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Comparing Environmental Costs: Fossil Fuel Extraction Versus Wind Turbine Life Cycles

Kevin Hella Nyapom[1], David Padi[2]

[1, 2]EUCLID University

Abstract: ***This study investigates the environmental implications of wind energy by conducting a comparative life cycle assessment of wind turbines versus fossil fuel extraction, particularly coal and natural gas. Despite wind energy's zero-emission operation, its material-intensive construction and end-of-life disposal contribute to notable environmental costs, including greenhouse gas emissions and non-recyclable waste. The findings suggest that while wind energy significantly reduces operational emissions, averaging 10–15 g co₂ per kwh compared to coal's 820 g, its life cycle impacts deserve attention. By 2050, turbine blade waste could exceed 43 million tons globally. This paper aims to inform policy and industrial decision-making by shedding light on the often-overlooked environmental burdens of renewable energy technologies.***

Keywords: Wind Turbine Life Cycle, Environmental Costs, Fossil Fuel Comparison, Renewable Energy Policy, Waste Management

1. Introduction

Renewable energy has emerged as the top solution for climate change and reducing Greenhouse gases (GHG). Coal, oil, and natural gas remain significant energy sources, providing 84% of the world's energy needs as of 2021.[1] However, wind power generation ranks highest among renewable technologies due to its technological maturity, solid infrastructure, and competitive costs.[2]. Renewable Energy (RE) technologies such as solar, wind, hydro, biomass, geothermal, and hydrogen have been introduced to generate electricity to overcome the current environmental crisis.[3]. Nonetheless, the environmental impacts resulting from the extraction and combustion of fossil fuels are responsible for 75% of total anthropogenic emissions.[4] The data from the International Energy Agency (IEA) shows that the energy sector contributes 40 Gt CO_2 annually, which endangers the planet and forces officials to look for more sustainable energy sources.[5]

Wind energy, as one of the most rapidly developing renewable energy sources, can become an effective response to the use of fossil fuels. Wind energy, which involves no direct emissions during electricity generation through turbines, is a powerful weapon in combating climate change. The cumulative installed wind power capacity was 743 GW at the end of 2020, and it has grown at an average annual rate of approximately 22%, starting from 24 GW in 2003. This has been boosted by reduced cost and increased technological improvements, such that the new turbines have a mean capacity of 4 MW, while some offshore designs provide up to 14 MW.

However, the life cycle analysis proves that even though wind turbines may be operationally efficient in terms of environmental impact, they have substantial negative implications regarding their complete life cycle. An LCA analysis that considers the effects of extracting materials and manufacturing through the end-of-life disposal of wind turbines revealed that these turbines use significant amounts of steel, copper, aluminum, concrete, and metals like neodymium. Similarly, a 3 MW turbine needs approximately 300 tons of steel and two tons of rare earth materials, products that pass through energy-intensive mining and processing stages. Despite those efficiencies, they cause significant emissions: cement manufacturing takes 8% of the global CO_2 emissions, and steel production takes 7 %.[6] Additionally, wind turbine blades, typically made from fiberglass composites, pose significant disposal challenges due to their limited recyclability. This leads to projections that over 43 million tons of blade waste will accumulate in landfills globally by 2050. [7]

This study aims to compare the environmental costs associated with fossil fuel extraction, such as coal and natural gas, and the full life cycle of wind turbines, highlighting the

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[6] World Economic Forum. (2019). *How Cement and Steel Contribute to Climate Change*. https://www.weforum.org/agenda/2019/09/the-hardest-sector-to-decarbonize-steel-cement-emissions/

[7] International Renewable Energy Agency (IRENA). (2016). *End-of-Life Management: Solar Photovoltaic Panels*. (Note: Although primarily focused on solar PV, this document provides relevant insights into the recyclability of renewable energy materials.) https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels

hidden ecological challenges of renewable energy. It provides critical insights and recommendations for policymakers and industry leaders, urging a more nuanced understanding of renewable energy technologies' hidden costs to support decision-making toward sustainable energy plans. This research is significant as it informs sustainable energy policies by addressing the overlooked environmental costs of clean energy technologies.

