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Recycling potential of wind turbines supporting by European Green Deal policy – comparative energy analysis between Poland and Germany

Abstract: The European Green Deal represents a landmark initiative aimed at steering the continent towards a sustainable future, with renewable wind energy occupying a central role in this transition. This research delves into the multifaceted aspects of renewable wind energy within the context of the European Green Deal, focusing on several key dimensions. Firstly, the study examines the energy generation associated with both wind energy and coal energy, providing a comparative analysis to underscore the environmental advantages of renewable alternatives. Through detailed case studies centered on coal mining regions in Poland and Germany, the socio-economic dynamics of transitioning from coal-dependent economies to renewable energy systems are explored, elucidating the challenges and opportunities inherent in such transitions.

The end-of-life management of wind turbines, particularly recycling and reuse, presents significant challenges. This paper analyzes the recycling potential of wind turbines in Poland and Germany under the European Green Deal policy. While up to 85% of turbine components can be recycled, composite material blades, made of glass fibers and plastic polymers, remain difficult to recycle due to their complex structure.

Furthermore, the research investigates the application of circular economy principles within the wind energy sector, emphasizing strategies for resource efficiency, recycling, and waste

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reduction. This research has the most important impact on the European Green Deal and makes a new European zone with the goal of achieving zero carbon emissions. By synthesizing these diverse strands, this study contributes to a comprehensive understanding of how renewable wind energy can serve as a linchpin for achieving sustainability objectives outlined in the European Green Deal.

Keywords: wind turbine recycling, European Green Deal, circular economy, renewable energy, sustainability

Introduction

The European Green Deal is a groundbreaking initiative that establishes a new development path toward a sustainable future for European Union countries, with renewable energy at the center. Among the key renewable energy sources, wind power offers numerous environmental and economic advantages over traditional coal power. This article examines the potential for wind turbine recycling in the context of the European Green Deal, with a focus on Poland and Germany.

These countries are at two different stages in the renewable energy adoption process. Germany, a leader in renewable energy, has set ambitious goals to reduce CO_2 emissions and phase out nuclear power, investing heavily in solar, wind, and biomass. In contrast, Poland remains heavily dependent on coal and natural gas, which poses a major challenge to its energy transition. By analyzing wind and coal power generation, this study highlights the environmental benefits of renewable energy and the socioeconomic implications of the transition from coal-based economies to renewable energy systems in these two countries.

End-of-life management of wind turbines is one of the main challenges in their life cycle, especially with regard to recycling and reusing their components. Despite technological advances, only up to 85% of wind turbine components can currently be recycled, with blades made of composite materials posing the greatest difficulties. Composite materials, such as fiberglass and polymers, are difficult to separate and process. Degradation of plastics at high temperatures and damage to glass fibers during separation further complicate the recycling process.

By synthesizing the results of various studies and exploring the potential for wind turbine recycling within a circular economy, this study provides a comprehensive understanding of how renewable wind energy can serve as a foundation for achieving the sustainability goals of the European Green Deal.

This article highlights the need for continued technological advances, policy support, and international cooperation to address the challenges of wind turbine recycling and the efficient use of secondary resources after dismantling. Increasing the recyclability of turbines can bring significant socioeconomic benefits, including the creation of new jobs in the green technology sector, increased energy security, and improved quality of life through reduced pollution. Promoting a circular economy in the wind power sector can contribute to a more sustainable and resilient energy system that is less vulnerable to external shocks, such as fluctuations in commodity prices or disruptions in supply chains.

Moreover, this study aims not only to analyze the technical aspects of wind turbine recycling, but also to understand the broader political, economic, and social context. Cooperation between Poland, Germany, and other European Union countries is crucial to developing and implementing innovative solutions to support the achievement of climate neutrality on the continent. This analysis is a valuable contribution to the discussion on the future of renewable energy and the key role that wind turbine recycling can play in achieving a more sustainable future.

1. Literature review

European energy policy is increasingly focusing on sustainability and reducing greenhouse gas emissions. The promotion of renewable energy sources, including wind energy, plays a key role in decoupling from fossil fuels and reducing carbon emissions. Turbine wind farms are an important part of the energy landscape, providing a significant proportion of electricity generation in many countries. However, their decommissioning after 20–25 years generates significant amounts of waste. Mainly blades constructed from CFRP (Carbon Fiber Reinforced Polymer) and GFRP (Glass Fiber Reinforced Polymer) composites are difficult to recycle due to the complex structure and different types of resins used. Conventional methods of dealing with composite waste, such as landfilling and incineration, not only generate toxic emissions but also have serious environmental and public health impacts (Khalid et al. 2023).

Over the past 10 years, the number of research papers and projects dedicated to the recycling of wind turbines has increased significantly, especially in the European Union zone. Currently, according to the Web of Science database, about 150 scientific articles with the keywords "wind turbine recycling" can be found (Fig. 1). Several ways of reusing wind turbine blades at the end of their useful life are encountered in the waste industry. Composite recycling methods include (Qureshi 2022):

- Mechanical processing of composites:
    - **Shredding and grinding.** This process involves mechanically shredding turbine blades into smaller fragments, which are then ground into powder. The resulting material can be used as filler in various industrial applications.
    - **Water jet cutting.** This method involves cutting composites using a high-pressure water jet to recover pure fibers and resins.
- Thermal processing:
    - **Pyrolysis.** The process involves the thermal decomposition of composite materials in an oxygen-free atmosphere at high temperatures. This allows the recovery of glass and carbon fibers and the partial recovery of the energy contained in the resins.
    - **Combustion.** High-temperature combustion can be used to recover energy from composites; however, it is a controversial method due to emissions.

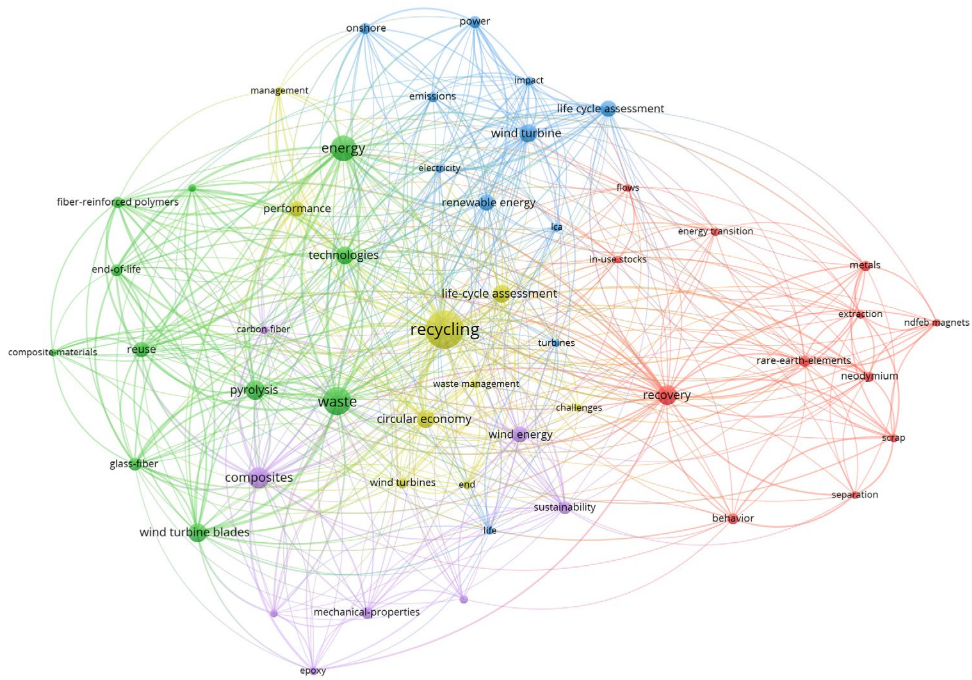

Fig. 1. Most traffic keywords in 150 research article in the EU zone

Rys. 1. Najczęściej wyszukiwane słowa kluczowe w 150 artykułach badawczych w strefie UE

- Chemical processing:
  - **Solvolysis.** The process involves the chemical decomposition of resins in organic solvents to recover carbon or glass fibers. Solvolysis can be carried out under a variety of conditions, including elevated pressure and temperature, to increase the efficiency of the process.
  - **Alkaline hydrolysis.** This method uses alkaline solutions to break down composites. It is an effective way to separate fibers from resins.
- Material recycling:
  - **Recycling metals.** Most wind turbine structures contain significant amounts of metals, such as steel, copper, and aluminum. These materials can be easily recycled and reused in the manufacture of new components.
  - **Casting and remelting.** Metals from turbine components are remelted and cast into new products, thus closing the material cycle.
- Innovative methods:
  - **Biological recycling.** The use of micro-organisms to degrade polymers in composites. This is a research area that holds promise for the development of new, more environmentally friendly recycling methods.

