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Economic Benefits of Recycling in the Supply Chain from a Circular Economy Perspective: A Case Study of Wind Turbines

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Abstract

The rapid global expansion of wind energy technologies has intensified the demand for critical and scarce raw materials, raising concerns regarding supply security, price volatility, and environmental sustainability. As wind turbines reach the end of their operational lifetime, recycling and recovery of materials emerge as a key strategy to mitigate these challenges within a circular economic framework. This study provides a quantitative assessment of the economic benefits associated with recycling wind turbine materials, with a specific focus on supply chain sustainability.

A 2.5 MW onshore wind turbine is analyzed using life cycle assessment (LCA)-based material composition data obtained from published literature. Material mass estimation is combined with reported recycling rates and market-based scrap prices to evaluate the recoverable economic value from end-of-life turbine components. The analysis considers major materials, including steel, cast iron, aluminum, copper, fiberglass, epoxy, and rare earth magnets, which together account for approximately 98% of the turbine mass.

The results indicate that around 84% of the total turbine mass is currently recyclable using existing technologies. Metallic materials dominate the recycling potential, with steel and cast iron representing the largest mass shares. The total recoverable economic value from recycling is estimated at €58,297 per turbine, equivalent to approximately €23,300 per MW of installed capacity. Steel (€22,483) and power cables (€32,209) contribute the highest economic returns due to their large quantities and high recycling rates. Although rare earth magnets constitute less than 1% of the total turbine mass, they exhibit significant economic and strategic importance, with a potential recovery value of up to €14,660 under increased recycling scenarios.

These findings demonstrate that material recycling can substantially offset decommissioning costs, reduce dependence on primary raw materials, and enhance supply chain resilience. The study provides quantitative evidence supporting the integration of circular economy strategies into wind turbine design, decommissioning planning, and renewable energy supply chain management.

Keywords

Circular Economy
Recycling, Wind Turbine
Supply Chain
Raw Material

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1. Introduction

With the expansion of advanced technologies in the field of renewable energy, industries reliant on equipment such as lithium-ion batteries, wind turbines, solar panels, and electric vehicles have increasingly come under global scrutiny (1, 2). These industries depend on specific minerals and elements, which are often associated with complex, concentrated, and vulnerable supply chains (3). Materials such as lithium, nickel, cobalt, neodymium, and dysprosium not only have limited extraction sources, but their processing is also predominantly concentrated in a few countries. This geographical concentration introduces significant geopolitical risks and increases countries' dependence on specific suppliers (4).

Beyond geopolitical challenges, severe price volatility, environmental constraints in extraction and processing, and social issues related to human rights in mining operations within developing countries threaten the sustainability of these supply chains (5). Furthermore, the rapid increase in global demand for these materials is accompanied by substantial delays in the development of new mining projects, which may lead to supply shortages in the near future (4). On the other hand, insufficient efficiency in recycling consumed materials—particularly in sectors such as batteries and wind turbine blades—has exacerbated industrial waste crises and intensified pressure on natural resources (6).

Under these circumstances, a comprehensive and multidimensional analysis of risks in the supply chain of raw materials critical to energy-related technologies is necessary. These risks not only affect industrial production capacity but also threaten countries' environmental objectives and broader strategies for transitioning to a low-carbon economy. Therefore, understanding these risks and developing effective management and mitigation strategies are key priorities in industrial and economic policymaking (7). Figure 1 illustrates the relative risk of various materials within the supply chains of emerging industries.

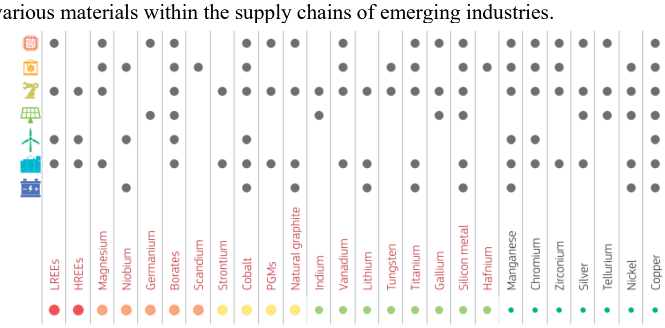

Figure 1 – Material Risk in the Supply Chain Across Different Technologies and Sectors of the Industry (7).