2. Renewable Energy: Wind Turbines

Renewable energy (RE) helps in sustainability and is of economic importance. It benefits the economy by reducing the cost of electricity generation, as it generates energy using natural, renewable resources[8]. Wind, used to develop wind turbines, is regarded as a zero-emission energy source during use. Windmills were employed to pump water between 1850 and 1970. The first major wind turbine (WT) of 12 kW was installed in Cleveland, Ohio, in 1888. During World War I, Denmark widely used 25 kW units. Wind generator research in the United States was influenced by airplane designs in Germany and the United Kingdom (between 1935 and 1970), which demonstrated that large-scale WTs were feasible. European progress continued after World War II[9]. The subsequent development of wind power applications and electricity generation continued to grow in the 19th century. Globally, wind energy is growing rapidly. Since 2021, the world's wind energy capacity has become a key renewable energy source. [10] The global wind power installation reached about 1,500 TWh in 2021 to meet 5% of the worldwide electricity requirement. The rating of wind turbines has also grown, with today's average wind turbines ranging from 4-8 megawatts and some offshore turbines with a power rating of up to 14 megawatts.[11] The need for more efficient development of higher-yielding technology specifies that every turbine is made of large quantities of metals and composite materials, affecting the ecosystems and resource availability.

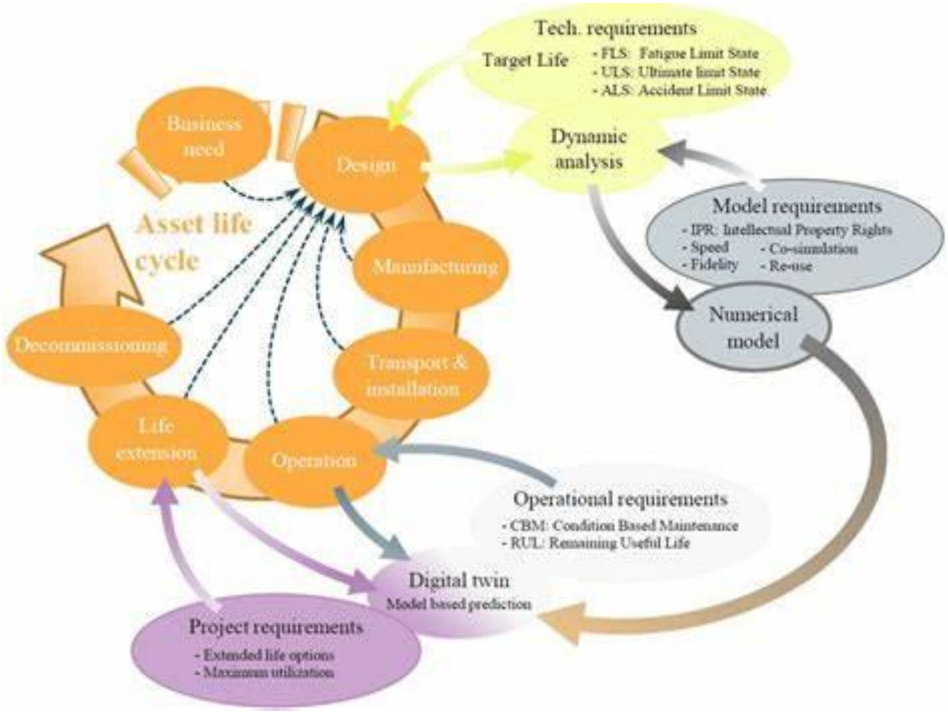

Figure 1: Wind turbine life cycle

b) The Life Cycle Assessment of Wind Turbines

The life cycle of a wind turbine includes four main stages: raw material procurement, processing, utilization, and the ultimate disposal stages. The last research in life cycle assessments has indicated that all the phases yielded different environmental pressures concerning carbon footprint, material use, and local biophysical surroundings.

