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The Role of Wind Turbine Siting in Achieving Sustainable Energy Goals

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Abstract: As global energy demands rise, there is an increasing need to transition from fossil fuels, which contribute to environmental harm and have limited reserves, to more sustainable and renewable energy sources. This shift is vital for both protecting the environment and ensuring long-term energy security. Renewable energy, such as wind power, plays a significant role in mitigating climate change and reducing greenhouse gas emissions while also being environmentally harmonious. Wind energy, in particular, is gaining importance as a clean, renewable source of power, with wind turbines serving as key components of this transformation. The success of wind energy projects depends largely on proper site selection. Factors such as wind potential, the topographical structure, environmental sensitivity, and legal considerations must all be carefully analyzed to ensure maximum performance and minimal environmental impact. The site selection process is crucial in optimizing energy production while promoting sustainability. Effective micro-siting strategies, which focus on the specific placement of turbines within a site, are also essential for improving energy efficiency and minimizing environmental disruption. This study highlights the importance of careful site analysis to ensure the successful and sustainable implementation of wind energy projects.

Keywords: renewable energy; site selection of wind turbines; sustainability; wind energy; wind turbines

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1. Introduction

Energy is one of the most fundamental needs for sustaining life on Earth, and with the rapid increase in global population, the demand for energy continues to rise. Historically, fossil fuels such as coal, oil, and natural gas have played a dominant role in fulfilling these growing energy needs. Their widespread use, coupled with the fact that global energy infrastructures have largely relied on them, has cemented their importance in the energy sector. However, this reliance on fossil fuels has also led to a series of significant environmental challenges, including pollution, climate change, and the depletion of finite natural resources. The environmental impact of fossil fuels has drawn increasing concern in recent years, leading to intensified efforts to explore and transition to more sustainable energy alternatives.

The use of fossil fuels has been directly linked to increased greenhouse gas emissions, which contribute to global warming and climate change. This situation has shifted attention to renewable energy sources, which offer a clean and inexhaustible solution to the global energy crisis. Wind energy significantly contributes to the reduction in greenhouse gas emissions, primarily carbon dioxide, by replacing fossil fuel-based power generation. Wind turbines are estimated to reduce carbon emissions by over 100 million tons annually in the USA alone. Each megawatt hour of wind energy produced avoids approximately 0.75 tons of carbon dioxide emissions, while a typical 2 MW wind turbine can prevent around 4000 to 4500 tons of carbon dioxide emissions each year [1,2], Globally, the transition to wind energy is projected to play a crucial role in achieving climate targets, with estimates suggesting that wind and solar could account for over a third of the necessary emissions reductions by 2030 to limit global warming [3].

Renewable energy sources such as solar, wind, hydropower, and geothermal power have emerged as critical in reducing environmental damage while meeting the world's energy demands. These sources are not only vital for energy security but also play a significant role in mitigating climate change and supporting long-term environmental sustainability [4].

In this era of rapid globalization and increasing energy demands, the world is faced with the challenge of meeting environmental concerns and energy needs. Fossil fuels, once the backbone of global energy production, are increasingly scrutinized due to their limited reserves and the detrimental impact of their consumption on ecosystems and human health [5]. The urgency of transitioning to sustainable and renewable energy sources has never been more pronounced, as societies strive to leave behind a healthier and more habitable planet for future generations [6]. This shared responsibility necessitates concerted efforts from governments, communities, and individuals alike [7].

The transition to renewable energy sources has become a global imperative in addressing climate change and promoting sustainable development. Wind energy, in particular, has emerged as a prominent player in this transition, providing a clean and abundant resource for electricity generation without depleting finite resources, making it a critical component of global efforts to transition to sustainable energy systems [8].

In the context of renewable energy sources, wind energy plays a significant role globally. As of 2022, wind power accounted for approximately 30% of total renewable electricity generation in the European Union, making it one of the largest contributors alongside hydro power, which contributed about 29.9%. Globally, in 2022, wind energy supplied over 7.8% of the world's total electricity generation, with approximately 2304 TWh produced [9,10].

The long-term potential of wind energy is evident when compared to fossil fuel reserves, which are expected to be depleted within the next two centuries. For instance, coal is projected to last approximately 240 years, natural gas for 55 years, and oil for only about 30 years [11], while wind energy, driven by natural atmospheric processes, is essentially infinite.

The transition to renewable energy, especially wind energy, not only addresses the pressing need for alternative energy sources but also enhances economic and environmental sustainability [12]. Wind energy projects are seen as a significant component of the global green energy transition, offering numerous advantages such as reduced greenhouse gas emissions and a lower environmental impact compared to fossil fuels [13]. This energy transformation is a cornerstone of contemporary environmental policies and economic strategies aimed at promoting sustainability and reducing the reliance on non-renewable resources.

As wind energy grows in importance, the role of wind turbines becomes increasingly vital in harnessing this renewable resource. However, the successful operation of wind turbines is closely linked to the strategic selection of their installation sites. The success and productivity of wind energy projects are significantly influenced by factors like wind availability, terrain features, and environmental suitability. The site plays a crucial role in the efficiency of wind energy production systems [14]. A carefully chosen location can optimize energy production and reduce environmental impact, making the selection process crucial to the overall success of wind energy projects [15,16]. Selecting a site and statistically analyzing wind speed are the most crucial factors in the development of wind farms. Understanding the seasonal fluctuations in wind speed and direction throughout the year significantly influences the economic viability of such projects [17].

