same or lower quality" [45]. The Recycle strategy will be assessed through the following indicators:

$$w_{R8,1} = \%_{recycle} \tag{26}$$

$$w_{R8,2} = \frac{N^{diff}_{ass.sep}}{N^{diff}_{ass.sep} + N^{diff}_{ass.non-sep}} \tag{27}$$

Table 1
Estimated costs and efficiency improvements associated with WTG refurbishment after 15 years of operation.

Refurbishment process	Costs	Efficiency impact
Rotor	3000000	$E_{ffadd} = 0.04 + \sum_{j=15}^{j=i} 0,001$ (20)
Rotor + Nacelle	5000000	$E_{ffadd} = 0.05 + \sum_{j=15}^{j=i} 0,002$ (21)

This metric quantifies the abilities of a product to be recycled. In fact the recycle process is possible with assembly that can be dismantled so the process can be made material by material.

2.5.10. Recover (R9)

This strategy aims to quantify the amount of the product that will proceed the following "Incineration of material with energy recovery" [45]. In this Circular indicator, the suggested metric is the following:

$$w_{R9} = \%_{recovery} \tag{28}$$

2.5.11. The circularity metric definition from the individual scores

The 9R framework suggests a hierarchy between the strategies regarding their circular level. To take this into account the 9Rs are split into three categories: "Smarter product use and manufacture" (R0,R1 and R2), "Extend lifespan of product and its parts" (R3 to R7) and "Useful application of materials" (R8 and R9). Each categories are then weighted in regards to their circular influence. The circular indicator score is then the following:

$$W = \frac{1}{26}\Bigg[4(W_{R1} + W_{R2}) + 3\Bigg(\frac{(W_{R3,1} + W_{R3,2})}{2} + \frac{(W_{R4,1} + W_{R4,2})}{2} + W_{R5} + \frac{(W_{R6,1} + W_{R6,2})}{2} + \frac{(W_{R7,1} + W_{R7,2})}{2}\Bigg) + 2\left(\frac{(W_{R8,1} + W_{R8,2})}{2}\right) + W_{R9}\Bigg] \tag{29}$$

The W indicator has been developed to quantify the circularity of extended product life cycles compared to conventional WTG lifespans, offering a comparative perspective across scenarios aligned with the 9R circular economy framework.

3. Results

3.1. Case study

The case study explores various end-of-life scenarios for a WTG, based on the technical and operational characteristics outlined in Table 2, V100 from Vestas as it is the most widely deployed turbine in France in terms of capacity [46]. This model has been selected for the study not only due to its prevalence but also because it may soon become unavailable on the primary market as manufacturers begin phasing out smaller rotor models (e.g., V100, V117, N117). Consequently, these turbines are likely to play a central role in the emerging second-hand market, making them ideal candidates for evaluating extended use and alternative end-of-life strategies.

This case study leverages the framework's capacity to deliver a holistic analysis, encompassing circular, environmental, and economic dimensions, to explore various WTG end-oflife pathways. It provides valuable insights into optimal strategies for turbine reuse, lifetime extension, and repowering.

The first location has an average wind speed of 6 m/s. The other locations have average wind speeds of 5, 7.5 and 7 m/s respectively.

Table 2
Technical and operational parameters of the Vestas V100 wind turbine generator (WTG) used in the case study [35,46].

Parameters	Values
Turbine rated power [MW]	2.8
Turbine rotor diameter [m]	125
Turbine hub height [m]	90
Number of components	25 000
WTG mass [t]	259
Percentage of the rotor mass compared to the WTG mass [%]	3
Percentage of the rotor + nacelle mass compared to the WTG mass [%]	18
CAPEX [EUR]	3 733 600
OPEX [EUR/kW/yr]	40

The various scenarios are detailed in Table 3, which summarises the different operations performed during a lifetime following the template "timing, costs, efficiency impact, extra mass".

The range of scenarios developed in this study offers a comprehensive, though non-exhaustive, exploration of key end-of-life strategies applicable to WTGs. Each scenario represents a distinct pathway, such as remanufacturing, repair, reuse, second-hand deployment, or repowering, enabling a detailed investigation of their respective economic, environmental, and circular impacts. This structured approach provides valuable insights into the trade-offs and benefits associated with each strategy, highlighting how specific interventions may enhance performance or sustainability depending on context. By comparing these scenarios using standardized indicators, the study supports evidence-based decision-making for project developers aiming to optimize WTG end-of-life strategies. Ultimately, the scenarios help identify which approaches are most suitable for extending asset life, minimizing emissions, reducing material use, and promoting circularity, thus contributing to the broader goal of transitioning the wind sector toward a more sustainable and circular economy.

3.2. Performance of end-of-life scenarios

The Table 4 offers an overview of the results giving the indicators values per scenario.

Table 4 summarizes the performance of the ten end-of-life scenarios assessed using economic, environmental, and circularity indicators. The baseline scenario (Scenario 0), representing a conventional 20-year lifetime without circular interventions, achieved an LCOE of 51.41 EUR/MWh, an NPV of EUR 2.89 million, and a circularity score of 4.02 %.

The implementation of remanufacturing strategies alone, Scenarios 1 and 2, increased circularity substantially, reaching 16.21% and 20.14%, respectively. However, these interventions resulted in higher LCOEs, 54.80–60.80 EUR/MWh, due to the significant refurbishment costs. While Scenario 1 improved NPV to EUR 3.07 million, the more extensive rotor and nacelle replacement considered in Scenario 2 reduced profitability, yielding an NPV of EUR 2.34 million despite slightly higher emissions savings.

Repair-based lifetime extension (Scenario 3), delivered the most favourable economic performance among the non-reuse pathways, achieving the lowest LCOE of all scenarios (49.03 EUR/MWh), and increasing NPV to EUR 3.75 million. Although the circularity gain remained moderate, 12.05%, the scenario generated nearly 2.2 million $kgCO_2eq$ of avoided emissions compared with the baseline. Combining repair and remanufacturing with an extended operational lifetime, Scenario 4, further improved overall performance, increasing NPV to EUR 3.78 million and generating more than 6.0 million $kgCO_2eq$ of avoided emissions while reaching a circularity score of 23.68%.