- **Hybrid technologies.** A combination of different recycling methods (e.g., mechanical and chemical) to maximize material recovery and minimize waste.

Currently, the most commonly used methods are still landfilling, recovery through incineration in cement plants, and various forms of downcycling (Zembrzuski et al. 2023).

The role of chemical treatment methods for composite waste, especially wind turbines, is being intensively researched because of their potential in recovering valuable raw materials. Moreover, there are many research projects that propose different technological solutions for recycling composite waste. Most of them show the potential of using ground turbine blades for different applications; however, for these innovative solutions to be fully successfully implemented, further research is needed to optimize recycling processes, reduce costs, and increase energy efficiency.

2. Method and data

The methods used in this article, combining literature review, quantitative data analysis, analytical research and policy analysis, provide a comprehensive, and multifaceted understanding of issues related to wind energy production and wind turbine recycling in the context of the European Green Deal.

The quantitative data analysis underlying this work was based on several main sources. Key statistics on wind and coal power production in Poland and Germany were obtained from national and international energy agencies, such as Eurostat, the International Energy Agency (IEA), and national statistical offices. Information on the number of end-of-life wind turbines and their recyclable components was gathered from industry reports and academic research. Comparative analyses of the energy efficiency and production costs of wind and coal power took into account variables such as CO_2 emissions, operating and maintenance costs.

The analytical research included a case study of coal mining regions in Poland and Germany and the processes of transition to renewable energy. Statistical methods were used to assess the socioeconomic dynamics of the transition from coal-dependent economies to renewable energy systems. A comprehensive comparison of CO_2 emissions between wind and coal power in Europe was also conducted. Case studies of wind and coal power in Poland and Germany enabled an analysis of total electricity production and coal mining in these countries.

A circular economy strategy for wind power was considered, analyzing the reasons why all wind turbine parts cannot be 100% recycled or reused. Based on the collected data and analysis, the material distribution of wind turbine parts and potential disposal methods are presented, taking into account available or developing specialized technologies.

3. Results and discussion

3.1. A comprehensive comparison of CO_2 emissions between wind energy and coal energy in Europe

The energy landscape in Europe is undergoing a significant transformation driven by the imperative to mitigate climate change and reduce greenhouse gas emissions. Central to this transition is the comparison between CO_2 emissions associated with wind energy and coal energy. Wind energy, as a renewable resource, is increasingly being deployed across Europe, while coal, a traditional fossil fuel, has historically dominated the energy mix but is now facing scrutiny due to its environmental impact. This essay aims to delve deeply into the comparative analysis of CO_2 emissions between wind energy and coal energy in Europe, exploring various facets such as technological advancements, lifecycle emissions, policy frameworks, economic implications, and environmental considerations. A map of keywords in scientific articles on wind energy in the EU is presented in Figure 2.

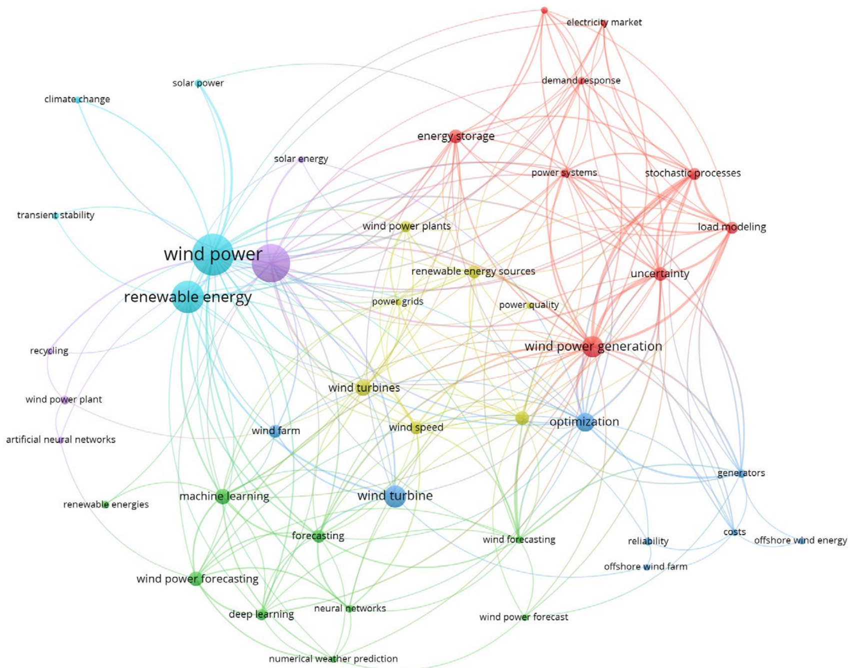

Fig. 2. Wind energy research article keyword map in EU (VOSviewer)

Rys. 2. Mapa słów kluczowych w artykułach naukowych dotyczących energii wiatrowej w UE

Wind energy

Wind energy has become a crucial part of Europe's renewable energy portfolio, offering a clean and sustainable alternative to fossil fuels. Technological advancements have significantly improved wind turbine efficiency and reduced costs, with modern designs capturing more energy and operating at higher capacities (Krohn et al. 2009.). Although wind energy has low operational emissions, lifecycle emissions from production to disposal are considerably lower than coal energy, enhancing its environmental sustainability (Tiwari 2011). Supportive policies at national and EU levels, such as feed-in tariffs and renewable energy targets, have driven investments and accelerated wind energy deployment, aligning with Europe's goal of achieving carbon neutrality by 2050.

Coal energy

Coal has been a key part of Europe's energy infrastructure, providing reliable and affordable electricity. However, due to its significant CO_2 emissions and air pollution, its role is being reassessed. Coal-fired power plants are major contributors to greenhouse gas emissions, releasing CO_2 and other pollutants harmful to human health and the environment. The environmental impact of coal includes deforestation, habitat destruction, soil erosion, and water contamination from mining operations (Yousefi et al. 2019). A map of keywords in scientific articles on coal energy research in the EU is presented in Figure 3. In response, European countries are transitioning

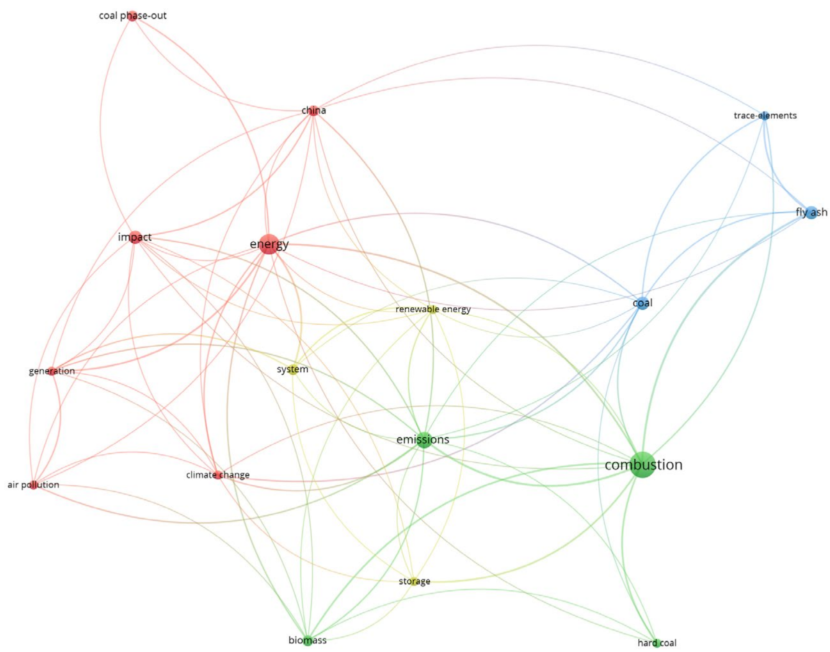

Fig. 3. Coal energy research article keyword map in EU (VOSviewer)

Rys. 3. Mapa słów kluczowych w artykułach dotyczących badań nad energią węglową w UE to low-carbon energy sources through policies like carbon pricing, emissions trading schemes, renewable energy targets, and coal phase-out commitments, recognizing the benefits of investing in cleaner energy solutions (Oliveira et al. 2019).

