

SOME ECONOMIC, TECHNICAL AND ENVIRONMENTAL CHALLENGES OF WIND ENERGY

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Abstract

This article examines recent global developments in the economic, technical, and environmental aspects of wind energy. It highlights the crucial role of emerging climate policies in ensuring a sustainable, eco-friendly energy future. In recent years, wind power capacity has grown significantly, while the cost of energy generated by wind turbines has fallen to the same level as nuclear energy. The effective planning and operation of wind farms requires accurate wind mapping at around 100 metres above ground level, which necessitates the development of advanced satellites and meteorological stations. The article also highlights the ecological benefits of wind energy, including the substantial reduction in toxic emissions resulting from replacing conventional power plants with renewable sources.

Keywords: wind energy, wind turbines, renewable energy, wind mapping, environmental impact, energy payback, sustainability

I. Introduction

Wind energy plays a crucial role in the transition to sustainable energy sources. By harnessing the kinetic energy of the wind to generate electricity, it has become a key component of the renewable energy sector, offering numerous advantages. However, like all energy sources, wind energy has its challenges and limitations. Understanding both its benefits and drawbacks is essential for ensuring a greener and more sustainable future.

New climate policies have begun to reduce the reliance on non-renewable fuels and promote the development of technologies that lower the cost of wind turbines. Between 2010 and 2020, global wind power capacity grew by nearly 10%. In 2020 alone, wind power capacity increased by 24%, reaching a record 75 GW. Wind power stations in China and the United States accounted for approximately 60% of this capacity [1]-3].

Critics of alternative energy argue that wind power is not financially viable, claiming that the cost per kilowatt of electricity produced by wind farms is higher than other energy sources and that wind turbines produce less energy over their lifetime than was required to manufacture them. In reality, these claims are inaccurate. In recent years, the reliability and efficiency of wind technologies have significantly improved, while costs have nearly halved. [4],[5],[6].

Today, the cost of energy produced by wind turbines is already competitive with that of nuclear power plants. In contrast, solar power stations have not yet achieved this, with the cost per kilowatt being 1.5 to 2 times higher. Naturally, gas and hydroelectric power plants are still more financially attractive (coal-fired plants, however, are no longer considered cost-effective). Over the next decade, the cost of solar and wind energy is expected to decline further, while the cost of nuclear and gas energy is likely to increase [7]-10]. As a result, wind energy will gain prominence—even without considering its environmental advantages.

III. Results

According to Vygon Consulting, in 2020, the average cost of electricity from new solar power plants in Russia was 9.5 rubles per kWh, from wind farms – 6.3 rubles per kWh, from nuclear power plants – 5.1 rubles per kWh, and from combined-cycle gas plants – 3.6 rubles per kWh [12]

A mid-2020 report by the International Renewable Energy Agency (IRENA) shows that the cost of renewable energy continues to decline compared to energy generated from fossil fuels. More than half of the renewable energy projects commissioned in 2019 delivered electricity at a lower cost than the most efficient new coal-fired power plants.