1) Material Extraction and Manufacturing

Fabricating an ordinary 3 MW wind turbine involves using about 300 tons of steel, 5 tons of copper, 2 tons of rare earth (Neodymium for the magnet), and concrete in large quantities.[12] Out of all industrial sectors, the steel and cement industries are most influential in raising levels of CO_2 emissions; as it is known, steel production produces 1.8 tons of CO_2 per ton of material, and worldwide cement production

[8] Kardooni, Roozbeh, Sumiani Binti Yusoff, and Fatimah Binti Kari. "Renewable Energy Technology Acceptance in Peninsular Malaysia." *Energy Policy* 88 (January 2016): 1--10. https://doi.org/10.1016/j.enpol.2015.10.005.

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[12] Atilgan Turkmen, Burcin, and Fatos Germirli Babuna. "Life Cycle Environmental Impacts of Wind Turbines: A Path to Sustainability with Challenges." Sustainability 16, no. 13 (2024): 5365.

contributes to about 8% of the total CO_2 emissions.[13] These materials alone are responsible for 85% of the total emissions of a neutral wind turbine, primarily because of steel and concrete production, electrical intensity, and other associated emissions.[14]

Another problem arises from mining other related materials used in turbines, such as rare earth materials like neodymium and dysprosium. Large, focused mines in China generate radioactive waste, such as thorium and uranium, which pollute the related soils and water resources. This contamination is invasive and damaging to ecosystems and has potential future negative impacts on nearby populations.[15] Solving these environmental problems means working on higher environmental regulations and buying environmentally friendly materials, which are crucial for the production of turbines.

2) Transportation and Installation

The transportation of wind turbine parts from the manufacturing point to the wind turbines' construction sites involves using heavy trucks and equipment. This stage releases about 20 tons of CO_2 per turbine because the assembly and shipping of such large and bulky structures require much fuel.[16] Offshore wind installations are slightly more demanding, as a rule. Some turbines must be installed at sea, requiring unique ships, hence another round of emissions. The grounding of turbines to the seabed can also harm local marine ecosystems through noise pollution that interferes with the navigation and communication of aquatic life.

3) Operation and Maintenance

In the satisfactory period, wind turbines are regarded as zero-emission power plants since they do not use fuel to produce electricity. Today, a wind-energy-based system is one of the cleanest and most mature options among all existing renewable energy sources. In such a situation, it is vital to understand the influence of a windmill farm on the environment[17]. Conversely, activities such as lubrication, gearbox, repair segment, and periodical examination entail extra emissions in addition to other resource costs, which tally slightly over 1-2% of the total emissions of the turbine during its life cycle. Turbines sited in the offshore region experience Make-offs due to the corrosive marine environment and, therefore, require more frequent maintenance than the onshore ones. For those components that need replacement, such as a rotor blade or a gearbox, extra transportation and equipment will be required, contributing to the additional life cycle environmental impact of wind turbines, given their useful life of 20-25 years.

4) End-of-Life and Decommissioning

Wind turbines are usually built to have a service life of 20-25 years before the structure is retired. Most turbine towers and nacelle structures are recyclable because they are primarily steel; however, blades are tricky to dispose of due to fiberglass composites. Currently, roughly 85% of retired blades are disposed of in landfills; the estimated quantity of blade waste by 2050 is higher than 43 million tons if trends persist. [18]

The potential for recycling efforts can cut down on the extent of blade disposal by as much as 49 percent, but obstacles in the form of technical and economic constraints constrain the use of such measures. Fiberglass recycling is technically challenging and economically unprofitable; thus, most manufacturers prefer landfilling. Therefore, more research on recycling technologies of composite materials is needed, together with policies in industries that stimulate proper handling of waste materials.[19]