There are some restrictive regions with high wind speeds that are not always ideal for wind farms, including locations like lakes and roads [18]. These factors pose the initial challenge in the decision-making process, diminishing the appropriateness of wind farms in the targeted location [19]. The unsuitable geological placement of wind farms has caused several negative effects, such as noise, shadow flicker, and the disruption of habitats, impacting the daily lives of nearby residents and the local ecosystem [20,21]. To examine the negative impact on humans, studies have been conducted to analyze the wind turbine syndrome and its historical context, evaluating the impact of wind turbine noise on health quality, sleep, and health [22–24]. The negative effects of wind turbines have been reported on wildlife. Birds are the most affected groups by collision with wind turbines, which also cause habitat losses in their movement corridors [25,26].

The typical lifespan of a wind turbine is around 20 years, and establishing wind farms involves significant costs. As a result, the process of choosing suitable locations is crucial for maximizing the return on this investment [27]. The substantial capital investment required for wind farms is another critical factor to consider, encompassing expenses for equipment, transmission lines, land usage, and maintenance. This makes wind energy more costly in comparison to fossil fuels. Selecting a site that aligns with the financial expectations of investors is one of the most crucial steps in the project development process. In other words, identifying economically viable and efficient locations for wind power generation is a costly endeavor influenced by various factors. The identification of such sites is linked to their wind potential, along with numerous other restrictive, economic, environmental, and social considerations that must be taken into account [28].

The process of selecting a site for a wind farm to achieve sustainable energy goals encompasses various factors, including socio-economic, geographic, ecological, and environmental considerations. The multi-criteria decision-making approach is effective in addressing complex and often conflicting issues (such as pros, cons, risks, and benefits) and is well suited for providing ranked alternatives for site selection [19]. The geographic information system (GIS) is a robust tool for gathering, storing, managing, analyzing, processing, and mapping geographic data. It plays a vital role in assessing potential sites and selecting locations for wind resources due to its capability to provide an indicator database and visual maps [18,29,30].

An essential topic of discussion among scientists and policymakers is the optimal location for wind power generation facilities. Addressing this issue is complex because of the trade-offs involved in sustainability. A sustainability trade-off means that achieving one sustainability goal may hinder the fulfillment of another. For instance, placing wind turbines in areas with the strongest wind resources to reduce generation expenses often conflicts with efforts to minimize other costs associated with the energy system [31–33].

Together with the optimal site selection, the recent technologies and challenges which affect wind energy generation and improving different turbine efficiencies are the research topics studied by researchers and engineers [34–36].

This study aims to examine the critical factors influencing wind turbine site selection and their implications for maximizing energy production while minimizing environmental disruptions and achieving sustainable energy. By thoroughly investigating site selection criteria such as wind potential, topography, environmental sensitivities, local community engagement, and legal frameworks, this research seeks to contribute insights into the development of effective wind energy projects that align with sustainability objectives. Through this exploration, we hope to contribute to more effective planning and implementation strategies that enhance the sustainability and efficiency of wind energy systems.

2. Wind Energy

The utilization of wind energy dates back to ancient times. Early humans who discovered wind power initially harnessed it for sailing ships and windmills. As fossil fuels have gradually depleted and their detrimental environmental impacts have become more apparent, alongside advancements in technology, the demand for wind energy has increased, positioning it as a significant source for meeting energy needs over time. Wind energy plants are also identified as one of the suitable energy production methods for sustainable energy projects.

As one of the renewable energy sources, wind energy is regarded as an eco-friendly energy resource that converts wind movement into electrical energy. Like other renewable energy sources, wind energy contributes to clean energy production, sustainability, energy independence, and economic benefits.

Wind energy plants utilize atmospheric wind as a resource for energy production, thereby minimizing environmental impacts and reducing greenhouse gas emissions while generating clean energy. The transition to wind energy not only helps mitigate climate change but also supports the movement decarbonization, which is vital for preserving ecological integrity and ensuring a sustainable future.

The continuous availability of energy as long as wind exists signifies its status as a sustainable energy source. Compared to depleting resources like fossil fuels, wind energy represents a more sustainable option. In addition, the scalability of wind energy technology allows for a range of applications, from small-scale residential installations to large offshore wind farms, making it adaptable to diverse energy needs.

Thus, wind energy plays a significant role in achieving low carbon targets, rendering energy production processes environmentally friendly and sustainable and effectively combating climate change as a domestic resource. Integrating wind energy into energy strategies will support energy security and reduce the dependence on fossil fuels.

On the other hand, wind energy also presents various challenges, such as its impact on landscapes, the potential disruption of bird migration routes, and noise pollution [37]. Therefore, it is essential to consider these factors when planning wind energy projects. Comprehensive environmental impact assessments and stakeholder engagement can help mitigate negative effects, ultimately leading to the successful implementation of wind energy initiatives.

Working Principle of Wind Turbines

The most important part of generating electricity with wind energy is the wind turbine. Wind turbines have a system consisting of three main parts [38]. These parts are the tower, rotor, blades, and nacelle, as seen in Figure 1.

