Chapter 5

Evaluating the Contribution of Expired Wind Turbines to Sustainable Cities and Communities

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Abstract

As the lifespan of wind turbines nears completion, it becomes imperative to assess their impact on the development of sustainable cities and communities. This study investigates the reduction of negative effects that expired wind turbines may have on environmental and social sustainability. As a qualitative technique, semi-structured interviews are conducted with a focus group of eight wind turbine experts. By employing a comprehensive evaluation framework, we examine the environmental footprint, economic considerations, and social implications associated with these aging renewable energy infrastructures. Understanding the challenges and opportunities posed by decommissioned wind turbines is crucial for crafting effective strategies toward a circular economy. The findings from this research aim to inform policymakers, urban planners, and environmental advocates on how to optimize the sustainable transition from active to retired wind turbines, fostering a more resilient and environmentally conscious future for cities and communities.

1. Introduction

In urban areas today, there's a significant increase in using fossil fuels for energy (Wilberforce et al., 2024; Hanif, 2018). These fuels are mainly used for transportation, buildings, and industry, but they harm air quality by releasing pollutants like particulate matter, carbon monoxide, and greenhouse gases. This pollution negatively affects people's health, reducing their quality of life and hurting the sustainability of urban development.

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To address this, it is crucial to shift towards renewable energy sources like wind, solar, and hydropower. These alternatives are eco-friendly, cut down carbon emissions, and help combat climate change. Embracing renewable energy not only makes cities cleaner and healthier but also improves energy resilience and security. Sustainable cities use these renewable sources to power homes, businesses, and infrastructure, creating a more self-sufficient and decentralized energy system (Ahmed et al., 2024). Additionally, adopting renewable energy supports economic efficiency, job creation, and innovation, putting sustainable cities at the forefront of a greener and more sustainable future (Subramanian & Salvi, 2023), and also supports the tourism industry (Alphan, 2024) in terms of willingness of tourists to pay for environmentally friendly accommodation (Frantal & Kunc, 2011).

Various forms of renewable energy, including wind power, biopower, solar power, geothermal power, and ocean power, derive their energy from the sun. With the exception of geothermal and ocean energy, these sources are considered infinite and environmental-friendly (Filom et al., 2021). Wind energy, in particular, stands out as a clean and reliable source, converting about 1-2 percent of the sun's energy into an endless power supply, surpassing the energy conversion of all Earth's plants combined by 50-100 times (Amini et al., 2020). The global potential for wind energy is around 10 million MW, capable of meeting 35% of the world's energy demand (Shukla et al., 2012). As of 2017, the installed capacity for global wind energy reached 540,000 MW, with projections anticipating a growth to 800.000 MW by 2021 (Fazelpour et al., 2017). Predictions also suggest a substantial increase in wind's share of electricity creation, from 3.5% in 2015 to an impressive 36% by 2050 (IRENA, 2018).

The influence of retired wind turbines on sustainable cities and communities is a subject of increasing importance in the realm of environmental and urban planning. As these turbines reach the end of their operational life, questions arise regarding their influence on the overall sustainability framework. The decommissioning process and the repurposing of these structures present challenges and opportunities that extend beyond their initial lifespan (Krauklis et al., 2021). According to the World Wind Energy Council, there are over 350.000 utility-scale wind turbines installed globally, the majority designed with a service life of 25 years at most (Marsh, 2017). As the turbines from the initial wind power installations in the 1990s approach the end of their expected lifespan, approximately two gigawatts of turbines were anticipated to undergo refurbishment in 2019 and 2020 (Belton, 2020). Denmark, a pioneer in early wind energy adoption, grappling with the substantial challenge of bulk disposal in the evolving landscape of wind energy. Typically, turbine rotors consist of three blades, varying in size from 12 m in the early stages of wind turbine development to an impressive 80 m and even larger in contemporary designs. A notable instance of longer blades is evident in Siemens Gamesa Renewable Energy's 14 MW turbines, featuring IntegralBlades that are 108 m long and rotor diameter of 222 meter. The imminent concern arises as many of these rotor blades are nearing the end of their lifecycle, emphasizing the urgency of effective recycling strategies. Looking ahead to the 2020s, recycling becomes an even more critical issue, especially considering that currently, aptly 90% of total mass of wind turbines can be recycled (Krauklis et al., 2021). Therefore, this exploratory study aims to conduct a thorough assessment of wind energy resources, focusing on optimizing the sustainable transition from active to retired wind turbines, contributing to a more resilient and environmentally conscious future for cities and communities, by using a semi-structured interview with a focus group.