The results highlight the strong influence of reuse strategies on both environmental and circular performance. Reuse in a lower-wind-speed location, Scenario 5, produced the least favourable economic outcome, with the highest LCOE, 64.47 EUR/MWh, and the lowest NPV, EUR 1.82 million, demonstrating the importance of site selection for second-hand deployment. In contrast, reuse in a higher-wind-speed location, Scenario 6, generated the highest NPV of all scenarios, EUR 3.82 million, while achieving substantial emissions savings of over 5.0 million kg CO_2 eq and a circularity score of 27.59%.

Scenarios combining reuse with repair and/or remanufacturing, Scenarios 7, 8, and 9, achieved the highest circularity performances, ranging from 25.56% to 31.31%. Scenario 9, which integrates repair, remanufacturing, and reuse, obtained the highest circularity score overall, 31.31%, while Scenarios 8 and 9 both delivered more than 5.3 million $kgCO_2eq$ of avoided emissions. Nevertheless, the additional intervention costs increased LCOE values to approximately 59 EUR/MWh and reduced NPV compared with simpler reuse pathways. Scenario 10, representing an earlier reuse event at a higher-wind-speed

Table 3
Overview of the end-of-life scenarios evaluated for the WTG in the case study.

Scenario n°	Year	Repair operation [Year [−], Costs [EUR], Efficiency impact [%], extra mass [t]]	Remanufacture operation [Year [−], Costs [EUR], Efficiency impact [%], extra mass [t]]	Reuse operation [Year [−], Costs [EUR], new location wind speed average [m/s]]
Scenario 0: Baseline scenario	20	None	None	None
Scenario 1: Change of rotor, y20	30	None	[20, 3000000, 0.04 + (year - 15) * 0.001, 7.77]	None
Scenario 2: Change of rotor + nacelle, y20	30	None	[20, 5000000, 0.05 + (year - 15) * 0.002, 46.6]	None
Scenario 3: Repair scenario	30	[15, 500000, 0.02,1], [25, 500000, 0.03,2]	None	None
Scenario 4: Repair Remanufacture scenario	50	[20, 500000, 0.02,1], [40, 500000, 0.03,2]	[30, 5000000, 0.05 + (year - 15) * 0.002, 46.6]	None
Scenario 5: Reuse scenario, lower average wind speed	35	None	None	[20, 5000000,5]
Scenario 6: Reuse scenario, higher average wind speed	35	None	None	[20, 5000000,7.5]
Scenario 7: Repair Reuse scenario	40	[20, 500000, 0.02,1]	None	[27, 500000, 7]
Scenario 8: Remanufacture Reuse scenario	40	None	[20, 3000000, 0.04 + (year - 15) * 0.001, 7.77]	[27, 500000, 7]
Scenario 9: Repair Remanufacture Reuse scenario	40	[27, 500000, 0.02,1]	[20, 3000000, 0.04 + (year - 15)*0.001, 7.77]	[27, 500000, 7]
Scenario 10: Reuse scenario, higher average wind speed	30	None	None	[15, 5000000, 7]

Table 4
Overview of economic, environmental, and circularity performance across the end-of-life scenarios for the WTG.

Scenario n°	LCOE [EUR/MWh]	NPV [EUR]	Total saved emissions [kg CO2 eq]	Circularity indicator [%]
0	51.41	2891361	0	4.02
1	54.80	3067846	2282575	16.21
2	60.80	2344839	2325373	20.14
3	49.03	3745075	2196979	12.05
4	52.72	3775538	6063091	23.68
5	64.47	1816584	1946544	21.48
6	53.11	3818876	5016159	27.59
7	52.72	3766412	5176421	25.56
8	59.01	2924966	5356736	30.66
9	59.97	2791041	5356736	31.31
10	59.00	2828738	3028914	24.82

location, produced intermediate results, combining significant emissions savings, 3.03 million $kgCO_2eq$, with a circularity score of 24.82%.

Overall, a clear trade-off emerges between economic performance and circularity. Repair-based lifetime extension provides the most favourable economic outcomes among the intervention strategies, whereas reuse and combined circular approaches deliver the largest environmental benefits and circularity gains. The results further demonstrate that the success of reuse pathways is highly dependent on the wind resource available at the secondary deployment site, making location selection a critical factor in maximizing both economic and environmental performance.

As the LCOE depends on both lifecycle expenditures and cumulative electricity generation, end-of-life interventions such as repair, remanufacturing, and reuse directly influence economic performance. Fig. 3a illustrates the evolution of LCOE across the assessed scenarios. Among all pathways, Scenario 3, which combines lifetime extension through repair operations, achieves the lowest LCOE, 49.03 EUR/MWh, highlighting the economic effectiveness of relatively low-cost interventions that extend operational life. In contrast, scenarios involving extensive remanufacturing and reuse activities generally exhibit higher LCOEs due to the substantial capital investments required. Scenario 5, representing reuse in a lower-wind-speed location, performs least favourably with an LCOE of 64.47 EUR/MWh, demonstrating the strong dependence of economic performance on site-specific wind conditions.

The AEY progression over time (Fig. 3b.) and its cumulative value (Fig. 3c.) further illustrate the benefits of lifetime extension and reuse strategies. Scenarios involving deployment at higher-wind-speed sites, particularly Scenarios 6, 7, 8, and 9, exhibit sustained increases in cumulative energy production due to improved wind resources and, where applicable, efficiency gains resulting from repair or remanufacturing operations. These improvements contribute significantly to enhanced environmental performance and, in several cases, increased net present value. Nevertheless, the additional costs associated with multiple interventions partially offset these gains, resulting in relatively high LCOEs for Scenarios 8 and 9 despite their favourable energy production profiles.

Fig. 3d presents the evolution of lifecycle costs across the different pathways. Considerable variation is observed between scenarios, reflecting the differing combinations of repair, remanufacturing, and reuse operations. While repair-based pathways require comparatively modest investments, remanufacturing and relocation strategies involve substantially higher expenditures. These results highlight the value of the framework as a decision-support tool capable of quantifying the trade-offs between economic performance, environmental benefits, and circularity outcomes. Rather than identifying a universally optimal solution, the model enables project developers to evaluate alternative end-of-life strategies according to project-specific objectives and constraints.