3. Non-Renewable Energy: Fossil Fuels

1) Social and Environmental Impacts relating to Fossil fuel extraction

Although the adoption of renewable energy sources for power generation is increasing, most power generation is still performed by utilizing fossil fuels due to the intermittency of RE and the high initial cost.[20]. Hydrocarbons, coal, and natural gas are widespread energy sources with significant environmental impacts and consequences throughout their extraction, processing, and burning. Fossil fuel-based energy sources are causing detrimental environmental issues such as global warming and climate change.[21]. According to the research, every phase of fossil fuel extraction involves severe ecological, health, and climate costs, posing the need to shift towards the green power industry.

a) Terracides and destruction of habitats

The industrial extraction of fossil fuels like coal, oil, and gas is an extensive land business that destroys habitats. Opencast mining, which contributes more than 65% of the world's annual coal production, entails the recurrent removal of vast

[13] Gencel, Osman, Omer Karadag, Osman Hulusi Oren, and Turhan Bilir. "Steel slag and its applications in cement and concrete technology: A review." Construction and Building Materials 283 (2021): 122783.

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[21] Ang, Tze-Zhang, Mohamed Salem, Mohamad Kamarol, Himadry Shekhar Das, Mohammad Alhuyi Nazari, and Natarajan Prabaharan.

soil and vegetation cover layers. In the United States of America, for instance, at least 800,000 hectares of land have been rendered unusable by surface mining, the wildlife displaced, and ecosystems permanently affected.[22] Mountaintop removal, employed in the Appalachian region, causes severe deforestation and produces post-mining habitats that cannot support prior mining biotic density. A comprehensive survey established that surface mining has been known to decrease average species richness by between 30% and 70%, a situation that highly degrades the ecosystem and weakens the ecosystem's ability to adapt to the changed conditions, produced by the World Resources Institute.

b) Air and Water Pollution

Mediated through the emission of gases that affect the air and water surrounding the extraction process, there are severe effects on the surrounding communities. Sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM) are often blamed for smog, acid rain, and resultant harm to both the countryside and the city.[23] Mountaintop removal mining is specifically dangerous to water sources. Over the waters of the nearby rivers and groundwater, various metals such as mercury, arsenic, and lead are released, which proves to be very dangerous to the health of the communities in that region that rely on the said water sources. These contaminants can bioaccumulate in fish and other species of water ecosystems, be transmitted through the food chain, and negatively impact human health.

It is also important to highlight that fracking or hydraulic fracturing for natural gas extraction affects water quality. Fracking calls for water pumping accompanied by sand and chemicals under high pressure to extricate gas from shale structures. This means it utilizes between 2 and 4 million gallons of water per well, which puts pressure on water resources worldwide, especially in dry climates. Some chemicals employed in fracking, like benzene and toluene, are cancer-causing chemicals found in aquifers close to fracking zones. They are known to cause cancer and respiratory diseases in those living close to them.[24]

c) Greenhouse Gas Emissions

Combustion of fossil fuel is still the primary contributor to anthropogenic carbon emissions, contributing to more than 80% of the global CO_2 emissions. Burning oil, coal, and gas emissions alone soared to 37 billion tons per the Global Carbon Project 2023 report, and 3 billion tons were indirect emissions. Methane, dissolved in oil and gas and brought to the surface during extraction, has a global warming effect of 80 percent that of CO_2 within the next 20 years; methane leaks from fracking and drilling are thus alarming. Global Methane Emissions Due to Fossil Fuel Industry in 202 Million Metric Tons – 150 Global Carbon Project) and significantly contributing to climate change in 2023.[25]

d) Occupational Health Risks

Health risks are mainly associated with fatigue, health impacts arising from the use of precipitation, and emissions of fossil fuels, especially coal, which pose high health risks to the miners, resulting in black lung disease. In the United States, the National Institute for Occupational Safety and Health, or NIOSH, has estimated that every fifth miner suffers from occupational respiratory diseases caused by inhalation of coal dust and, more recently, a growing number of young miners.[26] Oil and gas sector employees are also exposed to VOCs, which include benzene, which is known to cause cancer. Guernsey believes the following occupational hazards demonstrate the social cost of fossil fuel reliance.[27]