The analysis highlights the benefits of transitioning from coal to wind energy in Europe, emphasizing wind energy's lower lifecycle emissions, supportive policy environment, improved economic competitiveness, and greater environmental benefits (Table 1). This transition is crucial for mitigating climate change, enhancing sustainability, and securing a resilient energy future (Fig. 4).

TABLE 1. Comparison analysis

TABELA 1. Analiza porównawcza

Category	Coal	Wind
Lifecycle emissions	Higher emissions due to continuous combustion of coal during operation.	Lower carbon footprint, with emissions primarily from manufacturing and installation.
Policy frameworks	Faced increased costs due to regulatory measures like emissions standards, pollution controls, and carbon pricing.	Benefitted from supportive policies, including financing, permitting, grid integration, and market incentives.
Economic considerations	External costs such as environmental damage and health impacts are not fully reflected in market prices, making it less economically favourable.	Cost competitiveness has improved with declining technology costs and advancements.
Environmental Benefits	Associated with higher environmental and public health costs.	Offers reduced greenhouse gas emissions, air pollution, water consumption, and land use impacts.
Emission statistics	The average CO_2 emissions from coal-fired power plants in Europe are approximately 820 grams of CO_2 per kilowatt-hour (gCO_2/kWh) of electricity produced.	The average CO_2 emissions from wind energy are significantly lower, at around 12 grams of CO_2 per kilowatt-hour (gCO_2/kWh) of electricity produced.

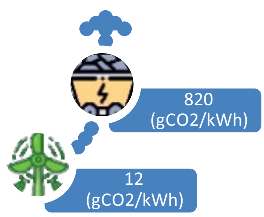

Fig. 4. Emission statistics: coal vs. wind

Rys. 4. Statystyki emisji: węgiel a energia wiatrowa

3.2. Case studies of wind power and coal in total electricity generation and coal mining: Poland vs. Germany

Germany

Coal mining in Germany has a rich history dating back to the Middle Ages, with the Ruhr Valley emerging as a major coal-producing region during the industrial revolution.

By the mid-20th century, coal mining reached its peak, fueling Germany's industrialization and economic growth (Brauers et al 2020). However, in recent decades, Germany has been undergoing a significant transition away from coal due to environmental concerns and the imperative to reduce greenhouse gas emissions (Fig. 5). This transition has led to the closure of many coal mines and a gradual phase-out of coal-fired power plants. The German government has implemented policies to support affected coal mining regions and workers during this transition. Investments in renewable energy sources, such as wind and solar power, have been prioritized as part of the country's energy transition (Energiewende). Despite the decline of coal mining, it remains a symbol of Germany's industrial heritage (Oei et al. 2020). As Germany moves towards a more sustainable energy future, coal mining continues to play a diminishing role, with efforts focused on mitigating its environmental impacts and facilitating a just transition for affected communities (Buschmann and Oels 2019).

A map of hard coal and lignite deposits in Germany is shown in Figure 6.

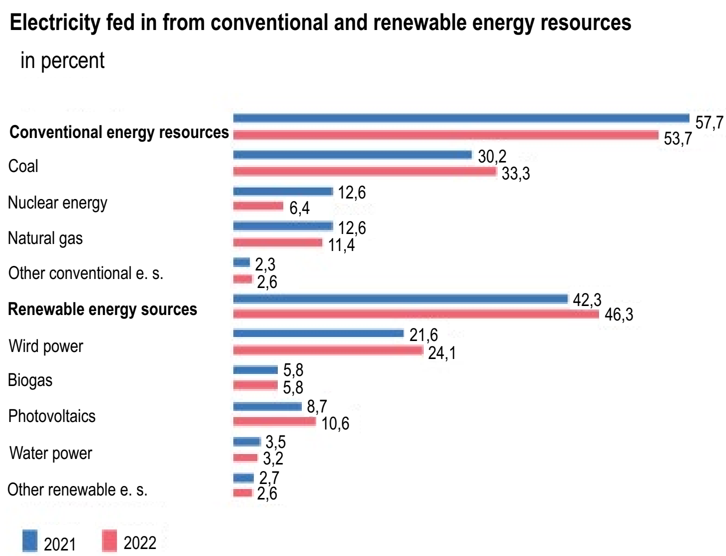

Fig. 5. Germany electricity production data for conventional and renewable energy

Rys. 5. Dane dotyczące produkcji energii elektrycznej w Niemczech w odniesieniu do energii konwencjonalnej i odnawialnej

Fig. 6. A map of coal deposits in Germany (Furnaro et al. 2021)

Rys. 6. Mapa złóż węgla w Niemczech

Gross electricity generation in Germany between 2019 and 2023 is summarized in Table 2.

TABLE 2. Gross electricity generation in Germany for 2019 to 2023

TABELA 2. Całkowita produkcja energii elektrycznej w Niemczech w latach 2019–2023

Energy source	2019		2020		2021		2022		2023	
	billion kWh	%	billion kWh	%	billion kWh	%	billion kWh	%	billion kWh	%
1	2	3	4	5	6	7	8	9	10	11
Total gross electricity generation	608.2	100	574.7	100	587.1	100	577.9	100	514.6	100

1	2	3	4	5	6	7	8	9	10	11
Brown coal	114.0	18.7	91.7	16.0	110.1	18.8	116.2	20.1	87.5	17.0
Hard coal	57.5	9.5	42.8	7.4	54.6	9.3	63.7	11.0	44.1	8.6
Nuclear energy	75.1	12.3	64.4	11.2	69.1	11.8	34.7	6.0	7.2	1.4
Natural gas	89.9	14.8	94.7	16.5	90.3	15.4	79.0	13.7	80.0	15.5
Petroleum products	4.8	0.8	4.7	0.8	4.6	0.8	5.7	1.0	4.9	1.0
Renewable energy sources	241.6	39.7	251.5	43.8	233.9	39.8	254.7	44.1	267.8	52.0
Wind power	125.9	20.7	132.1	23.0	114.7	19.5	124.8	21.6	137.8	26.8
Hydropower	20.1	3.3	18.7	3.3	19.7	3.4	17.6	3.0	19.5	3.8
Biomass	44.3	7.3	45.1	7.8	44.3	7.5	46.1	8.0	43.8	8.5
Photovoltaics	45.2	7.4	49.5	8.6	49.3	8.4	60.3	10.4	61.1	11.9
Household waste	5.8	1.0	5.8	1.0	5.8	1.0	5.6	1.0	5.5	1.1
Geothermal energy	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0
Other energy sources	25.4	4.2	24.8	4.3	24.5	4.2	23.8	4.1	23.1	4.5

The comparison of wind power and coal with total electricity generation in Germany is shown in Figure 7.