Fig. 3e and 3f shows the annual and cumulative emissions savings achieved under each scenario. Emissions savings are primarily driven by cumulative electricity generation and operational lifetime. Scenario 4 achieves the highest environmental benefit, with more than 6.0 million $kgCO_2eq$ of avoided emissions, primarily due to the extension of turbine operation to 50 years combined with remanufacturing and repair interventions. Reuse scenarios deployed in locations with favourable wind resources, including Scenarios 6, 7, 8, and 9, also achieve substantial emissions reductions ranging from approximately 5.0 to 5.4 million $kgCO_2eq$. In these scenarios, emissions savings increase markedly following the reuse event as additional electricity generation displaces grid-based electricity production. The results therefore confirm that both lifetime extension and strategic relocation to wind-rich sites represent effective approaches for maximizing the environmental benefits of circular end-of-life strategies for wind turbine generators.

The circular indicator results (Fig. 4) highlight trends in terms of circularity regarding the developed processes through the scenarios.

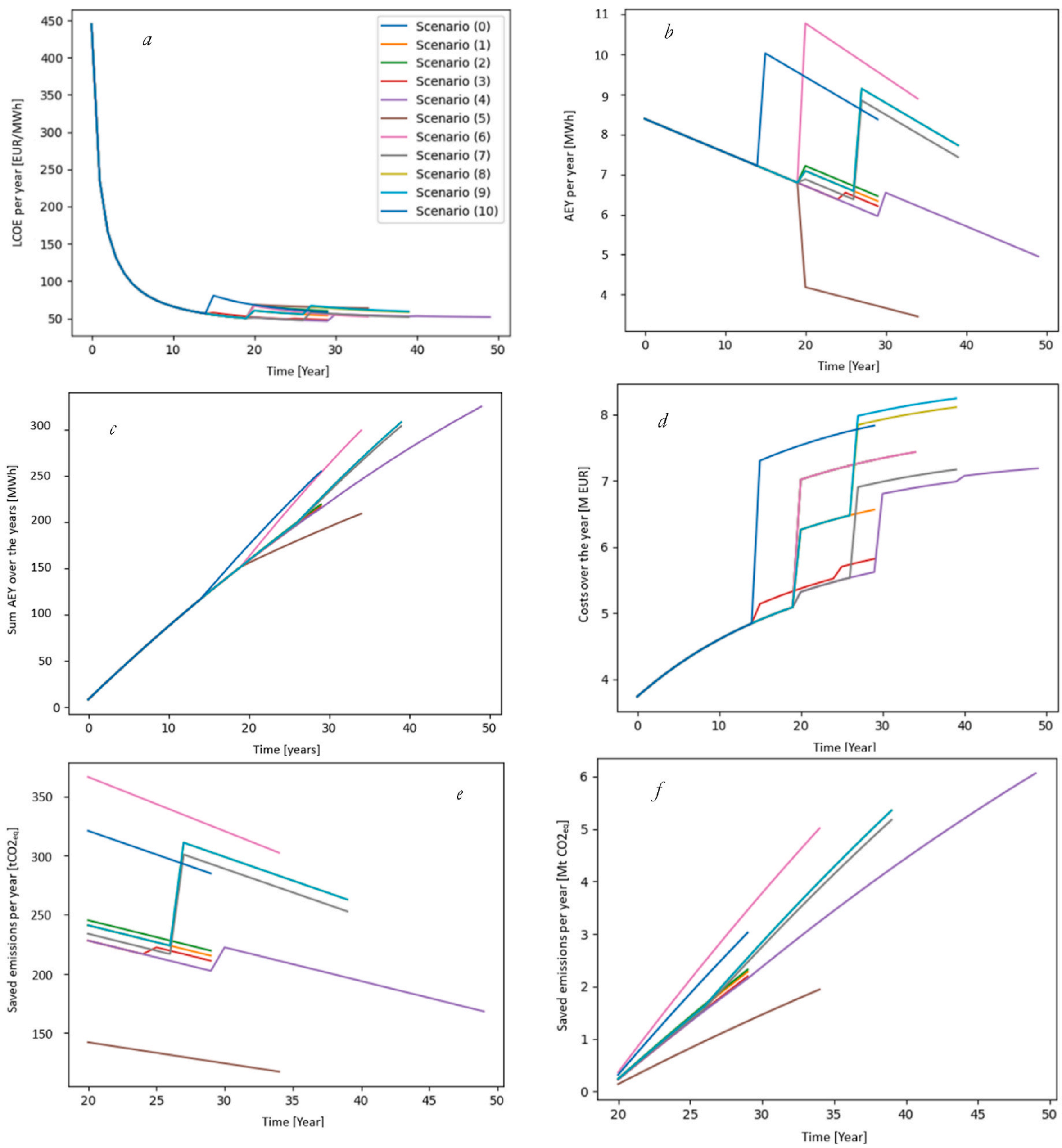

Fig. 3. Evolution of key performance indicators over the project lifetime for the end-of-life scenarios. (a) Levelized Cost of Energy (LCOE), (b) Annual Energy Production (AEP), (c) cumulative AEP, (d) cumulative costs, (e) annual CO_2-equivalent emissions saved, and (f) cumulative emissions saved.

First, all scenarios having a reuse process have their circularity indicator higher than 20 %, making reuse a strong option to develop the circularity of this sector. Moreover, and as said above in this section the contrast between the base line scenario and the others is quite important, highlighting the high potential to increase circularity in this sector. Each considered scenario shows a circularity indicator at least three times higher as compared to the baseline.

A consistent pattern emerges regarding circularity: reuse offers the most significant boost, followed by refurbishment, and then repair. Even modest interventions improve circularity substantially compared to the baseline. Scenarios 1 and 2, which focus on refurbishment, increase the circularity score from around 4% to over 15%. Scenario 3, representing repair alone, also contributes positively but to a lesser degree. These results demonstrate the critical role of circular strategies in transitioning the wind sector toward sustainable lifecycle practices.