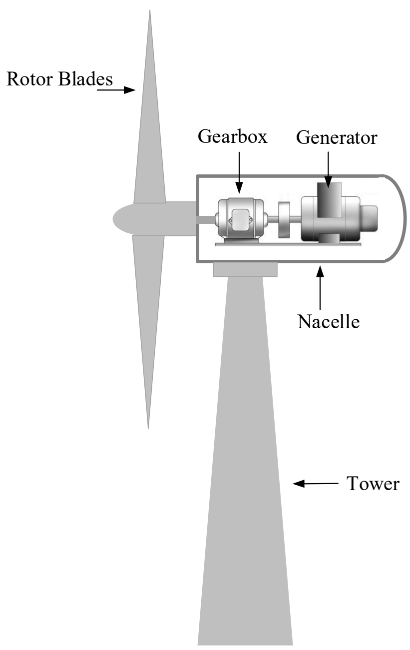


Figure 1. Wind turbine and content.

In a wind turbine, the blades start to rotate under the influence of the wind or air flow. The blades are connected to a shaft called the hub, which is called a rotor. The rotor is connected to a gearbox, which is connected to the generator. At the generator output, the electrical energy produced is delivered to consumers via a transmission line or storage system, completing the process.

There are many factors that affect wind turbine efficiency. These factors include technical parameters such as rotor diameter and blade design, gearbox and generator efficiency, the maintenance and operation of equipment, and environmental factors such as wind speed, direction, and site selection. Therefore, these factors should also be taken into account during the preparation, placement, and operation of a wind turbine project.

3. Determination of Wind Turbine Location

The selection of a wind farm location seeks to optimize energy production while also reducing costs and minimizing impacts. This process takes into account technical, economic, social, and environmental factors to assess whether the specified criteria are fulfilled. The decision-making phase of a wind turbine project is a critical point where basic decisions are made such as whether the project will be implemented, whether it will be financed, and whether the implementation process will be initiated. During the preparation phase of the project, the economic, technical, financial, and legal feasibility report of the project is prepared, and an investment decision is made or not based on the results of the report.

A feasibility study is a detailed analysis conducted to evaluate the potential of a wind energy project, identify risks, and make strategic decisions for the successful implementation of the project. With a feasibility report, the difficulties that will be encountered in the event of the project being realized are determined in advance, and clear information about the potential of the project is obtained. The flow diagram for the preliminary evaluation process is shown in Figure 2.

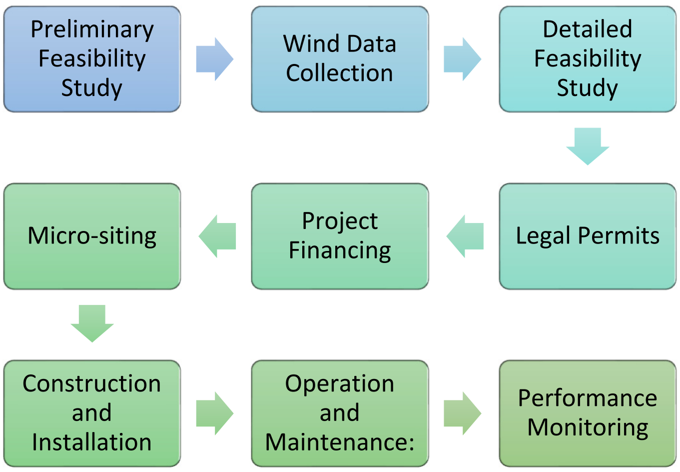


Figure 2. Preliminary evaluation process.

The location of a wind turbine has a direct impact on the efficiency, performance, and economic return of the turbine. The most basic input for wind turbines is wind speed. It is important for the wind to have a constant and continuous direction. Regular- and high-speed wind areas allow for more energy production. On the other hand, factors such as bird paths, shading, local habitats, and environmental effects also affect the efficiency of turbines. Therefore, wind turbine projects are created at the end of the process, in which many parameters are considered together.

As summarized in Figure 3, there are many factors to consider when choosing a wind turbine location. The evaluation of wind data, the examination of geographical features, the assessment of environmental impacts, the accessibility of infrastructure, and the examination of legal conditions are among the important issues. In addition, after determining the potential areas where the wind turbine will be installed, reconnaissance trips can be made to the area and information can be obtained from the local people who are familiar with the area.

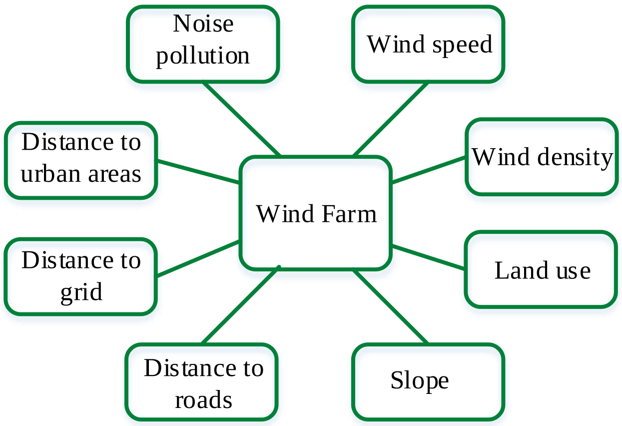


Figure 3. Factors affecting wind farm site selection.