The circular economy, as an alternative approach to resource management, plays a significant role in mitigating supply-chain risks. This model emphasizes recycling, regeneration, and material reuse, thereby reducing dependence on virgin raw material extraction and alleviating pressure on natural resources (1). Particularly in industries such as battery manufacturing and wind turbine equipment, the development of advanced recycling technologies and product redesign to facilitate recyclability constitutes effective measures to enhance supply chain sustainability (8). Moreover, by generating new streams of secondary materials, the circular economy can help reduce price volatility and increase the flexibility of supply systems, thereby facilitating the transition to clean energy and the achievement of environmental objectives.

Unlike previous studies, which mainly focus on environmental life cycle assessment (LCA) or conceptual discussions of the circular economy in the wind energy sector, this study provides a quantitative economic evaluation of material recycling in the wind turbine supply chain from a circular economy perspective. The main contributions of this study include: (i) integrating LCA-based material mass estimation with recycling rates and market-based scrap pricing, (ii) explicitly quantifying the economic value recovery from end-of-life wind turbines, and (iii) linking economic outcomes to supply-chain sustainability and material criticality. By combining environmental, economic, and supply risk dimensions in a single case study, this research offers an operational framework that goes beyond existing qualitative or environmentally focused studies.

2. Literature Review

The circular economy is viewed as an alternative to the linear economy or the "make-use-dispose" model, aiming to retain resources in circulation for as long as possible. The term "circular economy" was first introduced in 1990 and subsequently gained academic attention. It is regarded as a framework for establishing mechanisms that foster regenerative industrial transformations, leading to sustainable production and consumption (9). Over the past decade, researchers have widely advocated for the adoption of circular economy principles within supply chains. Most studies propose sustainable development as the primary objective of the circular economy (10). Kirchherr found that in the circular economy—as an alternative economic system to the "end-of-life" model—environmental and economic aspects are prioritized, focusing on recycling and reuse (11). Enciso-Alfaro also posits that the circular economy, through efficient resource use and environmental protection, promotes business growth and development (12).

The Ellen MacArthur Foundation has defined the Material Circularity Indicator (MCI), which is based on recycling and reuse rates, process efficiency, and the proportion of recycled and reused content in a product (13). One of the key challenges in the transition to a low-carbon economy is the growing dependence on rare earth elements. Circular economy strategies can reshape rare earth element supply chains by increasing secondary supply and reducing primary demand over the next three decades (14). Given the critical resources required for renewable energy production, these industries are heavily reliant on scarce raw materials, and the circular economy can help address this challenge and reduce dependency. Consequently, reshaping supply chain patterns and employing innovative approaches in this domain are imperative.

The circular economy can be regarded as a holistic and multidimensional concept, lacking a universally accepted definition. Instead, various perspectives exist, and suitability depends on the context. Nevertheless, establishing a definition that serves as a foundation for regulations, policies, and strategies is crucial (15). Furthermore, the circular economy may be considered an umbrella concept, as several other concepts are embedded within it (16). Table 1 presents a collection of definitions.

No.	Authors (Year)	Definition
1	Kirchherr et al. (2023)	The circular economy is a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.
2	Arruda (2021)	Circular Economy emerges as an effective tool for triggering a sustainable development process. This article aims to present different perspectives and definitions based on a literature review from 2015 to 2020.
3	Alhawari (2021)	A sound definition of a circular economy includes the main identified elements, organizational planning processes, customers and society, utilization of the ecosystem, and economic resource flows.
4	Scarpellini (2019)	The circular economy (CE) is a development model that seeks to minimize the negative impact of human activities by applying principles related to the "3 Rs": reduce, reuse, and recycle.
5	Hossain (2024)	A circular business model (CBM) is a business model designed inherently to support a regenerative system. Its goal is to maximize resource value through strategies like maintenance, reuse, and recycling.
6	European Parliament (2023)	The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended.
7	Figge (2023)	Circular resource use is one of several responses to the unsustainability of current resource use - a key problem in sustainable development. The economy as an open subsystem is embedded in a larger ecological system with limited resources.
8	Finamore (2024)	This paper aims to enable a comprehensive definition for a Circular Economy (CE) that will support its effective introduction in the building and construction sectors.