2. Literature Review

2.1. Extending Lifespan of Wind Turbines

One of the approaches in this regard is the efforts to extend the lifespan of wind turbines (Spini & Bettini, 2024), which is a challenge for sustainability (Krauklis et al., 2021). Older versions of wind turbines are installed in all markets. They are directly connected to the grid, no converter between the generator and the grid. So, rotational speed of the generator is load dependent and is almost fixed to grid frequency. Mainly, there are two version of these wind turbines: type-a and type-b.

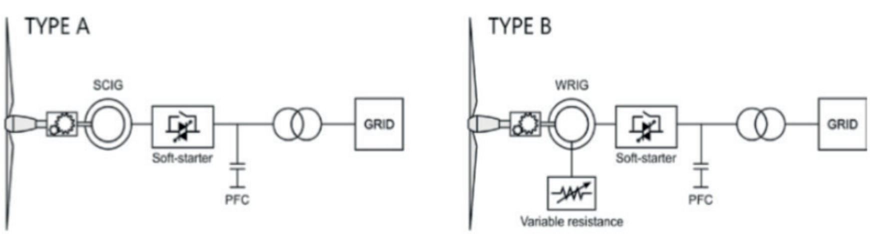

Figure 1: Two version of wind tubines

Type A is called SCIG (Squirrel-Cage Induction Generator) and generator speed is the number relation with stator and rotor windings. The speed of the generator can not be modified. Type B is called WRIG (Winding rotor induction generator). In this case, generator speed is not fixed. We can modify the speed with the variable resistance connected to the rotor but this control is limited. In these types of wind turbines, high mechanical stress and low power quality can be observed (flicker and uncontrolled reactive consumption), wind turbulences are directly transferred through the drive train, and low rotor aerodynamic efficiency as optimum TSR is only achieved for one wind speed.

So, what should be done to extend the lifespan of these turbines? The turbines should be made more efficient, and the grid quality should be improved. To achieve this, installing a full converter to completely control the speed of the generator is essential.

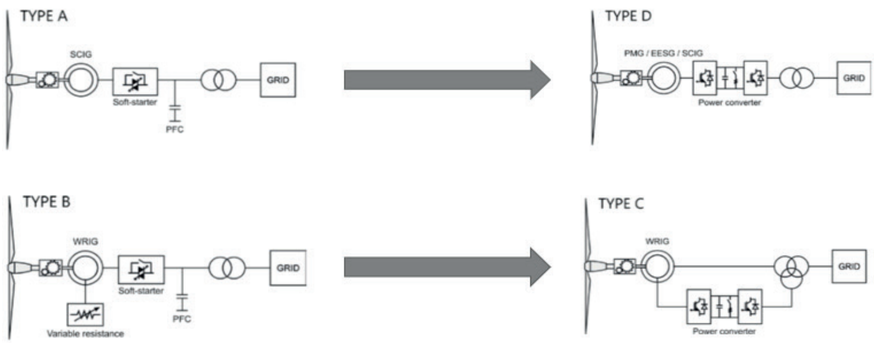

Figure 2: Full converter installed wind turbines

When a full converter is installed as shown above, and the speed of the generator is brought under control, we can achieve the following benefits:

- Efficiency increase (optimum operation point of the generator)
- Grid quality improvement (power factor correction capabilities)
- Load distribution (protects turbine from mechanicals stresses)
- Active power increases due to rotor power extraction thanks to the power converter

2.2. Designing for Recyclability for Sustainable Cities

One of the significant studies conducted in this regard is designing for recyclability. Longevity, extended lifespan, and optimal energy production are crucial factors in reducing the footprint per kilowatt-hour (kWh). Achieving high-value, low-cost recycling on a large scale is challenging given the current material options. Recycling serves as a facilitator for decreasing the footprint per kWh. Additionally, it's essential to take into account the environmental impact of materials (Siemens Gamesa RecyclableBlade, 2024). Most of the turbine recyclable (85-90% by weight) and low CO2 footprint. Composites remain a challenge. Figure 3 presents the components, materials, and disposal routes.