3.1. Review of Legal Factors

The legal factors in the site selection of wind turbines are crucial for the realization and sustainability of the project. These factors encompass various legal requirements that must be considered throughout the planning, permitting, construction, and operational phases of the project.

Wind turbine projects typically require permits from official planning authorities. In addition to these permits, many countries mandate an environmental impact assessment (EIA) for large-scale wind energy projects. This assessment evaluates the potential environmental impacts and includes recommendations for mitigating any adverse effects.

In addition to the permitting and approval processes, the ownership status of the land where wind turbines are to be installed, as well as urban planning considerations, are of significant importance. It is also essential to assess the noise and visual impacts that may arise from the installation of wind turbines and to comply with occupational health and safety regulations. Furthermore, attention must be paid to the restrictions or prohibitions regarding the construction of wind turbines within or near national parks, natural reserves, military zones, and other protected areas.

Legal considerations have a significant role in the site selection process for wind turbines, and these considerations can vary widely across different jurisdictions. These legal frameworks for wind turbine site selection can be grouped under the titles of federal regulations, state regulations, and local regulations. The interplay between federal, state, and local regulations creates a complex landscape that varies significantly across jurisdictions, affecting both the feasibility and timeline of wind turbine installations [39].

3.2. Examining Societal and Social Impacts

Community acceptance and support are critical factors in the site selection process for wind turbines. The attitude of local communities toward the project, including their positive perceptions and backing, plays a decisive role in the successful implementation of wind energy initiatives. Therefore, consultations and informational meetings with the community during the project planning phase are essential for building social trust and addressing any concerns that may arise. Additionally, incorporating local employment opportunities during the construction and operational phases of wind energy projects can contribute to the local economy and stimulate economic activity. This, in turn, is likely to enhance community support for the project in the region.

The site selection for wind turbines should be conducted in a manner that minimizes adverse impacts on wildlife and natural ecosystems while also ensuring the protection of cultural and historical heritage present in the areas where the turbines are to be installed. It is essential to respect the cultural values of the local communities in this context. Environmental impact assessments (EIAs) and conservation measures undertaken for this purpose should ensure that projects are implemented without disrupting the ecological balance.

On the other hand, the noise generated by wind turbines during operation can have adverse effects on local communities. To prevent a decline in the quality of life for residents, it is crucial to maintain an adequate distance between wind turbines and populated areas, as this significantly mitigates noise impacts. Consequently, it is generally recommended that the distance between turbines and residential areas be at least 500 to 1000 m. In addition to distance regulations, advanced turbine designs, sound insulation technologies, artificial sound barriers, and measures to suppress aerodynamic and mechanical noise can also be employed to further minimize noise pollution.

Furthermore, although individuals residing in areas designated for wind turbine installation may not serve as direct sources of data regarding wind energy potential, they can provide valuable feedback and insights in various aspects. This information can be critical for understanding the project's social acceptance, environmental impacts, and health and safety issues, as well as social effects related to esthetics and noise.

3.3. Examination of Geographical Features and Environmental Impacts

Geographical features hold significant importance in the site selection process for wind turbines, as they directly affect the efficiency, structural durability, and economic sustainability of the turbines.

When considering the influence of wind flow, variations in wind speed and direction, turbulence effects, accessibility, and seasonal changes, it becomes evident that geographical characteristics are a critical factor in planning wind energy projects and the placement of turbines. Proper analysis of these features will ensure that wind turbines operate at maximum efficiency and have a prolonged lifespan.

3.3.1. Wind Speed Variations

Wind speed is a primary factor influencing turbine power generation. The power output of a turbine is proportional to the cube of the wind speed, meaning small changes in speed can lead to substantial differences in energy production. For instance, at lower wind speeds, turbines may operate below their rated capacity, while at higher speeds, they may reach or exceed this capacity. However, excessive wind speeds can lead to turbine shutdowns to prevent damage, thus limiting energy production during high-wind events.

3.3.2. Wind Direction and Shear Effects

Changes in wind direction, particularly directional shear (the change in wind direction with height), can adversely affect turbine performance. Studies indicate that significant directional shear can lead to power losses exceeding 10% during specific conditions, particularly when the wind veers clockwise [40]. This effect is compounded by the presence of other turbines, which can create complex wake effects that further alter the incoming wind profile [41].

Research shows that turbines experience different performance levels based on the degree of directional shear. For example, large veering angles are associated with more significant performance losses compared to smaller backing angles. This suggests that understanding and modeling wind direction changes at various heights is essential for accurate energy production forecasts.

3.3.3. Turbulence Intensity

Turbulence intensity refers to the fluctuations in wind speed that occur due to atmospheric conditions. High turbulence can lead to both positive and negative impacts on turbine performance, such as the following:

- Positive effects: at lower wind speeds, increased turbulence intensity may enhance power output by allowing for a more uniform flow over the rotor blades [42].

- Negative effects: Conversely, high turbulence can lead to extreme loads on turbine components and reduce overall efficiency. It is associated with unstable atmospheric conditions where abrupt changes in wind speed can create challenges for turbine operation [43,44].

High-altitude regions typically experience stronger and more consistent winds, making mountain peaks or summits ideal locations for wind turbines. Similarly, hills, valleys, plains, and other landforms also influence wind flow. For instance, turbulence often occurs on the leeward side of hills (the side opposite to the direction of the wind), and high turbulence can damage the mechanical components of the turbines, thereby reducing energy production.