Table 1 – Definitions of Circular Economy

The proposed definition is as follows: "A circular economy is an economic system that replaces the concept of end-of-life with the reduction, reuse, recycling, and recovery of materials within production, distribution, and consumption processes. This system operates at the micro level (products, companies, consumers), meso level (industrial eco-parks), and macro level (cities, regions, countries, and beyond), intending to achieve sustainable development through simultaneous environmental and economic quality improvements". (10)

In summary, the circular economy and recycling play a vital role not only from an environmental perspective but also in economic performance and material supply security within the wind turbine industry. Increasing recycling rates and developing recycling-based supply chains can lead to cost reductions, reduced dependence on primary resources, and enhanced sustainability in the wind energy sector.

To better position the present study and identify existing research gaps, previous studies related to the circular economy and recycling in the renewable energy sector, particularly in wind turbines, are reviewed in Table 2. These works focus on different aspects of the topic: some emphasize the conceptual foundations of the circular economy, others highlight life cycle assessment and material recycling, while a few explore design models and economic evaluations. However, as summarized in the following table, a clear gap remains in comprehensive research that simultaneously addresses the economic and environmental dimensions of material recycling within the wind turbine supply chain.

No.	Authors (Year)	Title	Key Findings / Strengths / Limitations
1	Kirchherr et al. (2017)	Conceptualizing the Circular Economy: An analysis of 114 definitions	Provides multiple definitions of CE; strong conceptual contribution, but limited practical applications.
2	Korhonen et al. (2018)	Circular Economy as an Essentially Contested Concept	Critically discusses different perspectives on CE; highlights the lack of a universal definition.
3	Graedel et al.	UNEP Recycling Rates	Offers global recycling rate

	(2011)	of Metals: A Status Report	benchmarks for metals; a valuable data source, but focuses mainly on metals.
4	Bonou et al. (2016)	Life Cycle Assessment of Onshore and Offshore Wind Energy	Demonstrates that recycling reduces environmental impacts in wind energy, primarily LCA-based.
5	Jensen (2018)	Circular Economy in the Wind Industry	Introduces closed-loop approaches in wind energy; emphasizes challenges of recycling composite blades.
6	Ardente et al. (2008)	Energy Performances and Life Cycle Assessment of an Italian Wind Farm	Analyzes LCA of a wind farm; provides insights into energy and environmental performance, but limited economic discussion.
7	Sieros et al. (2012)	Upscaling Wind Turbines: Theoretical and Practical Aspects	Proposes models for material mass estimation; useful for material forecasting, but lacks focus on recycling economics.
8	Andersen et al. (2014)	Recycling of Wind Turbines: DTU International Report	Comprehensive study showing over 85% of turbine materials can be recycled; highlights practical recycling pathways.
9	Diez-Cañamero et al. (2023)	Circular economy performance and carbon footprint of wind turbine blade waste management alternatives	Provides a strong quantitative environmental assessment. However, it mainly focuses on environmental impacts and does not include a detailed economic valuation.
10	Hanes et al., (2021)	The Circular Economy Lifecycle Assessment and Visualization Framework: A Case Study of Wind Blade Circularity in Texas	Provides a case study on the mechanical recycling of wind turbine blades. However, the scope is limited to blades and does not assess the overall material recovery potential or supply chain sustainability of complete wind turbines.
11	Cieślewicz et al., 2025	End-of-Life Strategies for Wind Turbines: Blade Recycling, Second-Life Applications, and Circular Economy Integration	Presents a comprehensive system-level review, with a particular emphasis on blade recycling technologies. The study is technology-oriented, with limited quantitative analysis of economic benefits.

Table 2 – Previous studies related to the circular economy and recycling in the renewable energy sector

As the comparative review illustrates, most previous studies have focused either on conceptual circular economy frameworks or on environmental assessments, such as life cycle assessment (LCA). While these contributions are valuable, they often overlook an integrated assessment of the economic and environmental dimensions of recycling in the wind turbine industry. This gap is addressed in the present study by quantifying the economic benefits of recycling within a circular economy framework and linking these outcomes to supply chain sustainability.