2) Comparative Analysis

a) Emissions and Pollution

Wind power produces considerably fewer LCEs than conventional fossil resources. Papers published by the National Renewable Energy Laboratory show that coal-fired electricity emits around 820 grams Co_2 per kWh over its life cycle. On the other hand, wind turbines emit about 10 to 15 grams Co_2 per kWh. These figures speak for wind about greenhouse emissions since the wind energy utility, unlike most energy sources, does not emit greenhouse gases during its operation. Indirect emissions from wind are concentrated in the manufacturing, transportation, and decommissioning phases, suggesting that better recycling solutions must be found to reduce the emissions from these sources.[28] Fossil fuels discharge pollutants at every extraction, processing, and burning stage. These are Sulfur dioxide (SO_2), Nitrogen oxides (NOx), and Particulate matter (PM), which lead to airborne pollution and pollute the environment through acid rains. The WHO study also supports this information, revealing that 7 million people die prematurely due to emissions from the burning of fossil fuels. [29]

b) Use of Resources and Waste

Wind turbines also need substantial resources, such as steel and copper for blades and nacelles, respectively, and neodymium, used for the turbines' magnets. While these materials are infinitely recyclable, they are not without

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[28] National Renewable Energy Laboratory (NREL). *Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update*. Retrieved from https://www.nrel.gov/docs/fy21osti/80826.pdf

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adverse effects on the environment; the mining and processing of rare earths is hazardous to the soil and water. Further, turbines incorporate fiberglass blades, and currently, 85% of such blades are buried in landfills because recycling composite material is challenging and expensive. About one thousand Gg of wind turbine blade waste will be generated annually. Without effective means to recycle this waste, it will reach over 43 million tons by 2050.[30]

Comparing this to entirely finite fossil fuels and getting them requires digging into resources that cannot be replenished. Burning coal and oil products produces considerable amounts of ash and sludge, some of which consist of materials such as mercury and lead, which are dangerous pollutants in water. This waste is a problem that lasts for a long time, causing environmental issues, especially when the fossil fuel plants are shut down without proper cleanup.

c) The Ability of the Habitats to Sustainably Support Land Use and Support Biological Diversity.

Wind farms take up substantial space, although the disturbance to the land is rarely as permanent as that caused by fossil fuel extraction. According to the U.S. Energy Information Administration (EIA), the spaces between the turbines, for example, are always helpful for farming or grazing and, therefore, compatible with other activities. Nevertheless, wind turbines are hazardous to birds, bats, and other wildlife species that are important to humans. The emphasis has been on some of the adverse environmental effects of wind energy facilities, which include impacts on ecosystems such as wildlife.[31]. According to the U.S. Fish and Wildlife Service report, wind turbines are responsible for an estimated $140,000–$328,000 in bird fatalities through impact each year. The above impacts can be alleviated by selecting the correct sites and employing impact reduction measures.

Open-pit mining for fossil fuels necessarily brings significant long-term societal impacts to habitats through the removal and destruction of topsoil and vegetation. Locally, open-pit mining eliminates up to 70% of the local biota and, hence, is environmentally unbalanced. Continuing, the fact that access to fossil fuel sites can remain impossible for several years after leaking, and in some cases, may never be possible, is definitive proof of the effects of these energy sources on the environment. [32]

d) Energy Return on Investment (EROI)

One of the most important indicators for evaluating the sustainability of energy resources is Energy Return on Investment. Fossil fuels have traditionally shown high EROIs, such as oil at approximately 20:1, but the contribution is decreasing with increasing energy costs of operations in extraction. Wind energy, with an EROI ranging between 15. It has been established that the cost relationship of concentrated solar power to fossil fuels is about 1 to 30:1 and more if turbines last for 20-25 years. Increasing turbine duration to 30 years can push the benefits of the EROI of wind-sustained power even higher.[33]