Obstructions such as buildings, trees, and other structures can alter the speed and direction of the wind. In areas with numerous barriers, wind flow can become irregular, adversely affecting turbine performance. Conversely, unobstructed surfaces allow for higher wind speeds. Therefore, expansive open areas where wind can flow freely are more suitable for wind turbines. In such areas, wind speeds tend to be more stable and stronger, leading to improved turbine performance.

Additionally, landforms and accessibility, as well as infrastructure (such as roads and power lines), are crucial considerations. Rugged or hard-to-access terrains can increase construction costs, while flat land facilitates the foundational construction of turbines, thereby reducing costs.

Moreover, the potential sites for turbine installation should also take into account bird migration paths, migratory routes, natural habitats, and protected species.

Another reason why geographical features are pivotal in obtaining wind models is due to seasonal variations. In different geographical regions, wind speed and direction may change according to the seasons. In some areas, winds may be stronger in the summer months, while in others, they may peak in winter. These fluctuations affect annual energy production forecasts and turbine placement strategies. Power curves, which indicate the amount of energy turbines can generate at specific wind speeds, are utilized to estimate energy production. Consequently, employing wind models that account for geographical factors allows for the prediction of future wind conditions using wind atlases specific to the region, historical wind data obtained from meteorological stations, and climate models.

3.4. Evaluation of Wind Data

The assessment of wind data is critical to the success of a wind turbine project. These data are utilized to determine the wind potential and variability of a specific region.

In a potential site for a wind turbine project, a wind measurement system should be established to measure and record wind speed. For this, anemometers are installed at various heights to collect data on wind speed. Concurrently, wind vanes are employed to ascertain the wind direction, which is crucial for the orientation and placement of the turbine. The anemometers and wind vanes are positioned at heights close to the planned rotor height of the turbine (e.g., 10 m, 30 m, 60 m).

The power available in the wind P_{wind} is given by the kinetic energy of the moving air in (1).

$$P_{wind} = \frac{1}{2}\rho A V^3 \quad (1)$$

where

ρ is the air density (approximately 1.225 kg/m^3 at sea level);
A is the swept area of the turbine blades, ($A = \pi R^2$), with R being the radius of the rotor;
V is the wind speed (m/s).

The actual power $P_{turbine}$ that can be extracted by the wind turbine is given by (2).

$$P_{turbine} = \frac{1}{2}\rho A V^3 C_p \quad (2)$$

where C_p is the power coefficient, a dimensionless number representing the efficiency of the turbine in converting wind energy to mechanical energy. The maximum theoretical value of C_p is 0.593 (known as the Betz limit), but real turbines typically have C_p values between 0.3 and 0.5 [45].

The power generated by a wind turbine is influenced by the wind speed that impacts its blades. However, the relationship between power and wind speed is not directly proportional, as can be seen in Table 1, which shows the manufacturer data for a 60 kW wind turbine [46].

Table 1. Wind speed and power of a wind turbine.

Wind Speed (m/s)	1	2	3	4	5	6	7	8	9	10	11	12	13
Power (kW)	0.0	0.0	1.7	6.0	13.0	24.5	38.0	52.5	58.7	59.7	59.9	59.9	59.9
Wind Speed (m/s)	14	15	16	17	18	19	20	21	22	23	24	25	
Power (kW)	59.9	59.9	57.5	55.0	52.0	49.1	46.8	45.0	43.0	42.0	41.0	40.5	

Each turbine has its own characteristics. To accurately calculate the output of a particular turbine at a specific wind speed, it is required to use its power curve. Figure 4 shows the power–speed characteristics of NPS Northern Power NPS 60-24 60 kW wind turbine with a 24.4 m diameter constructed by Northern Power Systems in Reno at Italy [46].

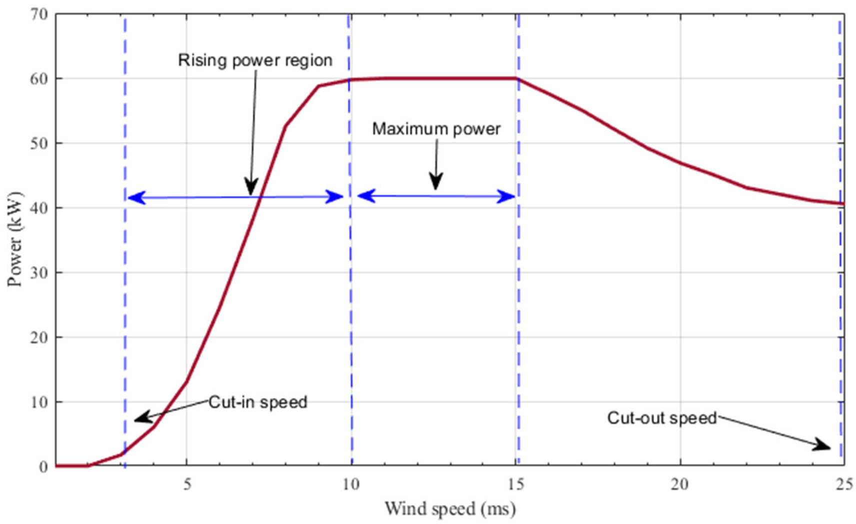


Figure 4. Power–speed curve of Northern Power NPS 60-24 wind turbine.