Compared with existing studies, the present research differs in both scope and methodological focus. While studies such as Bonou et al. and Diez-Cañamero et al. (17, 18) Primarily emphasizing environmental impacts using LCA, this study explicitly incorporates economic valuation of recycled materials based on market prices. Conceptual works on the circular economy (9, 10) provide valuable theoretical foundations but lack quantitative operational analysis. Furthermore, unlike blade-focused studies (19, 20), the current research evaluates all major wind turbine materials, offering a holistic supply chain sustainability perspective.

3. Methodology

This study employs a life cycle assessment (LCA) approach combined with quantitative data analysis. The material composition of wind turbines was derived from published LCA studies, including reports by Vestas and other academic sources. Curve-fitting models were used to estimate material masses, after which recycling rates were applied to determine recoverable material values. Economic calculations were based on price data from the London Metal Exchange and relevant industry reports. MATLAB was used for curve fitting and numerical analysis.

In recent years, the rapid growth of the wind energy sector and the increasing installed capacity of turbines have emerged as key strategies for reducing greenhouse gas emissions and combating climate change. (3) The wind turbine industry has evolved into a modern industrial-scale sector. Global wind energy capacity has experienced a significant increase over the past decade. This capacity growth is illustrated in Figure 2, which depicts the annual installed capacity. (21)

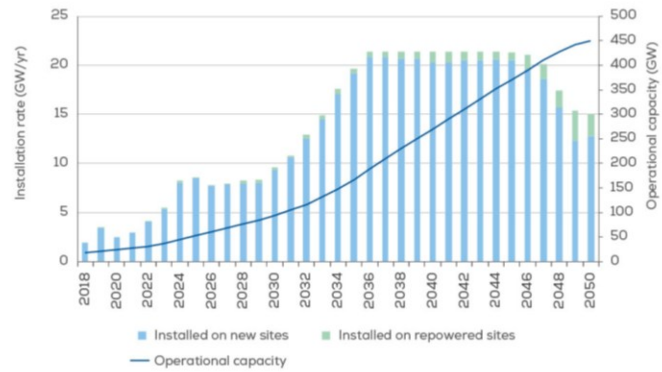

Figure 2 – Installation Rate in Gigawatts per Year (Left Axis) and Operational Capacity (Right Axis) Required to Reach 450 GW by 2050 (22)

In Iran, the Seventh Five-Year Development Plan (2024–2028) targets an installed renewable energy capacity of 12,000 MW, representing a tenfold increase over the current level. Renewable electricity generation is also projected to reach 21,000 GWh by the end of the plan period. Under Article 46 of the plan, key ministries, including Petroleum, Energy, Industry, Mines and Trade, and Interior, are mandated to address energy imbalances and increase the share of renewable energy in the national electricity supply. In addition, pursuant to Article 12 of the Law on Removing Barriers to Competitive Production and Improving the Financial System, these ministries are required to promote the development of solar and wind power plants, self-supplying power plants in industrial, agricultural, commercial, public, and residential sectors, vehicle electrification with priority given to urban public transport, and the provision of heating and cooling for buildings in southern coastal regions using geothermal heat pumps.

However, this rapid growth also presents challenges, including the need for limited and critical raw materials to manufacture wind turbine components. It is essential that, alongside theoretical research and studies, empirical and operational research be conducted within organizations and companies to develop product development strategies that incorporate circular economy principles. (23) Upon decommissioning wind turbines, the materials recovered must be effectively managed. Proper disposal and resale in the waste market yield financial benefits and reduce environmental impacts by decreasing the demand for primary raw materials. The global recycling rates for key metals such as steel, copper, and aluminum exceed 50%; however, relative to the fraction of recycled content in the total metal input, there remains significant room for improvement in metal recycling (24)

The most relevant materials required for wind power generation and the main components of a wind turbine are listed in Figure 3 (7).

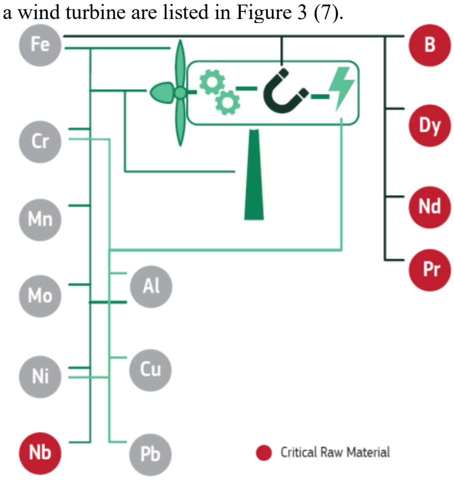

Figure 3 – Raw Materials Used in Wind Turbines (7)

The construction cost of wind turbines, particularly those utilizing generators containing rare earth elements, is significantly influenced by metal prices. Concerns regarding the adequacy of rare earth element supply to meet the increasing global demand for a sustainable energy transition have substantially intensified since 2011, when China imposed near-export restrictions.