3.3. Sensitivity analysis

A sensitivity analysis was conducted to evaluate the influence of key input parameters on the economic and environmental performance indicators of the framework. Six parameters were independently varied by ±20% from their baseline values: turbine lifespan, average wind speed, operating expenditure (OPEX), electricity price, grid electricity emission factor, and wind electricity emission factor. The resulting variations in LCOE, NPV, and avoided emissions are summarized in Figs. 5–7.

In this sensitivity analysis, the baseline is considered to be a scenario fixed as: 30 years lifespan, average windspeed of 6 m/s, no repair, remanufacture or reuse operations.

The analysis reveals that wind speed is the most influential parameter affecting the economic performance of the system. A 20% decrease in average wind speed results in a 79.9% increase in LCOE and a 104.3%

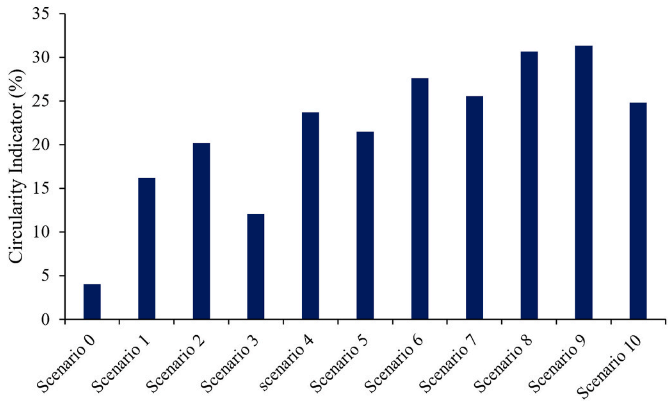

Fig. 4. Circularity indicator values across the end-of-life scenarios for the WTG.

reduction in NPV, while a 20% increase decreases LCOE by 32.7% and increases NPV by 114.3%. These results demonstrate the strong dependence of project viability on the quality of the wind resource and confirm that site selection remains the primary determinant of economic performance throughout the turbine lifecycle.

Electricity price represents the second most influential parameter for NPV, generating variations of ±47.0% for a ±20% change in market price. As expected, electricity price does not affect LCOE directly, as it influences revenues rather than production costs. Similarly, OPEX has a moderate impact on economic performance, causing NPV variations of approximately ±8.8% and LCOE variations of ±6.5%.

The environmental indicator exhibits a different sensitivity profile. Turbine lifespan is identified as the dominant factor affecting avoided emissions, with variations ranging from −58.4% to +53.6%. This result reflects the direct relationship between operational lifetime and cumulative electricity generation. Wind speed is the second most influential environmental parameter, leading to changes of up to ±48.7% in avoided emissions. The carbon intensity of the displaced electricity mix also plays a significant role, producing variations of ±25.9%. In contrast, the assumed emission factor of wind-generated electricity has a comparatively limited effect, altering total avoided emissions by less than 6%.

Overall, the sensitivity analysis highlights that economic indicators are primarily governed by factors influencing energy production and revenue generation, particularly wind speed and electricity price. Environmental performance, on the other hand, is mainly driven by operational lifetime, wind resource availability, and the carbon intensity of the electricity being displaced. These findings reinforce the importance of strategic site selection and lifetime extension measures when evaluating circular end-of-life pathways for wind turbine generators. Furthermore, they demonstrate that uncertainties related to wind resource assessment are likely to have a substantially greater influence on project outcomes than uncertainties associated with operating costs or emission factors.

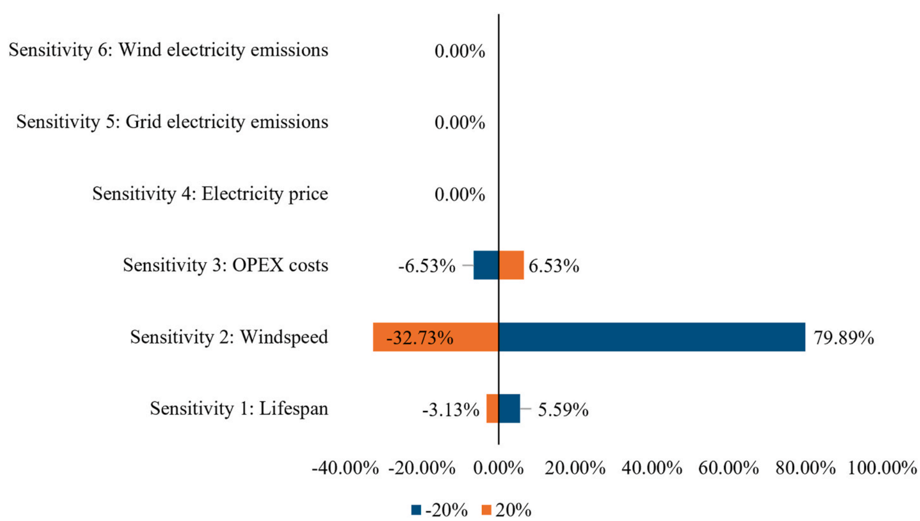

Fig. 5. Sensitivity analysis on the LCOE.

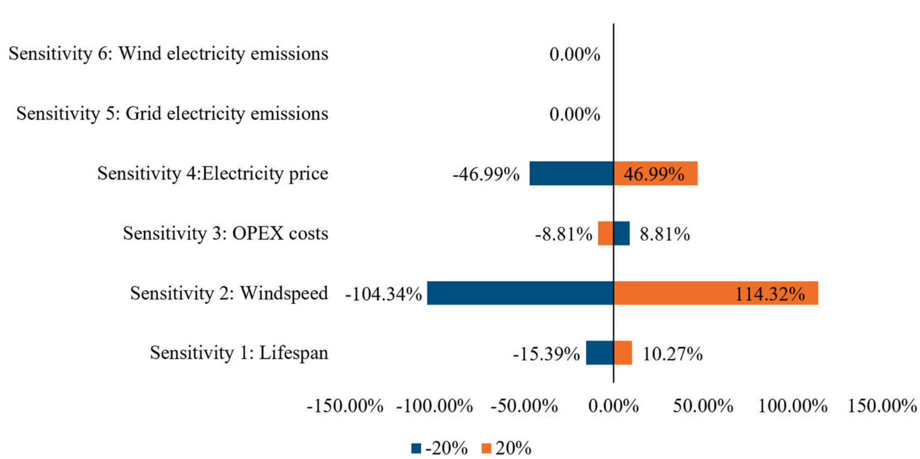

Fig. 6. Sensitivity analysis on the NPV.