The power–speed characteristic of a wind turbine describes how the output power changes with wind speed. This curve is generally divided into four key regions as follows:

- Region 1 (cut-in wind speed): The minimum wind speed at which the turbine starts to generate power. Below this speed, power output is zero. The cut-in wind speed in Figure 4 is 3 m/s.
- Region 2 (rising power): between the cut-in speed and the rated speed, the power output increases with the cube of the wind speed, following the equation mentioned above.
- Region 3 (rated power plateau): When the wind speed reaches the rated speed, the turbine operates at its maximum rated power. This region represents a constant power output, achieved by adjusting the blade pitch or using control systems to avoid overloading.
- Region 4 (cut-out wind speed): If the wind speed exceeds a certain limit (the cut-out speed), the turbine is shut down to prevent mechanical damage, and the power output drops to zero. The cut-in wind speed in Figure 4 is 25 m/s.

Once the measurement devices are installed, continuous data collection occurs over a period of six months to one year. This duration allows for a comprehensive understanding of seasonal variations and regional wind patterns. The gathered data are systematically recorded at regular intervals, resulting in the creation of a comprehensive dataset.

By analyzing the obtained dataset, which includes the average wind speed, speed and direction distribution, and turbulence intensity, a more accurate evaluation of the temporal variations in wind speed and direction can be achieved. Consequently, this facilitates the selection of the most suitable turbines, ensuring that the installation and alignment processes are carried out with optimal efficiency. Additionally, these data can also be used to generate annual energy production forecasts.

Wind power and frequency play crucial roles in the site selection process for wind turbines. Understanding these concepts helps optimize energy generation, ensuring that wind farms are both economically viable and environmentally sustainable. The potential for generating wind energy at a site is primarily determined by the wind speed, which is measured in meters per second (m/s). Higher average wind speeds correlate with greater energy production potential. Wind power density (WPD) is a critical metric that combines wind speed with air density to estimate the amount of power available in the wind per unit area. It is typically expressed in watts per square meter (W/m^2). Wind frequency refers to how often specific wind speeds occur at a location over a given time period. These data are crucial for predicting energy output and determining the suitability of different turbine models. For instance, if a location has frequent high winds, it may be appropriate to install larger turbines that can capture more energy. Typical average wind powers and frequencies are listed in Table 2.

Table 2. Average wind powers and frequencies.

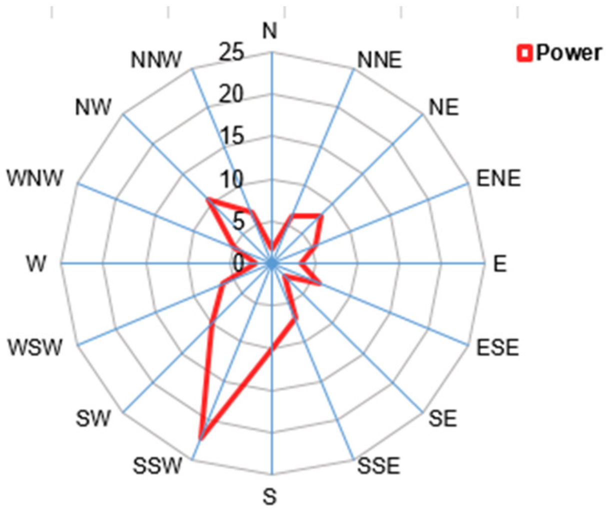
Direction	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Frequency	9.8	32.1	8.6	1.5	5.6	1.6	7.5	13.1	6.6	2.2	0.9	1.1	3.7	13.4	9.0	4.0
Power	1.7	5.98	6.94	5.52	3.45	3.56	9.89	14.95	22.31	10.92	1.04	6.32	2.07	5.06	10.7	6.55

Figure 5a,b shows the wind rose representations of the power and frequency with directions, respectively. A wind rose is a graphical representation that illustrates the frequency and direction of wind at a specific location over a defined period. Understanding a typical wind rose in terms of power and frequency is essential for optimizing wind turbine site selection and predicting energy output. The wind rose given in Figure 5 includes 16 cardinal directions, with each segment spanning 22.5 degrees. Each spoke represents a specific wind direction. In Figure 5a, the wind power with respect to directions is represented. The power rose illustrates the average power per square meter for each direction. This information is vital for determining which directions contribute most effectively to overall energy production. In Figure 5a, the direction SSW seems to contribute most of the energy generation for this location.

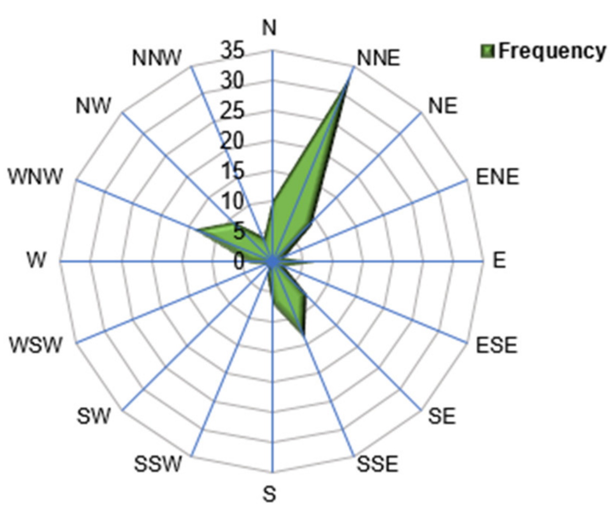
In Figure 5b, the length of each spoke indicates how often the wind blows from that direction. Longer spokes indicate higher frequencies of wind from that direction, which is NNE in this figure.