Bottleneck assessments for wind turbines indicate that material supply risk represents the highest risk within the supply chain. This risk diminishes downstream to a moderate risk for processed materials and components until it manifests as a latent risk for assemblies. Therefore, enhancing the recycling and reuse of materials is critically important not only from an environmental perspective but also economically and in terms of supply security. This has given rise to the circular economy approach in the wind turbine industry, which aims to preserve material value and reduce dependency on primary resources, thereby improving sustainability.

The decommissioning of wind turbines is gaining increasing significance as the existing fleet ages. ORE Catapult estimates that approximately 1.5 GW of wind capacity worldwide will require decommissioning by 2030, increasing to 13 GW by 2040. Essentially, 85 to 90 percent of materials used in wind turbines—including foundations, towers, gearbox components, and generators—are potentially recyclable.

As illustrated in Figure 4, wind turbines consist of five main components:

Foundation: For onshore turbines, the foundation is typically a concrete block often buried underground. Offshore turbines are anchored to floating platforms or fixed bases secured to the seabed.

Tower: Towers are constructed from steel cylinders designed to withstand tensile forces and can range in height from 3 meters to over 110 meters.

Rotor: Wind turbine blades feature aerodynamic airfoil designs. Typically, a wind turbine rotor comprises three blades attached to a central hub. The blades are hollow and commonly made from composite materials to maximize strength and minimize weight.

Nacelle: Positioned atop the tower, the nacelle houses the electromechanical systems of the turbine, including the gearbox, generator, inverters, hydraulics, bearings, and drive shaft.

Generator: Located within the nacelle, wind turbine generators convert the kinetic energy produced by the rotating rotor blades into electrical energy.

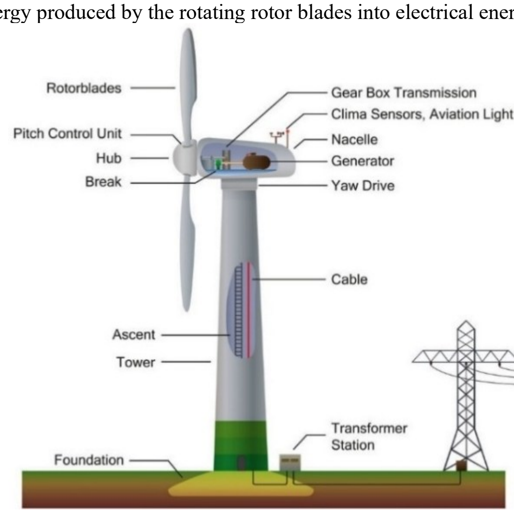

Figure 4 – Components of a Wind Turbine

For this research, the primary materials considered in the construction of wind turbine components, foundations, and cables include steel, cast iron, aluminum, copper, fiberglass, epoxy, and magnets. These materials constitute up to 98% of the total mass of materials used in a wind turbine. Additionally, these materials represent substances with significant economic and environmental impacts.

Several published product life cycle studies were analyzed to collect relevant material quantity data. In total, 30 product life cycle studies with sufficiently detailed material mass data applicable to this research were identified. Among these evaluated studies, the product life cycle assessment published by Vestas was utilized. (25) Similarly, data from other published product life cycle studies that specified material mass for wind turbines in general were also employed. (26-29)

Sieros et al., in their theoretical and practical advancements of wind turbines, proposed that Equation 1 accurately represents the material distribution. (30) Equation 1 is governed by the curve-fitting coefficients a and b, where M denotes the material mass, and X is a parameter characterizing the wind turbine specification. This equation was chosen as it provided a better curve fit for material mass, as indicated by lower R^2 values.

$$M = a * X^b \qquad (1)$$

The aggregation of material mass was performed using MATLAB's curve-fitting toolbox. Table 3 presents the coefficients a and b for Equation 1 corresponding to each material. Additionally, the R^2 values, indicating the goodness of fit, are provided to offer an overview of the curve fitting accuracy.