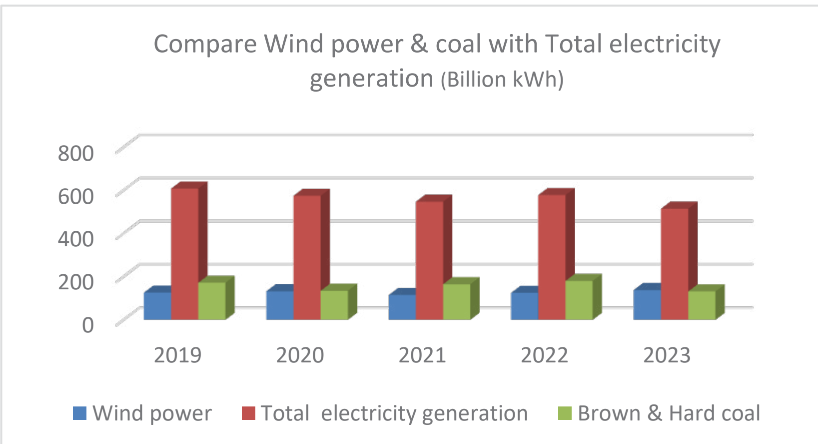

Fig. 7. Data showing comparison of wind power and coal with total electricity generation in Germany

Rys. 7. Dane prezentujące porównanie produkcji energii wiatrowej i węglowej z całkowitą produkcją energii elektrycznej w Niemczech

Poland

The coal region in Poland primarily refers to the Silesian Voivodship, located in the southern part of the country (Fig. 8). This region has a long history of coal mining and is one of the most significant coal-producing areas in Europe. Coal mining in Silesia dates back to the 18th century and has been a crucial part of Poland's economy and industrial development (Bukowski et al. 2018). The coal extracted from this region has been used to power electricity generation, heat homes, and fuel various industries.

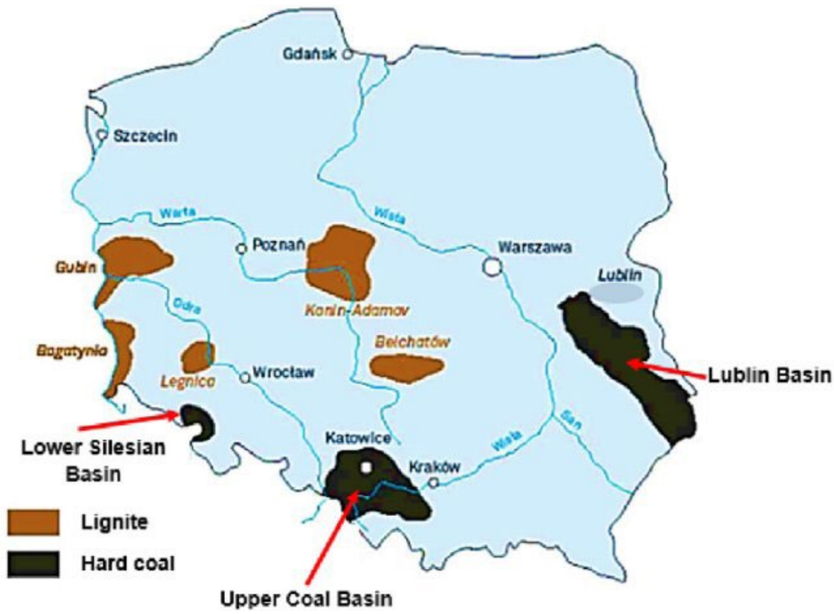

Fig. 8. Poland coal regions map (Saigustia and Robak 2021)

Rys. 8. Mapa regionów węglowych Polski

Similar to the Ruhr region in Germany, the coal industry in Silesia has faced challenges in recent years due to factors such as economic changes, environmental concerns, and competition from alternative energy sources (Śniegocki et al. 2022). Coal mines in the region have been gradually closing down, leading to job losses and socio-economic challenges for local communities. Poland, like many other countries, has been undergoing a transition away from coal in favor of cleaner energy sources as part of its efforts to address climate change and meet European Union emissions targets (Janikowska and Kulczycka 2021). However, this transition has been slower compared to some other European countries due to the significant role coal has played in Poland's energy mix and economy.

Despite the challenges, the Polish government has been working on strategies to diversify the economy of the Silesian region and support the transition to cleaner energy sources. This includes investments in renewable energy, technology, and other industries to create new opportunities for growth and employment in the region while also addressing the environmental and social impacts of coal mining (Śniegocki and Bukowski 2021).

The European Union

Europe, Germany, and Poland all face challenges related to coal production, CO_2 emissions from coal power generation, and the expansion of wind power electricity generation. While Europe and Germany have made significant strides in transitioning to cleaner energy sources like wind power, Poland's heavy reliance on coal presents obstacles to reducing emissions and increasing renewable energy capacity.

Comparison of electricity generation from coal in Germany, the EU, and Poland

Europe

Coal production in Europe has been declining in recent years due to environmental concerns and the shift towards cleaner energy sources. Many European countries have been phasing out coal mining operations.

Germany

Historically, Germany has been one of Europe's largest coal producers, particularly of lignite (brown coal). However, in recent years, there has been a concerted effort to reduce coal production and phase out coal-fired power plants (Keles and Yilmaz 2020).

Poland

Poland has significant coal reserves and has traditionally relied heavily on coal for both electricity generation and industrial purposes (Figs. 9, 10). Coal production in Poland remains relatively high compared to other European countries (Paraschiv S. and Paraschiv L.S. 2020).

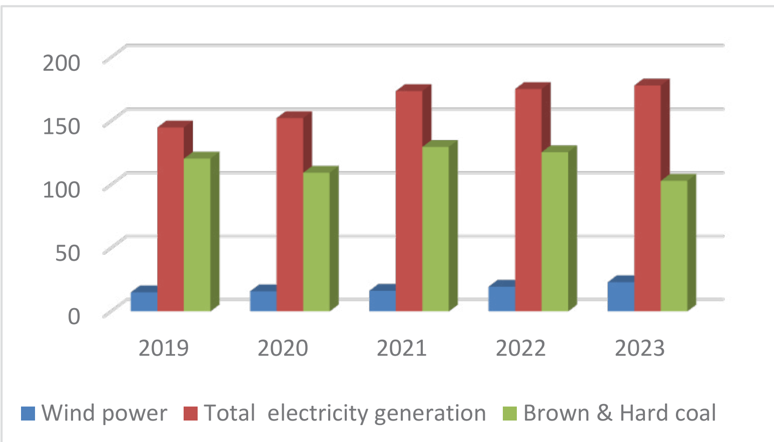

Fig. 9. Comparison of wind and coal power with total electricity generation [billion kWh] in Poland

Rys. 9. Porównanie produkcji energii wiatrowej i węglowej z całkowitą produkcją energii elektrycznej [mld kWh] w Polsce

Fig. 10. Wind and coal power plant locations in Poland

Rys. 10. Lokalizacje elektrowni wiatrowych i węglowych w Polsce

Comparison of CO_2 emissions from coal power generation in Europe over time

Europe

The European Union has been actively working to reduce CO_2 emissions from coal power generation as part of its climate goals. Policies such as the EU Emissions Trading System (EU ETS) and the Coal Phase-Out Initiative have contributed to a decline in CO_2 emissions from coal-fired power plants.

Germany

Despite its efforts to transition to renewable energy, Germany still has some coal-fired power plants in operation, contributing to CO_2 emissions (Fig. 11). However, the country has committed to phasing out coal entirely by 2038, which should lead to a significant reduction in CO_2 emissions from coal power generation.

Poland

Poland's heavy reliance on coal for electricity generation results in relatively high CO_2 emissions from coal-fired power plants. The country faces challenges in reducing these emissions due to its dependence on coal and the political and economic factors involved in transitioning to cleaner energy sources.

Comparison of total electricity generation from wind power across Europe [billion kWh]

Europe

Wind power has seen significant growth in Europe, with many countries investing in wind energy infrastructure both onshore and offshore. Europe is a global leader in wind energy capacity and generation (Fig. 12).