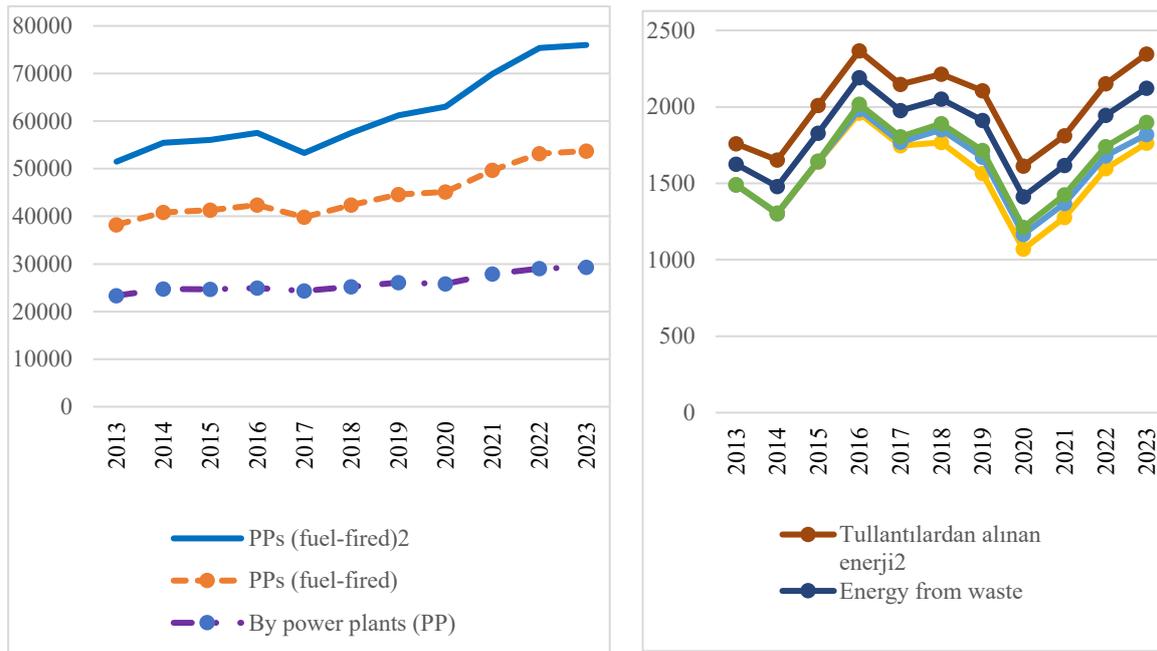
In general, the operational costs of new onshore wind installations are lower than those of many existing coal-fired power plants. Analysis suggests this trend will continue until coal is phased out entirely. Replacing coal-fired plants with a total capacity of 500 GW with solar and wind power could save the energy system up to \$23 billion per year and reduce annual CO₂ emissions by about 1.8 gigatons—equivalent to 5% of global CO₂ emissions in 2019. According to the International Energy Agency (IEA), electricity production is the largest source of carbon dioxide emissions across all industries [11], [12].

Over the past decade, the cost of generating renewable electricity has dropped sharply thanks to technological advancements, economies of scale, cheaper equipment, increasingly competitive supply chains, and accumulated experience among developers. Since 2010, the operating costs of industrial wind power stations have decreased significantly—by 39% for onshore and 29% for offshore facilities. Globally, the cost of wind energy declined by approximately 9% compared to the previous year, falling to \$0.053 per kWh for onshore and \$0.115 per kWh for offshore wind power.

Table 1: *Installed Capacity of Wind Power Plants by Country (MW), 2018–2020*

Country	2020	2019	2018
China	290000	237029	209529
USA	122328	105433	96363
Germany	62784	61357	59313
India	38625	37529	35129
Spain	27446	25808	23494
Great Britain	24167	23515	20743
France	17949	16646	15313
Brazil	18010	15452	14707
Canada	13588	13413	12816
Italy	19850	10512	9958
Turkey	9305	8056	7369
Other countries	110000	96035	84814
Total	744000	650085	589547

According to the Global Wind Energy Council (GWEC) 2020 report, the number of wind farms worldwide is expected to rise significantly. However, a potential shortage of necessary materials and price increases for wind turbine components may arise. If the current growth rate of wind energy is maintained, wind power alone could be sufficient to meet the planned green energy transition targets by 2035–2040 [13].



Graph 1: Dynamics of electricity production in Azerbaijan for 2013-2023

Source: Compiled by the author based on data from the ARSK

It is planned to increase the share of renewable energy sources in the country's total electricity production to 20–30%. By the end of 2027, approximately 1,870 MW of "green energy" is expected to be integrated into the national energy system. To achieve these goals, reforms are being implemented in the energy sector. It is anticipated that the installed capacity of the Unified Energy System (UES) will reach 8,000 MW, and energy transmission and load flows to neighboring countries—Georgia, Turkey, and Iran—will increase by about 3,000 MW. Additionally, due to the construction of new high-voltage substations and the development of distributed generation, the total transfer capacity of the UES of Azerbaijan will increase, ultimately reducing technological losses to 5% in the future.

The growth in the number of wind power plants depends on a multitude of factors, making it nearly impossible to describe with a simple function. It is necessary to consider variables such as the cost of raw materials, production dynamics of components, changes in logistics costs, and levels of financial investment. Currently, due to global economic fluctuations—especially those linked to the COVID-19 pandemic—these factors remain unstable.