No.	Material	a	b	R^2
1	Steel	0.2043	1.571	0.84
2	Cast Iron	16.55	1.065	0.87
3	Fiberglass	0.03469	1.41	0.61
4	Epoxy	0.03642	1.76	0.6
5	Aluminum	0.6554	1.631	0.68
6	Copper	1.262	0.754	0.58

Table 3 – Equation coefficients and curve fitting (31)

Specific materials such as steel, cast iron, and fiberglass are utilized in multiple components of wind turbines. Only a limited number of product life cycle studies have detailed the material composition of each component. (17, 32-42) Table 4 presents the materials comprising each wind turbine component along with the percentage share of materials within each component.

No.	Component	Material	Ratio (%)
1	Rotor	Cast Iron	31.3
2		Steel	3.3
3		Fiberglass	79.4
4		Epoxy	100
5	Tower	Steel	76.6
6	Nacelle	Aluminum	100
7		Copper	100
8		Magnet	100
9		Steel	20
10		Cast Iron	68.7
11		Fiberglass	20.6

Table 4 – Material Ratios in a Wind Turbine

The criticality of various materials has been analyzed by the European Union. Criticality is a measure that indicates how economically and strategically essential a specific material is for the European economy. Among the 61 materials analyzed in 2023, 34 raw materials were identified as critical for Europe. (43)

The availability of practical substitute materials, together with secondary raw material production through recycling, reduces material criticality. Therefore, special attention should be given to mitigation measures for critical raw materials used in wind turbines. Table 5 presents the criticality ranking of materials used in wind turbines. The European Union critical raw materials report does not provide an explicit ranking; therefore, the rankings presented in the table are derived from supply risk and economic importance indicators (43). Rank 1 indicates the most critical material, while rank 5 represents the least critical. NdFeB magnets are the most critical materials used in wind turbines. China produces approximately 95% of the rare earth elements required for these magnets, posing a significant supply risk. Additionally, the currently low recycling rates of rare earth elements further increase their importance. The extensive use of cast iron and steel across all sectors in the EU makes them the next most important materials.

No.	Material	Rank
1	Magnet	1
2	Steel	2
3	Cast Iron	2
4	Aluminum	3
5	Fiberglass	4
6	Epoxy	4
7	Cable	4
8	Copper	5

Table 5 – Criticality Ranking of Wind Turbine Materials
(Source: Compiled by authors based on European (43))

Metal recycling is the main method for managing decommissioned wind turbine components. The United Nations Environment Programme has analyzed global average recycling rates for key metals. For end-of-life metals, recycling rates are estimated at 70–90% for steel, 40–70% for aluminum, and approximately 50% for copper (24). These rates vary depending on metal quality, concentration within a component, and existing infrastructure. In the case of wind turbines, due to the large quantities of materials in their components, the recycling rates are higher compared to the global average. Table 6 presents the material recycling rates for a wind turbine based on analyses reported in the wind turbine recycling study. (44)

The recycling rate is calculated using Equation 2:

$$Recycling\ Potential = \frac{\sum(Recycling\ Rate * Mass\ of\ Material)}{\sum \text{Mass of Material}} \qquad (2)$$

This represents the recycling rates of materials used in wind farms, based on data from Andersen et al. Current disposal of fiberglass and epoxy in cement kilns is considered as "recovery," and is therefore assumed to be 15% lower. A 50% recycling rate for foundations indicates partial removal

No.	Material	Recycling Rate (%)
1	Steel	92
2	Cast Iron	98
3	Fiberglass	15
4	Epoxy	15

5	Aluminum	95
6	Copper	98
7	Magnet	5
8	Cable	90

Table 6 – Recycling Rates of Wind Turbine Materials (24, 44)

4. Results

The 2.5 MW wind turbine under study has the following characteristics:

Rated Active Power: 2.5 MW

Rotor Diameter: 103.6 m

Hub Height: 85 m

Materials recovered from decommissioned wind turbine components have monetary value, which can be realized through reuse, remanufacturing, or recycling. Currently, most materials are recycled by selling them as scrap through recycling centers.