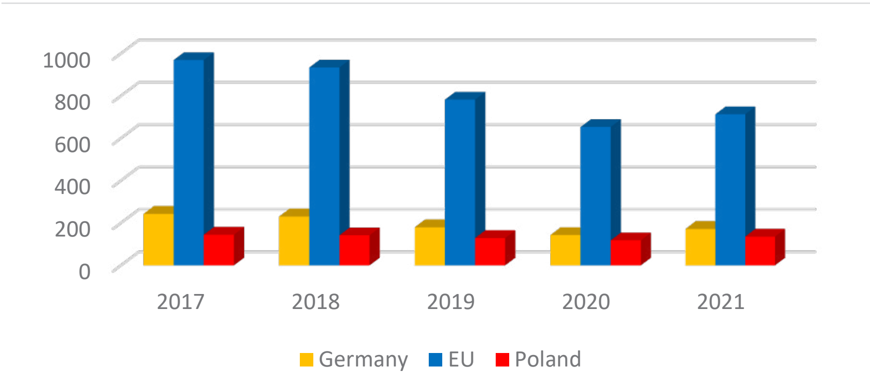

Fig. 11. Evolution comparison of CO_2 emissions by coal power generation in Europe

Rys. 11. Porównanie zmian emisji CO_2 z elektrowni węglowych w Europie

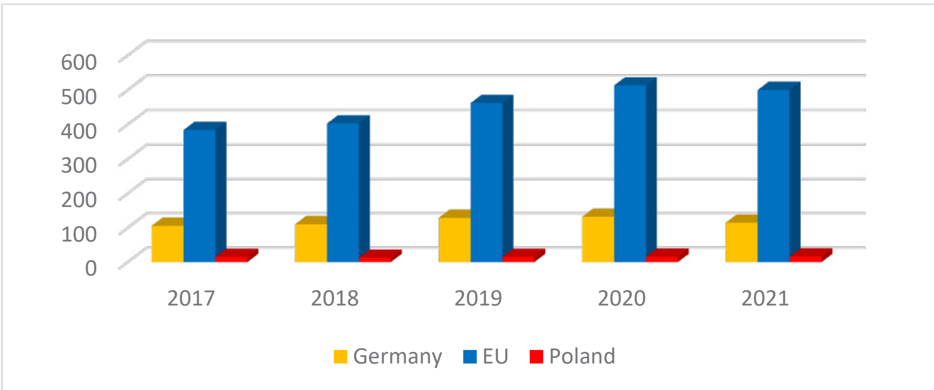

Fig. 12. Comparison of total electricity generation from wind power across Europe [billion kWh]

Rys. 12. Porównanie całkowitej produkcji energii elektrycznej z wiatru w Europie [mld kWh]

Germany

Germany has been a pioneer in wind energy deployment, particularly in offshore wind farms in the North and Baltic Seas. Wind power contributes a substantial portion of Germany's total electricity generation.

Poland

While Poland has been slower to adopt wind power compared to some other European countries, it has been making efforts to increase its wind energy capacity in recent years. However, wind power still accounts for a smaller share of Poland's total electricity generation compared to coal.

3.3. Circular economy strategy in wind energy

This article discusses the implementation of a circular economy strategy in the wind energy sector, aimed at minimizing waste, maximizing resource efficiency, and promoting a circular system for wind turbine materials. Key components of this strategy include designing turbines for durability and recyclability, conducting life cycle assessments, implementing extended producer responsibility policies, promoting reuse and refurbishment, investing in material recycling technologies, establishing circular supply chains, and fostering innovation and research unsustainable practices (Telsnig 2022). Overall, the goal is to reduce the environmental impact of wind energy production and contribute to a more sustainable energy transition.

Wind turbine parts, materials, and potential disposal methods

As wind energy becomes a vital part of the energy transition, wind blade equipment accounts for about 20% of multipurpose heavy lift freight transported by sea (Mendoza et al. 2022). Due to their large size and the specialized handling required, these cargos necessitate specific port terminals and specialized vessels. Wind turbines, along with their structures such as towers, can be significantly heavy, especially compared to the blades (Jensen et al. 2020).

With wind turbines introduced several decades ago, their replacement and recycling have recently become critical concerns. These turbines, having a lifespan of 20–30 years, need dismantling and recycling upon reaching the end of their operational life (Tyurkay et al. 2024). The complexity of wind turbine parts and the diverse materials used in their construction pose numerous recycling challenges (Fig. 13). However, efforts are underway to develop recycling

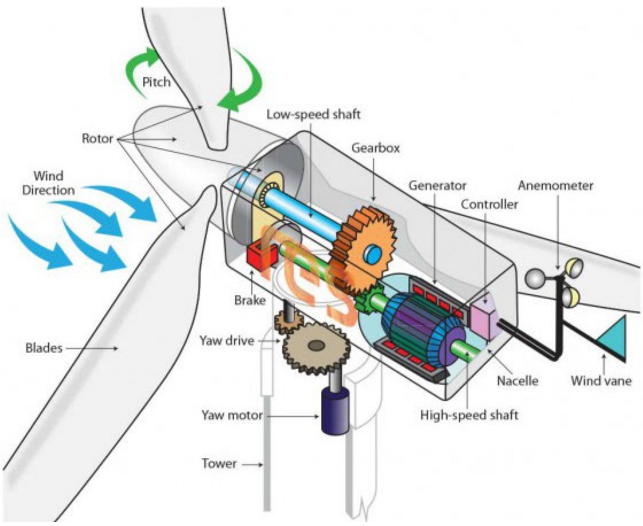

Fig. 13. Wind turbine important parts

Rys. 13. Ważne części turbiny wiatrowej

methods to address environmental issues (Diez-Cañamero and Mendoza 2023). Materials used in wind turbine construction include steel, copper, aluminium, fiberglass, and composites. Effective recycling necessitates efficient material separation, employing technologies such as magnetic separation, shredding, and sorting (Fig. 14) (Mendoza and Pigosso 2023).

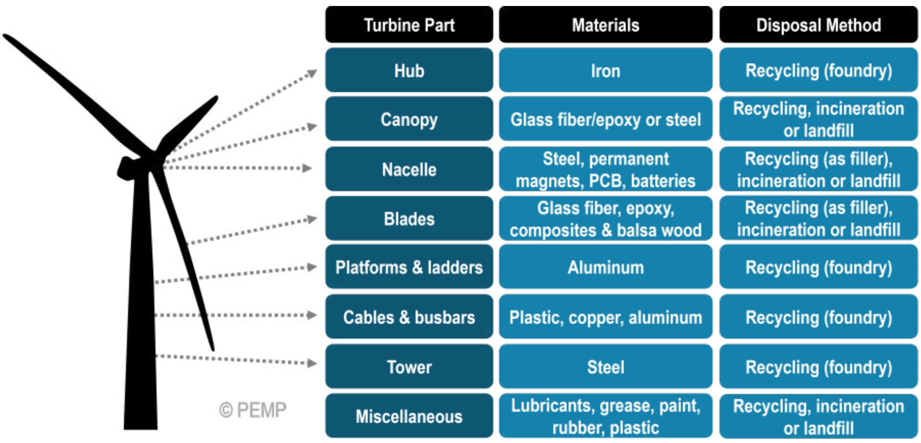

Fig. 14. Wind turbine parts materials and potential disposal methods
Source: adapted from Jensen (2019)

Rys. 14. Materiały, z których wykonane są części turbin wiatrowych, oraz potencjalne metody ich utylizacji

Specific technologies are available or being developed for the recycling of specific components of wind turbines:

Blade recycling: Because fibreglass and other composite materials are frequently used to make wind turbine blades, the recycling procedure is made more difficult by these materials' endurance. Some approaches focus on using chemical processes to break down composite materials, while others involve mechanically grinding the blades into small fragments. Nevertheless, a good number of wind blades wind up in landfills because there are still expensive alternatives.

Steel recycling: Steel is usually used to construct wind turbine towers and other structural parts. Steel may be recycled by melting it down and repurposing it to make new goods. This procedure is widely used in the recycling sector (Smith J. 2020).

Recycling of other materials: A lot of the electrical parts of wind turbines, such the wiring and generators, are made of copper and aluminium. Melting down these metals and using them again to create new parts is recycling. Rare earth elements are frequently found in permanent magnets used in wind turbine generators. In the process of recycling wind turbines, procedures for the effective recovery of these precious elements are being developed (Jones 2019).

Specific component reconditioning and reuse: Some parts, like generators and gearboxes, may be reconditioned and used again in different contexts. This can lessen the total need for new materials and increase the lifespan of some parts.

Wind turbine recycling is a constantly developing industry that frequently sees the introduction of new techniques and technologies. It's also crucial to remember that local laws and recommended procedures for recycling wind turbines may differ. For instance, several areas enacted Extended Producer Responsibility laws, which obliged wind turbine producers to be accountable for the recycling and end-of-life disposal of their devices. This may encourage producers to include recycling in their product designs. Not only are seaports crucial points in the supply chains for setting up new wind parks. Considering how close they are to numerous onshore and offshore wind farms, they can also serve as ideal hubs for setting up extensive wind turbine recycling initiatives. The port becomes more appealing as a place for material sourcing when the generated recycled material offers an extra source for recycling streams within the larger port cluster (Miller 2022).