Component	Material	Disposal route
Foundation	• Concrete • Steel	• Recycling or building material
Tower	• Coated steel	• Scrap metal to be re-used in steel mills
Drive train	• Cast iron • Steel • Lubricants	• Material recycling or re-processing
Generator	• Cast iron • Copper • Electronics	• Material recycling or re-processing
Electronics	• Cable • Switch boards	• Material and recycling
Rotor blades, Nacelle housing	• Fibre composites • Resins • Other (Sandwich core, coating, metal)	• Landfilling • Incineration • Cement co-processing

Figure 3: Components, materials, and ways of disposal (Siemens Gamesa RecyclableBlade, 2024)

2.3. Transforming Wind Turbine Blade Recycling Challenge

There are recycling efforts for several turbine parts, but composite materials in rotor blades have been more difficult to recycle. Previously, the sector could not recycle wind turbine blades upon decommissioning and the blades ended up as landfill. Along with Siemens Gamesa Renewable Energy's RecyclableBlade technology, the materials can be recycled and reused in other sectors for future generations (Siemens Gamesa RecyclableBlade, 2024). Figure 4 presents the picture of recycable blades of offshore and Figure 5 shows the life cycle stages of wind turbines.

Figure 4: SGRE recyclable blades of offshore (Siemens Gamesa RecyclableBlade, 2024)

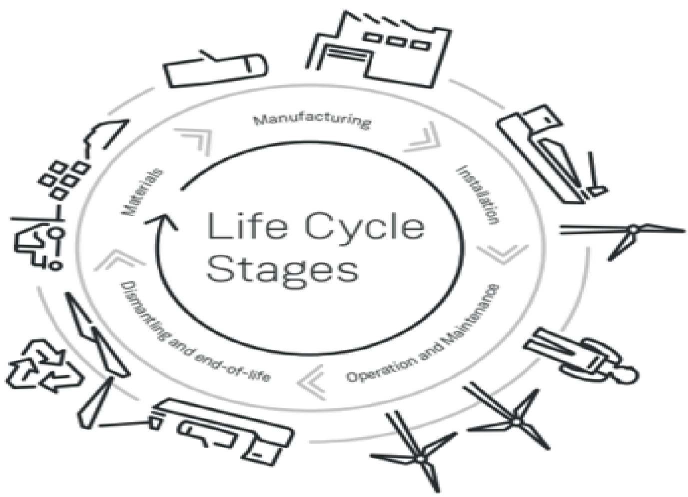

Figure 5: Life cycle stages of wind turbine from cradle to grave (Siemens Gamesa, 2019)

While many components of wind turbines can undergo recycling processes, the same cannot be said for composite wind blades, which present a distinct challenge (Jensen et al., 2020). The complexity arises from the fact that these blades, serving as the dynamic component exposed to intricate fatigue and environmental stresses, are engineered to endure these forces over several decades. Consequently, even after reaching the end of their service life, they remain exceptionally resilient to these loads. Blades typically comprise diverse material elements, including thermoplastic coatings, thermoset/glass fiber composites, and carbon fibers. This intricate composition makes it exceedingly challenging to separate and recycle the various components (Snieckus, 2020). Globally, wind energy industry utilizes a staggering two and a half million tons of composite material (Mishnaevsky, 2021). Figure 6 presents how to increase the lifespan of wind turbines.

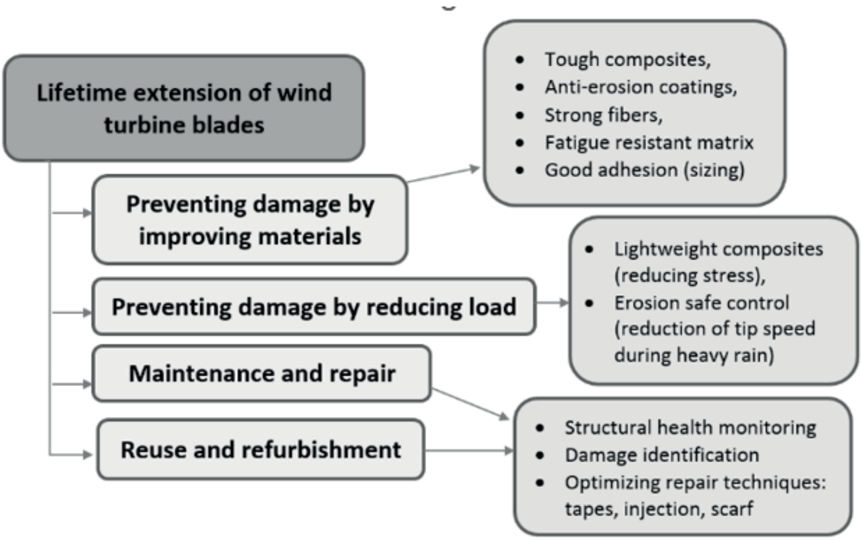

Figure 6: Extension of lifetime of wind turbines (Mishnaevsky, 2021)

3. Methodology

The methodology for this exploratory study will center around a focus group. Semi-structured interviews are used with a focus group of eight wind turbine experts, who have different backgrounds and work experiences in the wind turbine industry. The following 10 open-ended questions are asked, including the demographic features of respondents such as, gender, age, the level of work experience in the field, title in the organization, and their education background. The other questions (question 3- question 10) concern how the expired turbine influences the environment negatively, the effects on the economy and the society, how to build a sustainable ecosystem and how the wind sector can make the cities more sustainable, and the evaluation of the inclusion of wind turbines in a life extension program, according to expert opinions in the wind turbine sector.