Figure 5 shows the assessed scrap values of the materials, with steel, copper, and aluminum prices obtained from the London Metal Exchange. For fiberglass and epoxy, primarily found in turbine blades, owners typically face disposal costs of approximately €150 per ton, mainly covering transportation and incidental expenses, which may vary by national regulations.

Magnets contain valuable rare earth materials and are extensively used in wind turbines, resulting in a monetary value of approximately 11–12 USD/kg for the magnets (45). However, only a limited number of commercial companies recycle NdFeB magnets, so the scrap value may vary depending on the availability of recycling facilities. Cable recycling in Europe has attracted attention due to a scrap value of about €2,464 per ton. This relatively high value is primarily due to the copper content in cables. The monetary values shown in Figure 5 represent the amounts that a wind turbine owner can potentially recover through recycling.

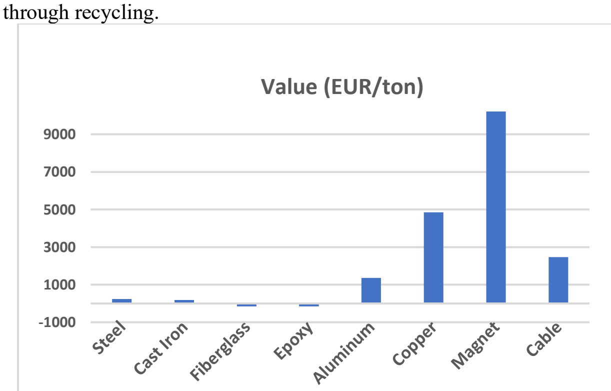

Figure 5 – Monetary Value of Wind Turbine Materials
(Source: Authors' calculations based on LME data and recycling rates reported by (44))

Figure 6 ranks the materials used in the studied wind turbine from highest to lowest mass. Steel, at 263 tons, is the most extensively used material, followed by 50 tons of cast iron. Cables account for 15 tons. Magnets, with less than 2 tons, represent the material with the lowest mass used in the wind turbine.

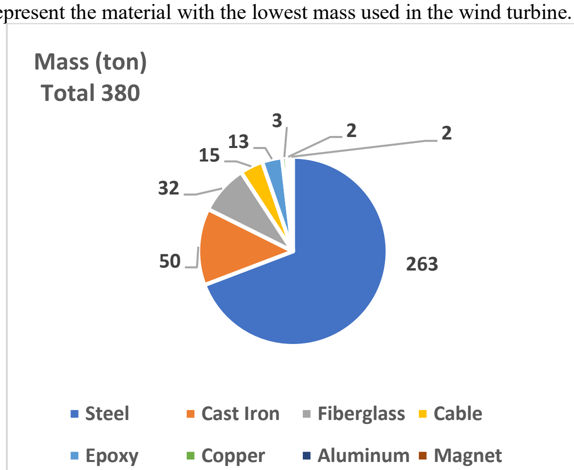

Figure 6 – Mass of Materials in the Studied Wind Turbine
(Source: Authors' calculations based on LME data and recycling rates reported by (44))

The monetary value from recycling is calculated using Equation 3:

$$\text{Monetary Value (EUR)} = \text{Mass(ton)} * \text{Monetary value}\left(\frac{\text{EUR}}{\text{ton}}\right) * \text{Recycling rate (\%)} \qquad (3)$$

According to Equation 3, a maximum of €32,209 can be obtained by recycling cables, providing a strong incentive to recover all cables. However, recycling infrastructure and processes vary by location, so the monetary value may differ. Steel, despite its relatively low value per ton, can generate €22,483 from scrap sales due to the large quantity used in the wind turbine. Currently, magnets are largely unrecycled; assuming a hypothetical recycling rate of 5%, they generate €814. However, with increased focus on magnet recycling in the near future and assuming a 90% recycling rate, magnets could recover €14,660 from just 2 tons in the wind farm. Disposal of fiberglass and epoxy, primarily in the blades, incurs costs for the wind farm owner. These costs vary depending on national regulations, highlighting the need for new measures to manage these materials effectively.

As summarized in Figure 7, a total of €58,297 can be recovered from material recycling in the wind turbine.