Addressing some challenges requires collaboration between industry stakeholders, research institutions, governments, and recycling experts to develop innovative solutions, improve recycling technologies, and create a supportive regulatory environment for wind turbine blade recycling.

Challenges: Wind turbine blades are typically large, composite structures made from fiberglass, carbon fiber, and other materials. Recycling them poses several challenges due to their size, composition, and the need for specialized recycling processes (Davis 2019).

Size reduction: One approach to recycling wind turbine blades involves shredding or cutting them into smaller pieces to facilitate handling and processing. This can be done using industrial shredders or cutting equipment specifically designed for composite materials.

Material separation: After size reduction, the materials in the blades need to be separated. This typically involves separating the fiberglass or carbon fiber from other materials like resins or plastics. Advanced separation technologies are being developed to improve the efficiency of this process (Taylor 2021).

Recycling technologies: Various recycling technologies are being researched and implemented to recover valuable materials from wind turbine blades. These include mechanical recycling, chemical recycling, and pyrolysis. Each method has its advantages and challenges in terms of efficiency, cost-effectiveness, and environmental impact (Anderson 2020).

Market demand: Developing a market for recycled wind turbine blade materials is crucial for the success of recycling efforts. This involves finding applications for recycled materials in industries such as construction, automotive, and consumer goods manufacturing.

Environmental benefits: Recycling wind turbine blades helps reduce the environmental impact of wind energy by diverting waste from landfills and reducing the need for virgin materials. It also conserves energy and reduces greenhouse gas emissions compared to manufacturing new materials from scratch.

Regulatory considerations: Regulatory frameworks play a role in promoting and incentivizing wind turbine blade recycling. Governments and industry stakeholders may implement policies such as extended producer responsibility or recycling targets to encourage recycling and support the development of recycling infrastructure.

Collaboration and innovation: Collaboration between industry stakeholders, research institutions, and governments is essential for advancing wind turbine blade recycling technologies and practices. Continued innovation is needed to overcome technical challenges and make recycling economically viable on a large scale.

Policy and regulation: Regulatory frameworks may play a significant role in promoting or hindering wind turbine blade recycling efforts. Lack of supportive policies, such as recycling targets or incentives, can impede progress, while clear regulations regarding waste management and environmental standards can provide guidance and stability for recycling initiatives (Harris 2019).

While wind turbines are often touted as a sustainable source of energy, 100% recycling of their components is now not possible and challenging due to several reasons.

Composite materials: Fibreglass reinforced with epoxy or other resins is a common composite material used to make modern wind turbine blades. It can be expensive and physically challenging to recycle these materials effectively without lowering their quality (Andersen 2019).

Technological restrictions: Advanced technology is still needed to recycle composite materials effectively. Although there are methods for recycling these materials, they are not currently widely used or economically viable to handle the quantity of turbine blades that are being retired (Smith R. 2020).

Economic viability: Recycling's economics are also very important. For now, firms may find it more economical to dump retired turbine blades in landfills instead of spending money on pricey recycling procedures.

Logistics: There are difficulties with both logistics and transportation. Due to the size and weight of wind turbine blades, it can be costly and impractical to transport them to recycling facilities.

Contamination: During their useful lives, blades may potentially get contaminated by rubbish, sand, or other substances. Recycling materials that are contaminated might be more expensive and time-consuming (White 2019).

This study explores the challenges and solutions associated with achieving 100% recycling of wind turbines. It places a strong emphasis on an all-encompassing strategy that includes stakeholder collaboration, infrastructure development, policy support, material research, advanced recycling technologies, design innovation, and the concepts of the circular economy. Manufacturers of wind turbines are advised to employ simpler materials, reduce the amount of sophisticated composites in their designs, and give priority to designs that make recycling and dismantling easier. Improving recyclability and efficiency requires research into new materials and cutting-edge recycling systems. It is advised to implement circular economy activities to maximize material reuse and reduce waste. Widespread recycling is thought to need infrastructure development, including the construction of specialized recycling facilities. Governments are urged to support policies that enhance recyclability and invest in recycling infrastructure by enacting laws, offering financial incentives, and sponsoring programs. Collaboration among industry stakeholders, researchers, governments, and environmental organizations is emphasized as essential for driving progress. By sharing knowledge, resources, and best practices, stakeholders can overcome challenges and accelerate progress towards achieving 100% recycling of wind turbines.

Conclusions

This exploration underscores the pivotal role of wind energy within the framework of the European Union's ambitious Green Deal project. By prioritizing renewable energy sources such as wind power, the EU aims to not only combat climate change but also to foster economic growth and environmental stewardship. Through a comparative analysis between wind and coal energy production, it becomes evident that wind energy offers significant environmental advantages, particularly in terms of reduced CO_2 emissions. Moreover, the transition from coal-dependent energy to renewable energy systems presents both challenges and opportunities, as exemplified by case studies from coal mining regions in Poland and Germany.

Crucially, this research highlights the potential of a circular economy approach to wind turbine recycling as a means to enhance resource efficiency and reduce waste in the renewable energy sector. By synthesizing insights from various studies, it becomes apparent that innovative recycling processes, particularly concerning components like NdFeB magnets and composite materials, can play a crucial role in diversifying the supply chain and mitigating environmental footprints (Andersen et al. 2021). Strategies for managing end-of-life turbine blades and maximizing the efficiency and sustainability of offshore wind farms further underscore the importance of embracing sustainable practices throughout the wind energy lifecycle.

Effective recycling is vital for the European Green Deal's goals of reducing waste and promoting resource efficiency, contributing to the EU's aim of carbon neutrality by 2050. Future efforts must focus on technological advancements, policy support, and international collaboration. Redesigning turbine components for easier disassembly and developing markets for recycled materials are essential steps (Clark et al. 2018).

In conclusion, while wind turbine recycling has advanced, achieving full recyclability remains challenging. This study contributes to a comprehensive understanding of how renewable wind energy can serve as a linchpin for achieving sustainability objectives outlined in the European Green Deal. Promoting a paradigm shift towards a circular and sustainable future in the wind energy sector emphasizes the EU's commitment to fostering resilience and low-carbon development (White 2020).

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References

Andersen, P. 2019. Recycling challenges of composite materials in wind turbines. *Journal of Sustainable Materials* 12(3), pp. 144–155.

Andersen et al. 2021 – Andersen, P., Brown, L. and Jones, M. 2021. Recycling processes for NdFeB magnets in wind turbines.

Beauson et al. 2014 – Beauson, J., Lilholt, H. and Brondsted, P. 2014. Recycling solid residues recovered from glass fibre-reinforced composites – A review applied to wind turbine blade materials. *Journal of Reinforced Plastics and Composites* 33(16), DOI: 10.1177/0731684414537131.

Beauson et al. 2016 – Beauson, J., Madsen, B., Toncelli, C., Brondsted, P. and Bech, J.I. 2016. Recycling of shredded composites from wind turbine blades in new thermoset polymer composites. Composites Part *A-Applied Science and Manufacturing* 90, pp. 390–399, DOI: 10.1016/j.compositesa.2016.07.009.

Bonou et al. 2016 – Bonou, A., Laurent, A. and Olsen, S.I. 2016. Life cycle assessment of onshore and offshore wind energy-from theory to application. *Applied Energy* 180, pp. 327–337, DOI: 10.1016/j.apenergy.2016.07.058.

Brauers et al. 2020 – Brauers, H. Oei, P.Y. and Walk, P. 2020 – Comparing coal phase-out pathways: The United Kingdom's and Germany's diverging transitions. *Environmental Innovation and Societal Transitions* 37, pp. 238–253, DOI: 10.1016/j.eist.2020.09.001.

Bukowski et al. 2018 – Bukowski, M., Śniegocki, A. and Wetmańska, Z. 2018. *From restructuring to sustainable development. The case of Upper Silesia*. Warszawa.

Buschmann, P. and Oels, A. 2019. The overlooked role of discourse in breaking carbon lock-in: The case of the German energy transition. *WIREs Climate Change* 10(3), DOI: 10.1002/wcc.574.