1. What is the title and expertise of the participant?

2. How many years of experience do you have in the wind energy sector?

3. How does an expired turbine affect the environment negatively?

4. What negative impact do expired turbines have on the economy?

5. In what ways do expired turbines negatively impact society?

6. Do you believe it is possible to minimize these negative effects and create a sustainable ecosystem?

7. In your opinion, what measures can be taken in the wind sector to make cities more sustainable?

8. What contribution can the improvement and reuse of turbines make to creating sustainable cities?

9. How do you evaluate the inclusion of wind turbines in a life extension program? Would enhancing the capacity, efficiency, and grid quality of expired turbines or transforming fixed-speed generators to variable-speed generators contribute socioeconomically?

10. Have you had any experience with a study or project related to this topic? If so, please briefly explain.

4. Findings and discussion

Table 1 presents the demographics in terms of gender, average age, average work experience of participants, their title, and education background. Ten questions were posed to eight different professionals in the wind energy sector. The collected answers are summarized in Table 2.

Table 1: Demographics

Items	**Percent**
Gender	100
Male	100
Female	0
Average age = 37.5 years old	100
Average work experience = 10.8 years	100
Title	
Mechanical Engineer	12.5
Electrical Engineer	12.5
Multibrand Engineer	12.5
Chief Engineer	12.5
Configuration Management Manager	12.5
Head of Electricals	12.5
Head of Conceptual Blade Design	12.5
Platform Project Manager	12.5
Education	100
Bachelor's degree	37.5
Master's degree	37.5
PhD. degree	25

Table 2 presents the key responses concerning wind turbines. The responses deal with how the expired turbine affects the environment negatively, the influences on the economy and the society, how to build a sustainable ecosystem and how the wind industry can create sustainable cities, and the assessment of the inclusion of wind turbines in a life extension program, according to expert opinions in the sector.

Table 2: Answers concerning wind turbines and their environmental impacts

Answer-3	All participants (100%) are aware of the environmental impact of expired wind turbines and believe that associated challenges can be addressed in the near future. Less experienced engineers express optimism about the potential solutions.	Experienced managers highlight that approximately 90% of the materials in these expired turbines can be recycled, emphasizing that the environmental impact is significantly lower when compared to other non-renewable energy sources.
Answer-4	According to 75% of participants, it is believed that the waste management and decommissioning costs associated with this issue would pose a disadvantage to the economy.	Two participants with doctorate degrees (25%) anticipate positive long-term effects on the economy. They posit that the replacement of decommissioned low-capacity wind turbines with new ones boasting higher energy production capacities will occur. It is noteworthy that policymakers in some countries are known to incentivize investors in this regard.
Answer-5	The main factor for the participants (75%) is job losses. The decommissioning of wind turbines can lead to job losses in the renewable energy sector. This can influence workers directly involved in turbine operating and maintenance, as well as those in other related industries.	Some other factors for participants can be merged in these three topics; • Reduced energy supply • Environmental concerns • Visual and aesthetic changes
Answer-6	Participants generally (90%) responded to this question with a humorous tone, mentioning that they work towards this and expressing an overall positive outlook.	Participants with over 20 years of experience (38%) in the sector foresee rapid advancements in the sector throughout their careers and anticipate that negative impacts will soon be completely alleviated.
Answer-7	Common idea: Implementing microgrid systems that incorporate wind energy can enhance the resilience and sustainability of urban energy infrastructure. These systems allow for localized energy production, reducing dependence on centralized power grids, and a reduction in transmission costs.	Some other factors for participants are; • Urban wind farms • Incorporate small-scale wind turbines into the design of green buildings and structures.