4. Conclusion

In conclusion, this research has indicated the difference between various energy sources of fossil fuel, for instance, coal and natural gas, and wind energy, so far as the environmental costs in their different life cycle stages are concerned. The enthusiasm for RE generation is thriving as the world becomes more and more conscious of the adverse effects of fossil and nuclear fuel-based power generation[34]. Despite wind energy's status as an emitter of zero onsite emissions, it escalates other emissions throughout the production process and transportation to installation sites and decommissioning areas. On the other hand, fossil energy, for instance, coal-fired electricity, is associated with greenhouse gas emissions of about 820 grams CO_2 per kWh, while wind energy is about 10-15 grams CO_2 per kWh. However, the costs of materials needed for wind turbine production, which include steel, copper, and rare earth elements like neodymium, are very high and amount to 300 tons of steel, 5 tons of copper, and 2 tons of rare earth elements for every 3MW turbine thus the need to ensure appropriate use of resources and sustainable supply chains. Further, caused by the poor recyclability of components, especially the fiberglass blades of wind turbines, 43+ million tons of blade waste could end up in landfills by 2050. These results underscore how difficult the shift to renewable energy is and stress that while wind energy is crucial for lowering global carbon emissions, its environmental cost across the life cycle should not be ignored. Despite minimal operational emissions, this paper reveals that wind turbines demand large quantities of raw materials and pose disposal challenges, particularly with fiberglass blades. By acknowledging these hidden costs, the energy sector can refine its strategies, invest in recyclability innovations, and develop policies supporting sustainable energy transitions.

5. Summary of Findings

Although wind energy yields outstanding environmental advantages over fossil energies, it has tremendous PLC costs. Coal-fired electricity produces 820 grams of CO_2 per kilowatt hour, while wind power produces 10-15 grams per

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kilowatt; nevertheless, the emissions during the manufacturing and disposal of wind power equipment are disproportionately high. A 3 MW wind turbine has 300 tons of steel, 5 tons of copper, and 2 tons of rare earth; thus, it has its fair share of carbon. Disposing of the waste remains a problem for both of these units; the blades used in the wind turbines are primarily non-recyclable; thus, by 2050, we will have accumulated 43 million tons of this waste, while fossil fuels generate toxic ash. They also state that land usage varies; wind farms are not as harmful as fossil fuel extraction, at the same time, killing between 140,000 and 328,000 birds per year from collisions; fossil fuel mining, however, can decrease the number of diversified species by as much as 70%. Wind's EROI of 15:1 is nicknamed biomass competitive with fossil fuels when the conversion rate is 1 to 30:1. Therefore. However, wind energy has minimal impacts, and resource and disposal concerns must be addressed.

6. Policy Implications and Future Directions

The results suggest that policies targeting the benefits of RES, especially wind energy, should also consider the environmental impacts of these resources. For this reason, the authorities must provide grants and subsidies to advance the use of more environmentally friendly materials and enhance the recycling potential of existing wind turbine parts, particularly those made of fiberglass, for which the corresponding waste is expected to reach 43 million tons in 2050. Solutions included legislating for improved recycling standards and supporting studies into recyclable components.[35] Furthermore, the rules stipulating reasonable supply chains, including the extraction of strategic metals and steel used in turbines, would be helpful to reduce the impact of turbines on the environment, as the extraction stage has a high level of CO2 emissions.

Energy policies regarding future energy generation should also prescribe where wind farms should be established to minimize effects on wildlife, as turbines are believed to kill between 140,000 and 328,000 birds annually in the United States. Measures to mitigate these effects include increasing awareness of and implementing best practices in siting new facilities and low-impact, avian-safe turbine design. Furthermore, increasing the operational lifespan of turbines from the typical 20-25 years to 30 years or more could improve wind energy's Energy Return on Investment (EROI), which ranges from 15:1 to 30:1.[36]

To overcome this limitation, future financing for renewable technologies must incorporate a life cycle analysis (LCA) investigation to guarantee that future breakthrough energy solutions include a systematic approach to emissions, resource consumption, and waste. So, regarding the lifecycle environmental impacts of renewable technologies, applying sustainable policy measures to the processes that develop and deploy those technologies ensures that policymakers drive the maximum positive environmental change without causing significant negative ecological consequences.

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