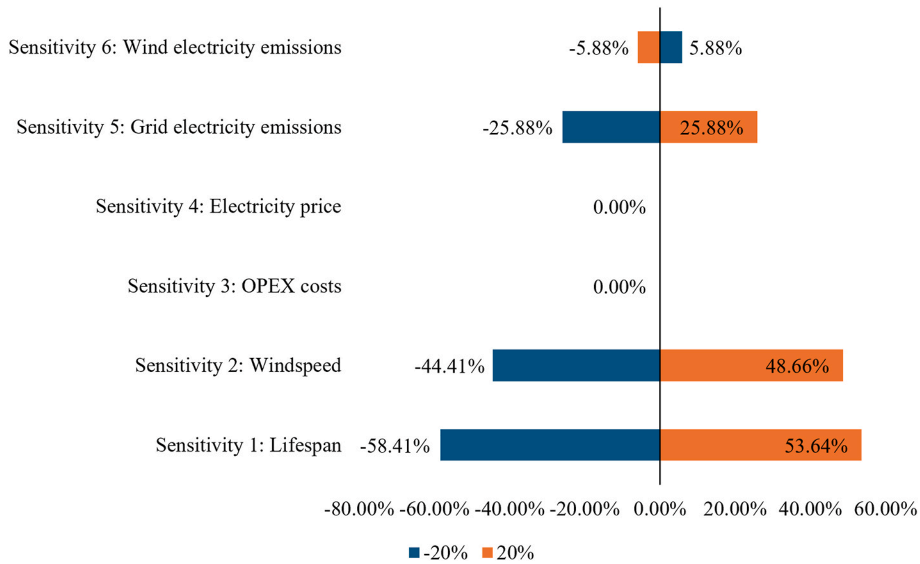

Fig. 7. Sensitivity analysis on the saved emissions.

4. Discussion

The results of this study provide valuable insights for stakeholders aiming to integrate circular economy principles into the end-of-life management of wind turbine generators (WTGs). By quantifying key indicators; economic performance, environmental impact, and circularity; the developed model supports informed decision-making and enables a systematic evaluation of different lifecycle strategies.

Rather than offering a one-size-fits-all solution, the model functions as a robust decision-support tool that accommodates the diversity of developer priorities and project-specific constraints. It allows users to explore multiple scenarios and assess the implications of repair, refurbishment, and reuse strategies. The case study demonstrates the model's practical applicability, particularly in evaluating the emerging second-hand WTG market and its potential relevance for project developers. However, the objective of the framework is not to provide highly site-specific predictions, but rather to offer a structured and adaptable methodology that can support strategic decision-making across a range of end-of-life contexts.

The findings highlight the significant benefits that circular strategies can deliver across economic, environmental, and circularity indicators. However, the performance of reuse strategies showed a strong dependence on the wind resource at the secondary site.Reuse scenarios, especially when deployed in locations with higher wind speeds, show the most promising outcomes in terms of NPV and emissions savings. For example, Scenario 6 achieves the highest NPV of all scenarios, with a net present value increase of 32% compared to the baselineand savings of more than 5,016t of CO_2-equivalent emissions. However, the feasibility of this scenario remains uncertain under current market and regulatory conditions, particularly due to challenges related to turbine certification and the availability of suitable high-wind-speed sites.

In terms of circularity, the model demonstrates that incorporating circular processes into the product lifecycle leads to substantial improvements. All scenarios involving reuse achieved circularity scores above 20%, a marked increase from the 4% baseline. Refurbishment also resulted in notable gains, while repair strategies produced more moderate improvements. Interestingly, Scenario 4, which combined repair and remanufacturing with the longest lifetime, delivered the highest emissions savings. However, its economic advantage was less pronounced than that of simpler repair-only or high-wind reuse strategies. These outcomes emphasize the importance of integrating circular design principles and early-stage planning into wind project development. Although the framework is intentionally designed to remain transparent and accessible, it is grounded in established technical formulations commonly used in wind energy assessments. Electricity production estimates are derived from turbine power equations and probabilistic wind resource modelling based on Rayleigh distributions, while economic performance is assessed using standard Levelized Cost of Energy (LCOE) and Net Present Value (NPV) methodologies. The circularity dimension is evaluated through an indicator based on the 9R framework, enabling the systematic comparison of alternative end-of-life pathways. Consequently, the simplicity of the framework should be interpreted as a deliberate methodological choice aimed at ensuring transparency, reproducibility, and adaptability, rather than as a simplification of the underlying engineering principles.

Despite its strengths, the model has several limitations that must be acknowledged. It relies on a limited set of inputs and simplifying assumptions, which introduce uncertainty into the results. As a theoretical framework, it should be interpreted as a decision-guiding tool rather than a precise predictive model. Moreover, long-term projections remain sensitive to external disruptions and evolving market and regulatory conditions, reinforcing the need for adaptable and flexible planning approaches. The scenarios presented in this study are intended to provide first-order comparisons between different circular economy pathways and to demonstrate the applicability of the framework. They do not capture the full complexity of turbine degradation mechanisms, site-specific wind variability, market evolution, or policy changes that may influence project outcomes. It should be noted that the environmental assessment developed in this study is intentionally simplified and is not intended to replace a comprehensive Life Cycle Assessment (LCA). The environmental indicator focuses on the quantification of potential avoided emissions associated with the additional electricity generation enabled by lifetime extension, refurbishment, repair, and reuse strategies. For the case study, avoided emissions are calculated by comparing wind electricity generation to the average carbon intensity of the French electricity mix (39 gCO_2eq/kWh), while wind-generated electricity is assumed to have an emission factor of 10 gCO_2eq/kWh. These assumptions were selected to provide a transparent and reproducible basis for comparing alternative end-of-life scenarios within a consistent framework. Consequently, the environmental results should be interpreted primarily as comparative indicators rather than precise estimates of absolute environmental impacts. Furthermore, emissions associated with refurbishment operations, transportation, component replacement, remanufacturing activities, and future changes in grid carbon intensity are not explicitly modelled.