Clark et al. 2018 – Clark, D., Johnson, R. and Miller, T. 2018. Policy support for wind turbine recycling. *Environmental Policy Journal* 22(2), pp. 145–157.

Davis, K. 2019. Challenges in Recycling Wind Turbine Blades. *Composite Materials Review* 12(2), pp. 178–189.

Diez-Cañamero, B. and Mendoza, J.M.F. 2023. Circular economy performance and carbon footprint of wind turbine blade waste management alternatives. *Waste Management* 164, pp. 94–105, DOI: 10.1016/j.wasman.2023.03.041.

Dupont, D. and Binnemans, K. 2015. Recycling of rare earths from NdFeB magnets using a combined leaching/extraction system based on the acidity and thermomorphism of the ionic liquid [Hbet][Tf_2N]. *Green Chemistry* 17, pp. 2150–2163, DOI: 10.1039/c5gc00155b.

Furnaro et al. 2021 – Furnaro, A., Herpich, P., Brauers, H., Oei, P.-Y., Kemfert, C. and Look, W. 2021. German Just Transition: A Review of Public Policies to Assist German Coal Communities in Transition. *Resources for the Future*, *Report*, November 21–13, 2021. [Online] https://www.rff.org/publications/reports/german-just-transition-a-review-of-public-policies-to-assist-german-coal-communities-in-transition/ [Accessed: 2025-09-21].

Giorgini et al. 2020 – Giorgini, L., Benelli, T., Brancolini, G. and Mazzocchetti, L. 2020. Recycling of carbon fiber reinforced composite waste to close their life cycle in a cradle-to-cradle approach. *Current Opinion In Green And Sustainable Chemistry* 26, DOI: 10.1016/j.cogsc.2020.100368.

Habib, K. and Wenzel, H. 2014. Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. *Journal of Cleaner Production* 84, pp. 348–359, DOI: 10.1016/j.jclepro.2014.04.035.

Harris, J. 2019. Policy and Regulation in Wind Turbine Blade Recycling. *Public Policy Review* 11(2), pp. 99–110.

Janikowska, O. and Kulczycka, J. 2021. Just transition as a tool for preventing energy poverty among women in mining areas – A case study of the Silesia region, Poland. *Energies* 14(12), DOI: 10.3390/en14123372.

Jensen, J.P. 2019. Evaluating the environmental impacts of recycling wind turbines. *Wind Energy* 22, pp. 316–326, DOI: 10.1002/we.2287.

Jensen, J.P. and Skelton, K. 2018. Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. *Renewable & Sustainable Energy Reviews* 97, pp. 165–176, DOI: 10.1016/j.rser.2018.08.041.

Jensen et al. 2020 – Jensen, P.D., Purnell, P. and Velenturf, A.P.M. 2020. Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind. *Sustainable Production and Consumption* 24, pp. 266–280, DOI: 10.1016/j.spc.2020.07.012.

Jones, A. 2019. Recycling Electrical Components of Wind Turbines. *Renewable Energy Review* 22(4), pp. 456–467.

Keles, D. and Yilmaz, H.Ü. 2020. Decarbonisation through coal phase-out in Germany and Europe – Impact on Emissions, electricity prices and power production. *Energy Policy* 141, DOI: 10.1016/j.enpol.2020.111472.

Khalid et al. 2023 – Khalid, M.Y., Arif, Z.U., Hossain, M. and Umer, R. 2023. Recycling of wind turbine blades through modern recycling technologies: A road to zero waste. *Renewable Energy Focus* 44, pp. 373–389, DOI: 10.1016/j.ref.2023.02.001.

Kilkis et al. 2019 – Kilkis, S., Krajacic, G., Duic, N., Montorsi, L., Wang, Q., Rosen, M.A. and Al-Nimr, Moh'd A. 2019. Research frontiers in sustainable development of energy, water and environment systems in a time of climate crisis. *Energy Conversion and Management* 199, DOI: 10.1016/j.enconman.2019.111938.

Krauklis et al. 2021 – Krauklis, A.E., Karl, C.W., Gagani, A.I. and Jorgensen, J.K. 2021. Composite Material Recycling Technology-State-of-the-Art and Sustainable Development for the 2020s. *Journal of Composites Science* 5(1), DOI: 10.3390/jcs5010028.

Krohn et al. 2009 – Krohn, S., Morthorst, P.E. and Awerbuch, S. 2009. *The economics of wind energy*. By the European Wind Energy Association.

Lefeuvre et al. 2019 – Lefeuvre, A., Garnier, S., Jacquemin, L., Pillain, B. and Sonnemann, G. 2019. Anticipating in-use stocks of carbon fibre reinforced polymers and related waste generated by the wind power sector until 2050. *Resources Conservation and Recycling* 141, pp. 30–39, DOI: 10.1016/j.resconrec.2018.10.008.

Lichtenegger et al. 2020 – Lichtenegger, G., Rentizelas, A.A., Trivyza, N. and Siegl, S. 2020. Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050. *Waste Management* 106, pp. 120–131, DOI: 10.1016/j.wasman.2020.03.018.

Mendoza, J.M.F. and Pigosso, D.C.A. 2023. How ready is the wind energy industry for the circular economy? *Sustainable Production and Consumption* 43, pp. 62–76, DOI: 10.1016/j.spc.2023.10.016.

Mendoza et al. 2022 – Mendoza, J.M.F., Gallego-Schmid, A., Velenturf, AP.M., Jensen, P.D. and Ibarra, D. 2022. Circular economy business models and technology management strategies in the wind industry: Sustainability potential, industrial challenges and opportunities. *Renewable and Sustainable Energy Reviews* 163, DOI: 10.1016/j.rser.2022.112523.

Miller, T. 2022. Seaports as Hubs for Wind Turbine Recycling. *Maritime Sustainability* 7(4), pp. 204––215.

Mishnaevsky, L., Jr. 2021. Sustainable End-of-Life Management of Wind Turbine Blades: Overview of Current and Coming Solutions. *Materials* 14(5), DOI: 10.3390/ma14051124.

Naqvi et al. 2018 – Naqvi, S.R., Mysore Prabhakara, H., Bramer, E.A., Dierkes, W., Akkerman, R. and Brem, G. 2018. A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy. *Resources Conservation and Recycling* 136, pp. 118–129, DOI: 10.1016/j.resconrec.2018.04.013.

Oei et al. 2020 – Oei, P.Y., Brauers, H. and Herpich, P. 2020. Lessons from Germany's hard coal mining phase-out: policies and transition from 1950 to 2018. *Climate Policy* 20, pp. 963–979, DOI: 10.1080/14693062.2019.1688636.

Oliveira et al. 2019 – Oliveira, T., Varum, C. and Botelho, A. 2019. Wind power and CO_2 emissions in the Irish market. *Energy Economics* 80, pp. 48–58, DOI: 10.1016/j.eneco.2018.10.033.

Paraschiv, S. and Paraschiv, L.S. 2020. Trends of carbon dioxide (CO_2) emissions from fossil fuels combustion (coal, gas and oil) in the EU member states from 1960 to 2018. Energy Reports 6(8), pp. 237–242, DOI: 10.1016/j.egyr.2020.11.116.

Qureshi, J. 2022. A review of recycling methods for fibre reinforced polymer composites. *Sustainability* 14(24), DOI: 10.3390/su142416855.

Raoux et al. 2017 – Raoux, A., Tecchio, S., Pezy, J.-P., Lassalle, G., Degraer, S., Wilhelmsson, D., Cachera, M., Ernande, B., Le Guen, C., Haraldsson, M., Grangere, K., Le Loc'h, F., Dauvin, J.-C. and Niquil, N. 2017. Benthic and fish aggregation inside an offshore wind farm: Which effects on the trophic web functioning? *Ecological Indicators* 72, pp. 33–46, DOI: 10.1016/j.ecolind.2016.07.037.

Ren et al. 2021 – Ren, Z., Verma, A.S., Li, Y., Teuwen, J.J.E. and Jiang, Z. 2021. Offshore wind turbine operations and maintenance: A state-of-the-art review. *Renewable & Sustainable Energy Reviews* 144, DOI: 10.1016/j.rser.2021.110886.