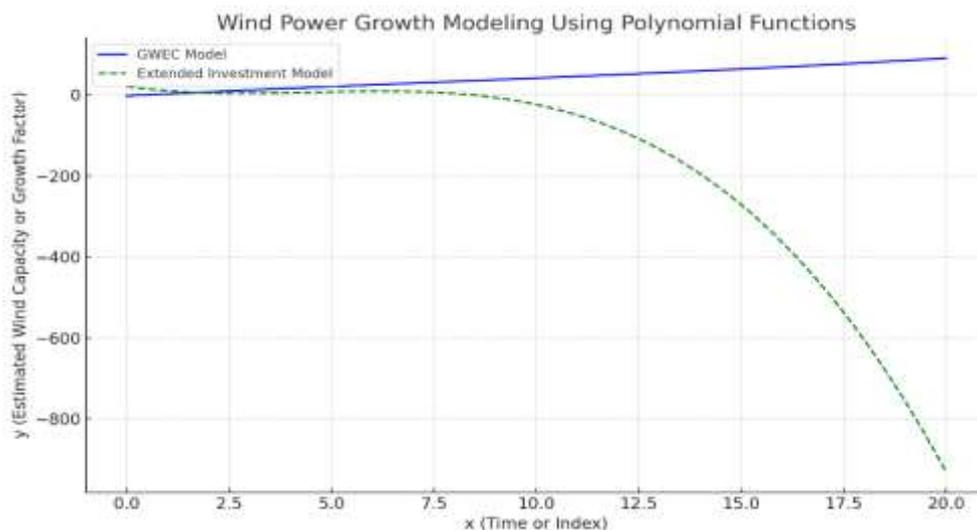
To model potential growth, a polynomial function is used. This approach separates the positive and negative effects of various factors and selects a power function for each group. The final model is the sum of these power functions, with a higher polynomial degree indicating that a greater number of factors have been taken into account. One such polynomial function, proposed by the Global Wind Energy Council (GWEC), is:

$$y = 0.0043x^3 - 0.1022x^2 + 4.978x - 2.4623$$

This model incorporates potential shortages of raw materials and the decommissioning and disposal of wind turbines. A second model is:

$$y = 0.0064x^2 - 0.2625x^3 + 3.5617x^2 - 13.909x + 20.683$$

This function additionally accounts for increased investments in wind power plants. The growth is partly driven by the rising prices of fossil fuels in Europe (particularly natural gas), which significantly increases production and operational costs that are no longer compensated by previous economic functions.



Graph 2: Polynomial Models of Wind Energy Growth

The graph presents a comparative visualization of two polynomial models forecasting the growth of wind energy capacity. The blue line represents the GWEC model, which estimates growth based on a set of baseline industry factors, including potential resource limitations and turbine decommissioning. In contrast, the green dashed line shows an extended model that also incorporates the impact of increasing investments in wind energy infrastructure [15].

The difference between the two curves highlights how capital inflows—driven by rising fossil fuel prices and a global push for energy diversification—can significantly accelerate development. The higher polynomial degree of the extended model reflects the influence of additional factors such as logistics costs, technological advancements, and financial incentives [13],[14].

Table 2: Classification of Wind Energy Resources at 10 and 50 Meters Above Ground Level

Class	Height, 10 m		Height, 50 m	
	Wind speed, m/sec	Specific power, W/m ²	Wind speed, m/sec	Specific power, W/m ²
1	0 – 4.4	0 - 100	0 – 5.6	0 - 200
2	4.4 – 5.1	100 - 150	5.6 – 6.4	200 - 300
3	5.1 – 5.6	150 - 200	6.4 – 7.0	300 - 400
4	5.6 – 6.0	200 - 250	7.0 – 7.5	400 - 500
5	6.0 – 6.4	250 - 300	7.5 – 8.0	500 - 600
6	6.4 - 7.0	300 - 400	8.0 – 8.8	600 - 800
7	7.0 – 9.0	400 - 1000	8.8 – 11.9	800 - 1200

At present, the development of wind maps at approximately 100 meters above ground level is considered a crucial task. This requires new satellites, meteorological stations, and ideally, the establishment of specialized units within energy companies capable of calculating optimal placements for wind turbines. These units should factor in not only wind speed but also terrain features, distances to nearby structures that could distort wind flow (including neighboring turbines), and other relevant geographical and environmental conditions.