This research can therefore serve as a foundation for future work across multiple domains. It can support further investigation into the development of second-hand WTG markets at specific locations, accounting for factors such as existing turbine stocks, manufacturing and refurbishment facilities, and potential deployment sites. Future research could also extend the framework by incorporating stochastic wind resource modelling, detailed component degradation and reliability models, uncertainty analyses, and dynamic market mechanisms. Such developments would improve the predictive capabilities of the framework while preserving its integrated assessment of economic, environmental, and circularity performance. In the public sector, the model can inform policy design aimed at fostering circular solutions and accelerating the transition to greener societies. In the private sector, it offers companies a structured approach to assessing end-of-life strategies based on the key performance indicators most relevant to their objectives.

Compared to previous studies that have made important contributions to wind turbine end-of-life (EoL) management, particularly regarding blade recycling, reuse, repurposing, and material recovery, this study offers a unified, scenario-based decision-support framework for comparing economic, environmental, and circularity outcomes. In fact, as most studies focus on either specific component, such as blades, or individual assessment dimensions, such as environmental impacts or recycling technologies, providing an integrated framework that evaluates multiple EoL strategies simultaneously from economic, environmental, and circularity perspectives offers a very new perspective for the development of circular strategies in the EoL WTG management. Table 5 summarizes how the present study differs from selected literature.

Aligned with Sustainable Development Goal 8 which aims to promote sustained, inclusive, and sustainable economic growth, this study demonstrates that circular economy strategies can simultaneously create economic and environmental value. The transition toward a more circular wind energy sector is both feasible and desirable, provided that enabling conditions such as supportive regulatory frameworks and market incentives are established.

Finally, the methodological approach presented in this research could be extended to other renewable energy technologies. For example, similar modelling efforts could be applied to solar panel end-of-life management, assessing recycling, refurbishment, and reuse pathways for rooftop or secondary-market applications.

In conclusion, this study underscores the strategic potential of circular economy principles in the wind power sector. It encourages developers to consider repair, refurbishment, and reuse not only as environmental imperatives but also as economically viable opportunities. While practical implementation may face short-term barriers, the proposed model lays a solid foundation for more sustainable project development and a long-term transition toward circularity.

5. Conclusion

This research has successfully developed and presented a model designed to assess end-of-life product management from economic, environmental, and circularity perspectives. As outlined in the objectives, the model specifically addresses the potential for circular economy integration within the wind energy sector, with a focus on the emerging second-hand market for WTGs. The findings demonstrate a tangible opportunity for the sector to transition towards more circular practices, offering significant benefits not only in terms of environmental impact, such as reduced emissions, but also from an economic standpoint, while enhancing the overall circularity of WTG lifecycle management.

The development of this model represents a valuable contribution to ongoing research on circular product lifecycle strategies. Despite operating with a limited set of inputs, the model integrates multiple key parameters, providing a practical and robust decision-support framework for stakeholders seeking to implement circular processes. Its application in the case study of WTG end-of-life scenarios has demonstrated both its relevance and effectiveness.

Designed for adaptability, the model is replicable and can be extended to assess end-of-life strategies for other energy technologies

Table 5
Differences between the study and selected literature.

Study	Main focus	Strategies considered	Assessment dimensions	Limitation/gap addressed by this study
Joustra et al. [24]	Investigates the effect of the original product design on the recovery and reuse of composite products, taking wind turbine blades as case material	Reuse	Technical and value-chain perspective	Focuses mainly on blades and EoL processing; does not provide an integrated economic, environmental, circularity decision framework.
Beauson et al. [47]	Overview of sustainable EoL management for wind turbine blades	Landfill, incineration, life extension, reuse, recycling	Technical and sustainability overview	Provides broad overview, but not a quantitative scenario-based decision model for whole WTG lifecycle strategies.
Tyurkay et al. [26]	Circular economy practices for EoL wind turbine blades in the construction industry	Recycling, reuse, secondary construction applications	Circularity and material-management perspective	Strong focus on blade waste and construction-sector valorization; limited integration of project-level economic and energy-performance indicators.
Deeney et al. [27]	Structured review of blade pathways toward circular economy	Avoidance, repurposing, recycling, energy recovery, disposal	Waste hierarchy and barriers	Shows that research remains heavily focused on recycling despite higher-value CE options, supporting the need for broader decision frameworks.
NREL CELAVI framework [48]	Circular economy lifecycle assessment and visualization	Circular supply-chain transitions	LCA, material flows, supply chains, costs	Powerful circularity modelling tool but not specifically developed as a WTG EoL strategy comparison framework using 9R-based circularity, LCOE, NPV, and saved emissions together.
Meng et al. [49]	Review of EoL management for full turbines	Reuse and recycling of composites, steel, rare-earth elements	Material recovery, scalability, trade-offs	Highlights uncertainty in economic viability and scalability, reinforcing the need for decision-support tools comparing alternative scenarios. Compare the environmental and economic trade-offs across mechanical, thermal and chemical recycling technologies, need to be broaden with other circular strategies.
Present study	Integrated framework for WTG EoL circular strategies	Repair, refurbishment, reuse, remanufacturing, repowering, recycling, recovery	LCOE, NPV, saved emissions, 9R-based circularity	Provides a unified, scenario-based decision-support framework for comparing economic, environmental, and circularity outcomes.

and industrial sectors. It serves as a decision-making tool for companies aiming to optimize end-of-life processes, supporting a strategic shift toward more sustainable operations. This study underscores that implementing circular strategies can yield varied but measurable impacts depending on the chosen process. For instance, reuse strategies show high potential, particularly when WTGs are relocated to sites with higher average wind speeds, whereas deployment in lower-wind areas may result in less favourable outcomes.

Although there is scope to enhance the model by incorporating more detailed inputs and additional parameters, its current structure provides a coherent and comprehensive overview of the economic, environmental, and circular implications of different end-of-life strategies. As such, the model offers strong support for decision-makers exploring sustainable alternatives in wind energy development and beyond.

6. Declaration

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. The process of report writing is integrated throughout the entirety of the project and is executed autonomously. The management of references was facilitated using Zotero, whereas generative AI was employed selectively to assist with the rephrasing and linguistic refinement of certain sections of the manuscript.