Although the dominant wind direction is seen to be from the NNE, the highest power density, as observed, is in a different direction, SSW, highlighting that power generation does not solely depend on the average wind direction [45].

Understanding which directions provide sufficient wind speeds is crucial for maximizing energy production. By analyzing the lengths of the spokes, developers can identify prevailing wind directions that contribute the most to energy generation. A dominant direction suggests that turbines should be oriented toward that direction for optimal performance.



(a)



(b)

Figure 5. Wind rose representation of (**a**) power and (**b**) frequency.

3.5. Utilization of the Griggs–Putnam Index

Prior to conducting technical measurements, the observation of natural elements can provide insights into wind direction and intensity. Figure 6 presents an AI-generated visual that serves as a preliminary indicator for determining wind direction and intensity based on the behavior of trees, rocks, and shrubs.

Figure 6. Observation of wind direction and intensity on trees.

The Griggs–Putnam Index, developed through the research of R.F. Griggs and P.C. Putnam, is a tool used to assess wind energy potential for the installation of wind turbines [47]. This index was specifically designed to predict wind speeds and aid in the planning of wind energy projects.

The Griggs–Putnam Index serves as a method for evaluating wind energy potential, grounded in the observation of how plants, such as trees and shrubs, are affected by wind. It enables the estimation of wind speeds in a particular area by analyzing the shape and damage experienced by vegetation due to wind exposure.

For instance, in regions where wind consistently blows in one direction, the inclination of trees toward that direction or the growth patterns and orientations of plant branches can be utilized to predict the strength and direction of the wind. Similarly, signs of desiccation and burn marks on the leaves and branches of trees and shrubs, caused by strong winds, may indicate a high intensity of wind in the area. Additionally, branch breakages provide information regarding wind intensity, while the uprooting or damage of tree roots, particularly in loosely packed soils, may signal elevated wind speeds. Furthermore, in areas where wind is particularly fierce, a decrease in plant density may occur or certain species may become dominant due to their greater resistance to wind.

The application of the Griggs–Putnam Index involves specific steps to observe the effects of wind on vegetation. Initially, the impacts of wind on plants in the area are observed and data are collected. Subsequently, the gathered observations are classified according to wind speed. Finally, these observations and classifications are analyzed to predict wind speeds, thereby determining the wind energy potential of the region.

As illustrated in Figure 7, which includes side views and the top views of the tree, the Griggs–Putnam Index is based on the degree of response exhibited by trees to wind [47].

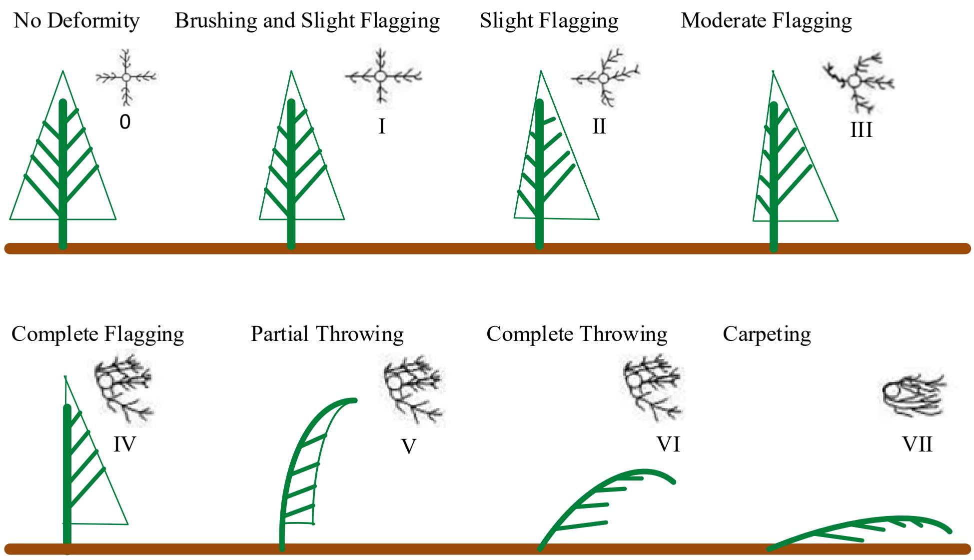


Figure 7. Griggs–Putnam Index [48].

As shown in Table 3, this response degree is categorized into seven classes, which are used to classify wind speeds ranging from 3 m/s to 25 m/s based on the deformation observed in the trees [48,49].

Table 3. Griggs–Putnam Index [48].

Index	**0**	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**
Wind Speed (m/s)	1–3	3–4	4–5	5–6	6–7	7–8	8–9	10+

3.6. Investigation of the Flagging Effect

In wind turbines, turbulent airflow can form around the rotor blades, resulting in irregular air movements known as flagging. These turbulent airflow patterns occur behind the wind turbines, specifically on the leeward side, and can significantly impact the performance and structural integrity of the turbines. This phenomenon creates low-pressure areas behind the turbine blades, resulting in turbulent flows that extend over a certain distance.