In the United States and European countries, wind energy resources are classified based on average annual wind speed or average annual specific power at 10 and 50 meters above ground level (Table 2).

Taking into account Europe's high population density, residential zones, valuable

agricultural lands, and protected areas, a significant portion of wind turbines are installed 100–200 meters offshore. In these zones, wind conditions are stable and there are no surface obstructions. However, due to the complexity of construction in such areas, the costs are considerably higher. The main challenge in this case is delivering the electricity from the generation site to consumers, which requires the construction of above-ground transmission infrastructure.

Regarding energy payback, as early as 2014, the School of Technical and Industrial Engineering at Oregon State University conducted a large-scale study using one of the most commonly used 2 MW Siemens wind turbines. The research showed that the energy payback period was just 5 to 7 months, even though the operational lifespan of wind turbines is at least 20 years.

The calculations in the study were based on conditions typical of the U.S. Northwest coast (with an annual yield of 6.12 GWh at 35% capacity factor), which is considered an average for the U.S. The methodology followed the international energy return on investment framework (ReCiPe 2008), which accounts not only for production costs but also for operational expenses over the full 20-year lifecycle.

The payback calculation took into account raw material extraction, manufacturing of turbine components, transportation from various factories, on-site installation, regular maintenance over the lifecycle (including the use of 273 to 546 tons of lubricating oil depending on the model), and eventual partial recycling and decommissioning. In contrast, fossil fuel power plants typically have longer payback periods, higher ongoing maintenance costs, and shorter operational lifespans compared to wind turbines.

Today, some of the largest wind turbines in mass production—despite an estimated cost of \$14 million—achieve faster payback. At wind speeds of 13–15 m/s, these turbines can generate 7–8 MW and are considered ideal for coastal installation. The rotors of these giant turbines exceed 150 meters in diameter and are capable of operating at wind speeds as low as 3–5 m/s.

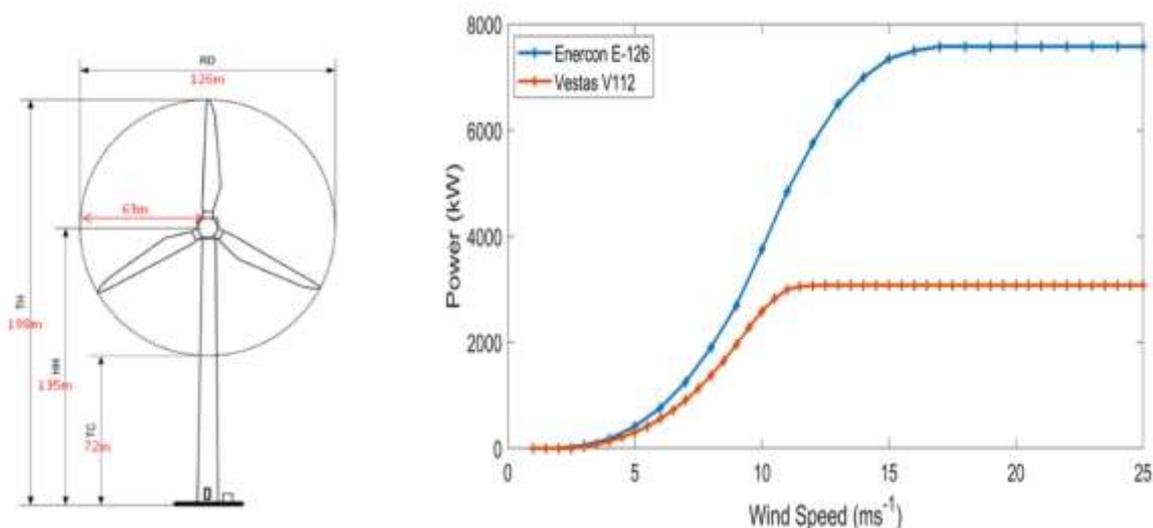


Figure 3: Diagram of the Enercon E126 wind turbine installation (a). Power curves of Enercon E126 and Vestas V112 turbines (b). The E126 model is capable of generating electricity at wind speeds up to 34 m/s.