CRediT authorship contribution statement

Pierre Doisy: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft. **Jagruti Thakur:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, 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.

References

[1] The Paris Agreement | UNFCCC [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement. (Accessed 22 February 2024).
[2] K. Richardson, et al., Earth beyond six of nine planetary boundaries, Sci. Adv. 9 (37) (Sep. 2023) eadh2458, https://doi.org/10.1126/sciadv.adh2458.
[3] J. Rockström, et al., Planetary boundaries: exploring the safe operating space for humanity, Ecol. Soc. 14 (2) (Nov. 2009), https://doi.org/10.5751/ES-03180-140232.
[4] U. N. Environment, 'Emissions Gap Report 2023', UNEP - UN Environment Programme. Accessed: February. 22, 2024. [Online]. Available: http://www.unep.org/resources/emissions-gap-report-2023.
[5] Energy transition holds key to tackle global energy and climate crisis'. Accessed: February. 22, 2024. [Online]. Available: https://www.irena.org/news/pressreleases/2022/Mar/Energy-Transition-Holds-Key-to-Tackle-Global-Energy-and-Climate-Crisis.
[6] Decarbonizing electricity is only one step towards a low-carbon energy system', Our World in Data. Accessed: February. 22, 2024. [Online]. Available: https://ourworldindata.org/low-carbon-electricity.
[7] Electricity consumption – electricity information: overview – analysis', IEA. Accessed: October. 07, 2023. [Online]. Available: https://www.iea.org/reports/electricity-information-overview/electricity-consumption.
[8] Wind power generation', Our World in Data [Online]. Available: https://ourworldindata.org/grapher/wind-generation. (Accessed 23 February 2024).
[9] Wind energy'. Accessed: February. 23, 2024. [Online]. Available: https://www.irena.org/Energy-Transition/Technology/Wind-energy.
[10] IEA, Tracking Clean Energy Progress 2023, Wind', 2023 [Online]. Available: https://www.iea.org/energy-system/renewables/wind#tracking.
[11] Giuseppe Costanzo, Guy Brindley, Wind Energy in Europe. 2023 Statistics and the Outlook for 2024-2030, 2024 [Online]. Available: https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaDdDVG9JYTJWNVNTSWhPV050WW1GMmFXaG5Zbk0xZFRsaGNHWTJlakY1T1RaaFpEUTNNQVk2QmtWVU9oQmthWE53YjNOcGRHbHZia2tpQVk1cGJteHBibVU3SUdacGJHVnVZVzFsUFNKWGFXNWtSWFZ5YjNCbElDMGdWMmx1WkNCbGJtVnlaM2tnYVc0Z1JYVnliM0JsSUMwZ01qQXlNeTV3WkdZaU95Qm1hV3hsYm1GdFpTbzlWVlJHTFRnbkoxZHBibVJGZFhKdmNHVWxNakFsTWtRbE1qQlhhVzVrSlRJd1pXNWxjbWQ1SlRJd2FXNGxNakJGZFhKdmNHVWxNakFsTWtRbE1qQXlNREl6TG5Ca1pqc2dZMjl1ZEdWdWRGOTBlWEJsUFNKaGNIQnNhV05oZEdsdmJpOXdaR1lpT3daVVNUSVJjMlZ5ZG1salpWOXVZVzFsQmpzR1ZFa2lDbXh2WTJGc0Jqc0dWQT09IiwiZXhwIjoiMjAyNC0xMC0xN1QxNjoyMDozMS42MzJaIiwicHVyIjoiYmxvYl9rZXkifX0=–2a7477b5ed75b8f13f4899929d9e401fd57952e4/WindEurope%20-%20Wind%20energy%20in%20Europe%20-%202023.pdf.
[12] European Commission, European wind power action plan, Oct 24 (2023).
[13] R. Bhandari, B. Kumar, F. Mayer, Life cycle greenhouse gas emission from wind farms in reference to turbine sizes and capacity factors, J. Clean. Prod. 277 (Dec. 2020) 123385, https://doi.org/10.1016/j.jclepro.2020.123385.
[14] R.H. Crawford, Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield, Renew. Sustain. Energy Rev. 13 (9) (2009) 2653–2660, https://doi.org/10.1016/j.rser.2009.07.008. https://linkinghub.elsevier.com/retrieve/pii/S1364032109001403.
[15] Raymond Aso and Wai Ming Cheung, 'Towards Greener horizontal-axis Wind Turbines: Analysis of Carbon Emissions, Energy and Costs at the Early Design Stage'.
[16] T. Rubert, D. McMillan, P. Niewczas, A decision support tool to assist with lifetime extension of wind turbines, Renew. Energy 120 (2018) 423–433, https://doi.org/10.1016/j.renene.2017.12.064. https://linkinghub.elsevier.com/retrieve/pii/S0960148117312685.
[17] L. Ziegler, E. Gonzalez, T. Rubert, U. Smolka, J.J. Melero, Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK, Renew. Sustain. Energy Rev. 82 (2018) 1261–1271, https://doi.org/10.1016/j.rser.2017.09.100. https://linkinghub.elsevier.com/retrieve/pii/S1364032117313503.
[18] Canadian Renewable Energy Association, Sustainable Energy: Recycling Renewables, 2021 [Online]. Available: https://renewablesassociation.ca/wp-content/uploads/2021/04/Recycling-Wind-Turbines-English-Web.pdf.
[19] Nina Vielen-Kallio, Olivier Amersfoort, End -of-Life phase and three circularity concepts for wind turbine blades (WP6.3), DECOM Tools Project 2022, Interreg Northern Sea Region' (2022) [Online]. Available: https://vb.northsearegion.eu/public/files/repository/20230131145553_WP6.3_Threecircularityconceptsforwindturbineblades.pdf.
[20] M. Jr. Leon, Recycling of wind turbine blades: recent developments, Curr. Opin. Green Sustainable Chem. 39 (Feb. 2023) 100746, https://doi.org/10.1016/j.cogsc.2022.100746.
[21] A. Tang, 'Repowered wind farms show huge potential of replacing old turbines', WindEurope. Accessed: November. 24, 2023. [Online]. Available: https://windeurope.org/newsroom/news/repowered-wind-farms-show-huge-potential-of-replacing-old-turbines/.
[22] J.P. Jensen, K. Skelton, Wind turbine blade recycling: experiences, challenges and possibilities in a circular economy, Renew. Sustain. Energy Rev. 97 (2018) 165–176, https://doi.org/10.1016/j.rser.2018.08.041.
[23] P. Liu, C.Y. Barlow, Wind turbine blade waste in 2050, Waste Manag. 62 (2017) 229–240, https://doi.org/10.1016/j.wasman.2017.02.007.
[24] J. Joustra, B. Flipsen, R. Balkenende, Structural reuse of high end composite products: a design case study on wind turbine blades, Resour. Conserv. Recycl. 167 (Apr. 2021) 105393, https://doi.org/10.1016/j.resconrec.2020.105393.
[25] J. Beauson, A. Laruent, D.P. Rudolph, J. Pagh Jensen, The complex end-of-life of wind turbine blades: a review of the European context, Renew. Sustain. Energy Rev. 16 (2022).
[26] A. Tyurkay, G.M. Kirkelund, A.T.M. Lima, State-of-the-art circular economy practices for end-of-life wind turbine blades for use in the construction industry, Sustain. Prod. Consum. 47 (Jun. 2024) 17–36, https://doi.org/10.1016/j.spc.2024.03.018.
[27] P. Deeney, P.G. Leahy, K. Campbell, C. Ducourtieux, G. Mullally, N.P. Dunphy, End-of-life wind turbine blades and paths to a circular economy, Renew. Sustain. Energy Rev. 212 (Apr. 2025) 115418, https://doi.org/10.1016/j.rser.2025.115418.
[28] CELAVI: circular economy lifecycle assessment and visualization framework [Online]. Available: https://www.nrel.gov/analysis/celavi.html. (Accessed 8 January 2024).
[29] Wayne Hicks, NREL researchers point to path for improved wind blade recycling rates [Online]. Available: https://www.nrel.gov/news/detail/program/2022/nrel-researchers-point-to-path-for-improved-wind-blade-recycling-rates?utm_source=chatgpt.com, 2022.
[30] M. Saidani, B. Yannou, Y. Leroy, F. Cluzel, A. Kendall, A taxonomy of circular economy indicators, J. Clean. Prod. 207 (2019) 542–559, https://doi.org/10.1016/j.jclepro.2018.10.014.
[31] B. Corona, L. Shen, D. Reike, J.R. Carreón, E. Worrell, Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics, Resour. Conserv. Recycl. 151 (2019) 104498, https://doi.org/10.1016/j.resconrec.2019.104498.
[32] H.S. Kristensen, M.A. Mosgaard, A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? J. Clean. Prod. 243 (2020) 118531 https://doi.org/10.1016/j.jclepro.2019.118531.
[33] T. Stehly, P. Beiter, P. Duffy, 2019 cost of wind energy review, Renew. Energy (No. NREL/TP–5000-78471), in: National Renewable Energy Laboratory (NREL), 2020. Golden, CO (United States).
[34] S. Krohn, P.-E. Morthorst, S. Awerbuch, The Economics of Wind, Energy', 2009.
[35] T. Stehly, P. Duffy, Cost of Wind Energy Review, 2021, 2022.