Saigustia, C. and Robak, S. 2021. Review of Potential Energy Storage in Abandoned Mines in Poland. *Energies* 14(19), DOI: 10.3390/en14196272.

Schreiber et al. 2019 – Schreiber, A., Marx, J. and Zapp, P. 2019. Comparative life cycle assessment of electricity generation by different wind turbine type. *Journal of Cleaner Production* 233, pp. 561–572, DOI: 10.1016/j.jclepro.2019.06.058.

Smith, J. 2020. Steel Recycling in Wind Turbine Manufacturing. *Journal of Sustainable Materials* 15(3).

Smith, R. 2020. Technological barriers in wind turbine recycling. *Renewable Energy Review* 25(4), pp. 412–425.

Śniegocki et al. 2022 – Śniegocki, A., Wasilewski, M., Zygmunt, I. and Look, W. 2022. *Just Transition in Poland: A Review of Public Policies to Assist Polish Coal Communities in Transition*. Resources for the Future. [Online:] https://media.rff.org/documents/Report_22-06_June_1_2022.pdf [Accessed: 2025-07-02].

Śniegocki, A. and Bukowski, M. 2021. Just Transition in Silesia: from coal-centric to coal-exit development pathways. *WiseEuropa*, pp. 41–50, DOI: 10.24352/UB.OVGU-2021-052.

Taylor, S. 2021. Material Separation in Wind Turbine Blade Recycling. Advanced Materials Science.

Tazi et al. 2019 – Tazi, N., Kim, J., Bouzidi, Y., Chatelet, E. and Liu, G. 2019. Waste and material flow analysis in the end-of-life wind energy system. *Resources Conservation and Recycling* 145, pp. 199–207, DOI: 10.1016/j.resconrec.2019.02.039.

Telsnig, T. 2022. *Mapping and analysis of current circular economy approaches in the wind energy sector*. JRC Technical Raport, European Commission. [Online:] https://setis.ec.europa.eu/document/download/e70027fe-f388-458a-957e-77e5e2453000_en?filename=JRC126705_2021_08_15_tr_wind_and_circularity_v11.pdf [Accessed: 2025-06-20].

Tiwari, A.K. 2011. Comparative performance of renewable and nonrenewable energy source on economic growth and CO_2 emissions of Europe and Eurasian countries: A PVAR approach. *Economics Bulletin. AccessEcon* 31(3), pp. 2356–2372.

Tyurkay et al. 2024 – Tyurkay, A., Kirkelund, G.M. and Lima, A.T.M. 2024. State-of-the-art circular economy practices for end-of-life wind turbine blades for use in the construction industry. *Sustainable Production and Consumption* 47, pp. 17–36, DOI: 10.1016/j.spc.2024.03.018.

Vander Hoogerstraete et al. 2014 – Vander Hoogerstraete, T., Blanpain, B., Van Gerven, T. and Binnemans, K. 2014. From NdFeB magnets towards the rare-earth oxides: a recycling process consuming only oxalic acid. *RSC Advances* 4, pp. 64099–64111, DOI: 10.1039/c4ra13787f.

White, N. 2020. Achieving sustainability in the wind energy sector. *Technology and Innovation Journal* 15(2), pp. 334–345.

White, S. 2019. Contamination issues in wind turbine blade recycling. Environmental Science & Technology.

Yang et al. 2017 – Yang, Y., Walton, A., Sheridan, R., Gueth, K., Gauss, R., Gutfleisch, O., Buchert, M., Steenari, B.-M., Van Gerven, T., Jones, P.T. and Binnemans, K. 2017. REE Recovery from End-of-

Life NdFeB Permanent Magnet Scrap: A Critical Review. *Journal of Sustainable Metallurgy* 3, pp. 122–149, DOI: 10.1007/s40831-016-0090-4.

Yousefi et al. 2019 – Yousefi, H. Abbaspour, A. and Seraj, H.R. 2019. Worldwide development of wind energy and CO_2 emission reduction. *Environmental Energy and Economic Research* 3(1), pp. 1–9, DOI: 10.22097/eeer.2019.164295.1064.

Zembrzuski et al. 2023 – Zembrzuski, J., Miśkiewicz, M., Sabik, A., Pyrzowski, Ł., Chróścielewski, J. and Wilde, K. 2023. Review of applications of used wind turbine blades for infrastructure construction (*Przegląd aplikacji zużytych łopat turbin wiatrowych na potrzeby budownictwa infrastrukturalnego*). *Mosty – budowa, wzmacnianie, przebudowa*, pp. 1–13, Poznań (*in Polish*).

Online sources

https://ec.europa.eu/eurostat
https://www.statista.com
https://stat.gov.pl
https://windeurope.org
https://wwindea.org
https://www.ewea.org
http://psew.pl
https://gwec.net
https://orcid.org
https://wwindea.org
https://www.iea.org
https://cleanpower.org
https://www.irena.org
https://scholar.google.com
https://cleangridalliance.org
https://www.researchgate.net
https://globalenergymonitor.org
https://www.webofscience.com
https://www.sciencedirect.com
https://www.roth-international.de
https://www.globalwindsafety.org
https://www.cleanenergycouncil.org.au
https://www.iea.org/countries/poland/coal
https://www.mdpi.com/1996-1073/16/22/7624
https://en.wikipedia.org/wiki/Wind_power_in_Europe
https://ourworldindata.org/grapher/coal-production-by-country
https://energy.ec.europa.eu/topics/renewable-energy/eu-wind-energy_en

Satyajit Chowdhury

Potencjał recyklingu turbin wiatrowych wspierany przez politykę Europejskiego Zielonego Ładu – analiza porównawcza energetyczna Polski i Niemiec

Streszczenie

Europejski Zielony Ład stanowi przełomową inicjatywę mającą na celu skierowanie kontynentu w stronę zrównoważonej przyszłości, a odnawialna energia wiatrowa odgrywa kluczową rolę w tej transformacji. Niniejsze badania zgłębiają wielowymiarowe aspekty odnawialnej energii wiatrowej w kontekście Europejskiego Zielonego Ładu, koncentrując się na kilku kluczowych wymiarach. Przede wszystkim w badaniu analizuje się wytwarzanie energii zarówno z energii wiatrowej, jak i węglowej, przedstawiając analizę porównawczą w celu podkreślenia korzyści środowiskowych wynikających z alternatywnych źródeł energii odnawialnej. Na podstawie szczegółowych studiów przypadków skupiających się na regionach wydobycia węgla w Polsce i Niemczech badana jest dynamika społeczno-gospodarcza przejścia od gospodarek uzależnionych od węgla do systemów energii odnawialnej. Wyjaśniane są także wyzwania i możliwości związane z takimi przemianami.

Zarządzanie turbinami wiatrowymi po zakończeniu ich eksploatacji, w szczególności recykling i ponowne wykorzystanie, stanowi poważne wyzwanie. W niniejszym artykule przeanalizowano potencjał recyklingowy turbin wiatrowych w Polsce i Niemczech w ramach Europejskiego Zielonego Ładu. Mimo że 85% elementów turbin można poddać recyklingowi, łopaty wykonane z materiałów kompozytowych, takich jak włókna szklane i polimery plastikowe, są trudne do recyklingu ze względu na swoją złożoną strukturę.

Ponadto badania dotyczą zastosowania zasad gospodarki o obiegu zamkniętym w sektorze energii wiatrowej, z naciskiem na strategie efektywnego wykorzystania zasobów, recyklingu i redukcji odpadów. Badania te mają największy wpływ na Europejski Zielony Ład i tworzą nową strefę europejską, której celem jest osiągnięcie zerowej emisji dwutlenku węgla. Dzięki połączeniu różnych wątków niniejsze badanie przyczynia się do kompleksowego zrozumienia, w jaki sposób odnawialna energia wiatrowa może służyć jako podstawa do osiągnięcia celów zrównoważonego rozwoju, określonych w Europejskim Zielonym Ładzie.

Słowa kluczowe: recykling turbin wiatrowych, Europejski Zielony Ład, gospodarka o obiegu zamkniętym, energia odnawialna, zrównoważony rozwój