When wind speeds reach 25 m/s, turbines are shut down for safety reasons. While it may seem that the blades should spin faster at higher wind speeds, that's not the case. In reality, depending on the wind speed, they rotate slowly—only about 5–11 revolutions per minute—and generate minimal noise. The reliability of these wind turbines stems from their simple design: they are gearless and use direct drive technology. One of the most powerful wind turbines—

though not the largest—is the German-made Enercon E126, with a capacity of 7.58 MW (see Figure 3). Many of these turbines have been installed in Sweden, where their combined capacity reaches 4 GW, accounting for 10% of the country's electricity production. Although renewable energy sources make up 60% of Sweden's energy mix, the country is not among the global top 10 producers of wind energy. That top spot is held by China, which leads the world in both wind and nuclear power plant construction.

As mentioned earlier, wind energy installations demonstrate the highest efficiency in coastal areas, where wind speed and stability are significantly higher. Before designing large-scale wind farms, it is essential to consider the wind map at the height corresponding to the turbine rotor's location, as well as the so-called "dead zone" of the generator—an area where airflow is distorted and weakened due to the proximity of turbines. Excessive density of turbine placement can result in a loss of power. Standard meteorological data are typically recorded at a height of 10 meters above the ground, while wind data at rotor height is critical for wind turbines. This justifies the need for launching specialized meteorological satellites for wind energy purposes.

The construction of large wind turbines is more cost-effective: both operational and capital costs for renewable energy remain low. According to the U.S. Energy Information Administration's 2021 report, solar and wind power plants are the most economical in terms of construction and operation.

Despite the obvious advantages, there are ongoing discussions in society regarding the environmental impact of wind energy: threats to birds, acoustic and infrasound pollution, as well as potential electromagnetic radiation. However, modern studies show that the number of birds killed by wind turbines is significantly lower compared to those killed by domestic cats, collisions with building glass, or electrocution from power lines. When accounting for 1 GW of generated energy, wind farms cause five times fewer bird fatalities compared to traditional fossil fuel power plants. The design of modern turbines includes low blade rotation speeds and the absence of attractive nesting sites, which reduces risks for birds.

As for noise and radiation, sanitary regulations in various countries stipulate a minimum distance between wind turbines and residential buildings—ranging from 500 to 1000 meters. Electromagnetic radiation levels rapidly decrease with distance, and even in close proximity to the installation, they do not exceed background levels that we encounter daily from Wi-Fi or mobile devices. In terms of noise, the turbine's sound is no louder than a lawn mower and significantly quieter than thermal power plants.

International studies (e.g., Resonate Acoustics commissioned by the Department of Environment of South Australia, as well as monitoring in Canada and Germany) have confirmed that the levels of infrasound and acoustic impact from wind farms are similar to those in other rural and urban areas and do not negatively affect humans, animals, or insects.

An issue that warrants attention is the potential microclimate change caused by large wind farms. While turbines in small-scale installations do not have a significant climate impact, a full transition to wind energy could alter local wind patterns and, potentially, air temperature. Since wind turbines partially absorb the kinetic energy of the airflow, weakening it, further research is needed to determine whether this effect can be used, for example, to combat soil erosion in regions with aggressive wind activity.

Offshore (marine) wind farms are of particular interest due to their smaller climate impact. Their main drawback remains the high installation costs and the need for underwater cables to transmit energy to land.

IV. Conclusion

Wind energy is a key element in the global transformation of the energy sector aimed at sustainable and environmentally safe development. The main advantages of this technology—renewability, low operational costs, minimal water consumption, and reduced dependence on fossil fuels—make it a strategically important factor in achieving energy independence and reducing greenhouse gas emissions.

Regression analysis revealed a high degree of correlation between wind energy growth rates and the level of government subsidies, tax incentives, as well as a reduction in capital costs due to technological progress. Statistically significant coefficients ($p < 0.01$) for investment variables in the capacity growth model confirm their critical role in accelerating the transition to green energy.

At the same time, sensitivity models showed that the growth in the number of installed turbines should be accompanied by strict adherence to environmental and spatial standards to minimize potential damage to the environment and public health.

Thus, with the integration of environmental standards and the maintenance of investment dynamics, wind energy remains one of the most promising forms of generation, ensuring economic growth while simultaneously reducing climate and environmental risks. Its role in the future energy system will depend on the ability of countries to adapt economic support tools and develop infrastructure to meet the needs of the rapidly growing sector.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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