[36] M. Ali, J. Matevosyan, J.V. Milanović, Probabilistic assessment of wind farm annual energy production, Electr. Power Syst. Res. 89 (Aug. 2012) 70–79, https://doi.org/10.1016/j.epsr.2012.01.019.
[37] A.K. Azad, M.G. Rasul, M.M. Alam, S.M.A. Uddin, S.K. Mondal, Analysis of wind energy conversion system using weibull distribution, Procedia Eng. 90 (2014) 725–732, https://doi.org/10.1016/j.proeng.2014.11.803.
[38] Huaiping Jin, Lixian Shi, Xiangguang Chen, Bin Qian, and Biao Yang, 'Probabilistic Wind Power Forecasting Using Selective Ensemble of Finite Mixture Gaussian Process Regression Models'.
[39] Iain STAFFELL and Richard GREEN, Hoes does Wind Farm Performance Decline with Age', 2014.
[40] C. Mone, M. Hand, M. Bolinger, J Rand, D Heimiller, J Ho, Cost of wind energy review, National Laboratory of the Rockies (2015), 2017.
[41] Mott MacDonald, UK Electricity Generation Costs Update, 2010. https://assets.publishing.service.gov.uk/media/5a797fe840f0b642860d89de/71-uk-electricity-generation-costs-update-.pdf.
[42] Y. Kikuchi, T. Ishihara, Assessment of capital expenditure for fixed-bottom offshore wind farms using probabilistic engineering cost model, Appl. Energy 341 (Jul. 2023) 120912, https://doi.org/10.1016/j.apenergy.2023.120912.
[43] RTE, Bilan Électrique 2023 Rapport complet_29fev24, 2024.
[44] Ryan Wiser, et al., Chapter-7-Wind-Energy-1', 2011.
[45] J. Potting, M. Hekkert, E. Worrell, A. Hanemaaijer, CIRCULAR ECONOMY: MEASURING INNOVATION IN THE PRODUCT CHAIN, 2017.
[46] Capegemini and FEE, Analyse du marché, des emplois et des enjeux de l'éolien en France [Online]. Available: https://www.connaissancedesenergies.org/sites/connaissancedesenergies.org/files/pdf-actualites/ObsEol-2023_EncreNous-webHD_20230918.pdf.
[47] Leon Mishnaevsky Jr., Sustainable End-of-Life Management of Wind Turbine Blades: Overview of Current and Coming Solutions, MDPI, 2021 [Online]. Available: https://www.mdpi.com/1996-1944/14/5/1124?utm_source=chatgpt.com.
[48] NatLabRockies/celavi, Python. National Laboratory of the Rockies, Dec. 06, 2025 [Online]. Available: https://github.com/NatLabRockies/celavi. (Accessed 4 June 2026).
[49] F. Meng, et al., End-of-life management for wind turbines, Nat. Rev. Clean Technol. 1 (10) (Oct. 2025) 677–698, https://doi.org/10.1038/s44359-025-00097-3.