Answer-8	The most popular answer was extended lifespans coupled with increased efficiency. According to the participants, maximizing the benefits of each wind turbine at maximum efficiency over an extended period is the most significant contribution to sustainable cities.	Additionally, achieving high efficiency with less investment compared to new investments will also benefit the economies of cities.
Answer-9	Since this is a specific question, only a few individuals responded (25%), there appears to be a consensus on the socio-economic benefits, emphasizing energy cost savings and reduced environmental impacts for cities.	Furthermore, there is an advocacy for the implementation of these programs on all old turbines globally by wind turbine manufacturers.
Answer-10	Six participants have directly or indirectly played roles in projects of this nature. The Platform Project Manager led the project to convert fixed-speed generators to variable-speed generators, while the Electrical Engineer contributed to the design of the converter used in the same project. The Configuration Management Manager and Chief Engineer have worked on compatibility projects between different turbine types.	The Head of Electricals managed the recycling and reuse processes of electronic components used in turbines. Lastly, the Head of Blade Design provided support for research and development processes in renewable blade technologies.

The fundamental quotes are shown below;

"…the expired turbines negatively impact the environment by posing challenges in recycling, especially with composite rotor blade materials, often leading to landfill disposal and environmental concerns."

"…continuous efforts in research, technology development, and sustainable practices can contribute to resolving these issues. As someone who has witnessed the rapid resolution of seemingly insurmountable bottlenecks in this sector over the past two decades, we'll soon cease to discuss such issues."

"Leveraging advanced turbine designs, integrating smart grid solutions, fostering community collaboration, and ensuring lifecycle management are essential measures for the wind sector to significantly enhance urban sustainability."

"Improving and reusing turbines can contribute to sustainable cities by increasing energy efficiency, reducing waste, and fostering a more eco-friendly urban environment."

In recent decades, substantial investments have been made in wind turbines, elevating their significance in national electricity systems. Efficient management of these assets can be greatly enhanced through the improvement of cost-effective monitoring strategies. Such strategies hold the potential to extend the lifespan of existing turbines, reduce insurance costs by mitigating operational risks, and optimize designs, ultimately enhancing competitiveness in the energy sector. The evolving wind energy market and future scenarios present various challenges, with this work specifically focusing on experimental tools for managing wind energy assets throughout their operational lifetime. It explores diverse end-of-life management strategies for turbine blades, including disposal, lifespan, reuse, recycling, and the improvement of innovative blade materials. While options like using more durable materials for increased service time are available, the improvement of extra-durable blades is anticipated in the future. Reactive measures for installed blades involve improved maintenance, repair procedures, and condition-based maintenance for early damage detection, offering transitional solutions until advanced recycling technologies and new blade materials become prevalent (Pacheco et al., 2024). In addition, preparation for low carbon infrastructure decommissioning is key for avoiding colossal economic and environmental costs at end-of-use (Resource Recovery From Waste, 2024).

In light of the responses received, it becomes apparent that individuals with diverse educational backgrounds, varying levels of experience, and distinct roles in different sectors approach the topic with unique perspectives. Nevertheless, a shared consensus prevails: renewable energy stands as a pivotal sector for the development of sustainable cities, and the meticulous consideration of material selection, lifespan, efficiency, and capacities serves as critical parameters in the construction of enduring sustainable urban environments.

5. Conclusion

This study embarked on a comprehensive exploration of wind energy resources, with a specific emphasis on optimizing the sustainable transition from active to retired wind turbines. The findings presented herein contribute valuable insights to the broader discourse on fostering a resilient and environmentally conscious future for cities and communities through renewable energy initiatives.

The assessment highlighted the significance of adopting strategic measures for the life extension of wind turbines, underscoring the potential socio-economic and environmental benefits of such endeavors. By addressing the challenges associated with retired turbines, this study has provided a foundation for sustainable practices that align with the evolving needs of urban development.

However, it is imperative to acknowledge certain limitations inherent in this research. Through a focus group approach with only eight wind turbine experts in the industry, the exploratory study was conducted. The perspectives of customers and energy sector investors on this matter were not known when conducting this study. Opinions regarding investing in high-cost wind turbines and equipment for more sustainable cities and communities were not solicited.

Future research endeavors could delve deeper into the economic feasibility of life extension programs, considering factors such as upfront costs, return on investment, and financial incentives. Furthermore, exploring advanced recycling technologies for turbine components and investigating the integration of wind energy with other renewable sources could enhance the comprehensiveness of sustainable practices in the field. In essence, while this unique study serves as a crucial stepping stone toward a sustainable future powered by wind energy, continued research and exploration will be essential to refine strategies, address emerging challenges, and propel the transition toward a more resilient and environmentally conscious energy landscape, which can also help the tourism industry revitalize itself through clean energy practices.

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