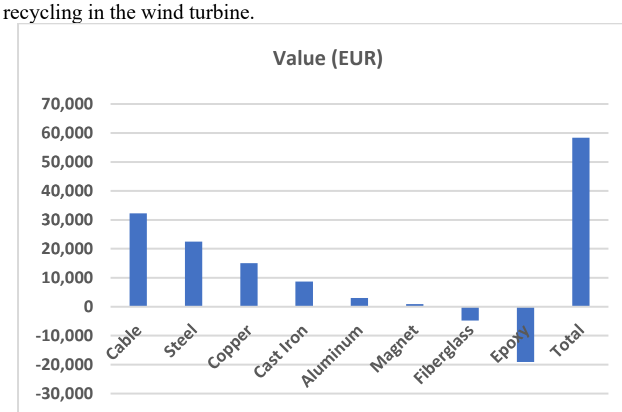

Figure 7 – Recovered Value from Recycling Materials in the Studied Wind Turbine
(Source: Authors' calculations based on LME data and recycling rates reported by (44))

The recycling potential of a wind turbine illustrates the percentage of the turbine that can be recycled. Using the recycling rates presented in Table 6 and the material masses shown in Figure 6, the recycling potential of the wind turbine is 84%. This represents the fraction of the turbine that is currently recyclable. By increasing the recycling of fiberglass and epoxy, an even higher recycling potential can be achieved.

5. Discussion and Conclusion

The results indicate that recycling materials from a single 2.5 MW wind turbine can generate approximately €58,297, equivalent to about €23,300 per MW of installed capacity. Metallic materials contribute more than 95% of the total recovered value, emphasizing their dominant role in circular supply chains. Despite their small mass share, rare earth magnets show high strategic and economic importance, with the potential to account for up to 25% of total recycling value under higher recycling rates.

The results of this study demonstrate that a circular economy can significantly enhance the sustainability and supply chain security of raw materials in the wind turbine industry. Recycling metallic materials such as steel, copper, and aluminum, which constitute most of a turbine's mass, reduces demand for virgin mineral extraction and creates economic benefits for recyclers and industry stakeholders. This approach also reduces greenhouse gas emissions, energy consumption, and other environmental impacts associated with raw material extraction and processing, thereby improving overall environmental performance. Furthermore, by reducing dependence on geographically concentrated resources and mitigating risks from price volatility and material scarcity, supply chain resilience is strengthened against market shocks and geopolitical uncertainties.

However, technical challenges in recycling composite materials and rare earth elements used in turbine components still hinder the full exploitation of recycling potential. Current technologies for recycling these materials are not yet optimized, and the high costs of recycling processes have limited widespread activity in this area. The development of advanced and efficient recycling technologies, including chemical and mechanical recycling methods, could transform the recovery of these materials and substantially enhance their economic value. Therefore, investment in technological research and international collaboration to develop innovative recycling methods is essential to realize the full potential of a circular economy in this sector.

Policymaking and the establishment of coherent legal frameworks are crucial for promoting the adoption of a circular economy. Policies such as extended producer responsibility, financial incentives for recycling technology investments, and design standards for product recyclability can motivate industries to transition toward a circular economy. Fostering a culture of recycling and reuse among all stakeholders, including manufacturers, consumers, and governments, is also essential for successful implementation. Cross-sector collaboration and the development of transparent, sustainable supply chains can further improve efficiency and reduce recycling costs.

Finally, it is recommended that future research specifically focuses on the development of innovative recycling technologies for composite materials and rare earth elements, as these two areas currently pose the greatest limitations in recycling processes. Additionally, studies examining the socio-economic impacts of implementing circular economy models at national and international levels can assist policymakers in formulating more effective strategies. Comprehensive life cycle analyses (LCA) and more detailed environmental assessments can also improve the understanding of the benefits and challenges of circular economic implementation in the wind turbine industry, providing practical guidance to enhance process efficiency. Overall, continued interdisciplinary research and international collaboration in this field will be key to advancing toward a sustainable, environmentally responsible industry.

Quantitatively, this study demonstrates that up to 84% of wind turbine materials are recyclable using current technologies. The recovered economic value can partially offset decommissioning costs and reduce dependence on primary raw materials. These numerical results provide strong evidence that circular economy strategies can improve both economic performance and supply chain sustainability in the wind turbine industry.

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