The flagging effect arises not only from airflow and wind speed but also due to the aerodynamic characteristics of the blades. Sudden changes in wind speed and direction can exacerbate turbulence, meaning that both the velocity and direction of the wind influence the severity and impact of the flagging effect. The wind turbine blades disrupt the airflow, leading to changes in direction that generate irregular and turbulent airflows behind the blades.

Turbulent airflows can impede the optimal speed and angle of rotation of the rotor blades, potentially diminishing the energy production efficiency of wind turbines. Furthermore, these turbulent flows can impose irregular loads on the turbine blades and other components, resulting in structural wear and an increased need for maintenance. In wind farms, where turbines are installed in proximity to one another, the flagging created by one turbine can adversely affect the performance of the turbines positioned behind it, leading to decreased energy output and structural degradation.

To mitigate the negative effects of flagging, careful consideration must be given to turbine placement, technological improvements, and environmental factors.

Maintaining adequate spacing between wind turbines and nearby homes can help alleviate the impacts of flagging. For this purpose, it is recommended that the distance between turbines be six to ten times the diameter of the turbine rotor [50]. Turbines need to be placed at this distance from other buildings and structures to ensure safety and avoid hindering wind flow. A typical space between a home and wind turbine is represented in Figure 8 [51]. For safe operation, the height of the turbine blade from the ground needs to be two times and the distance between the turbine and the nearby homes or obstacles needs to be about twenty times the obstacle height (H).

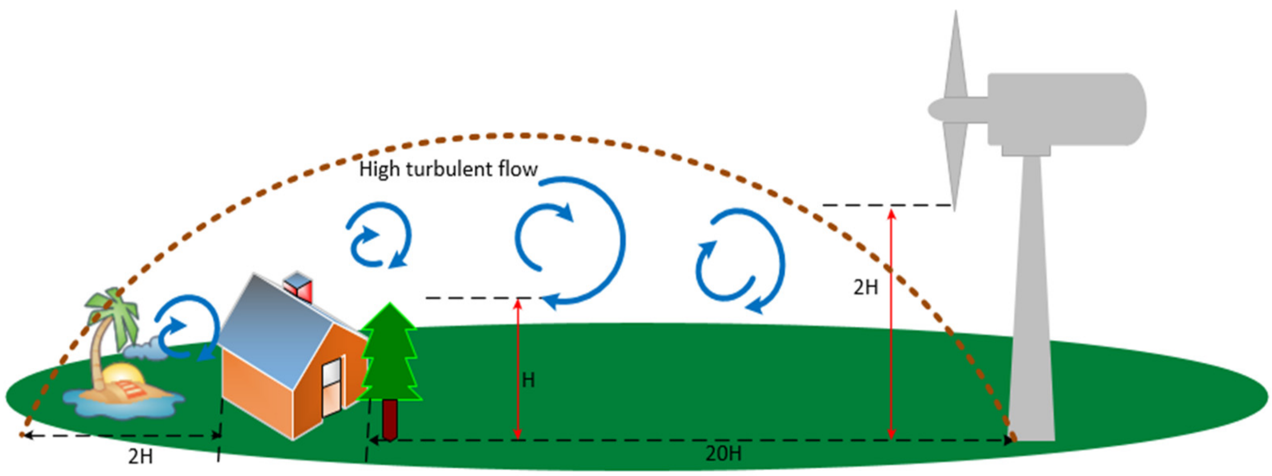


Figure 8. Obstruction of the wind by nearby objects.

In addition to ensuring optimal spacing, the layout of the turbines, advancements in rotor designs that improve aerodynamics, and the development of intelligent control systems to optimize the angle and speed of the rotor blades can all contribute to the reduction in turbulence. A wind rose diagram, as in Figure 5, can be used to visualize how often different wind speeds occur at a site. Understanding this distribution helps predict when flagging might occur.

Another factor that affects the distance from the wind turbine is the potential range of the flying fragments from blades, such as ice blocks or broken turbine blades. This potential range is based on several factors, including the size and mass of the fragments, the angle of ejection, and environmental conditions such as wind speed. Ice fragments can be thrown considerable distances from a wind turbine. Studies indicate that under a 20 m/s wind speed, ice can be thrown 350 m away from the turbine [52]. The blade debris may reach up to 518 m depending on the various factors. The distance that fragments can be thrown is influenced by the initial velocity, release angle, and the mass and shape [53–55].

3.7. Micro-Siting

Micro-siting refers to the process of determining the optimal locations for the placement of wind turbines within wind energy projects. The primary objective of micro-siting is to maximize the efficiency of the turbines and, consequently, the overall energy production.

To achieve this goal, data related to wind speed, direction, and density variations are analyzed to identify the locations where turbine efficiency will be at its peak. During the micro-siting process, it is crucial to consider various topographical features that directly influence wind flow, such as terrain slope, elevation differences, and physical obstacles like buildings and trees, as changes in wind direction or turbulence can adversely affect turbine performance [56].

Another significant factor in the micro-siting process is the distance between turbines. To minimize interaction and turbulence between turbines and to prevent efficiency losses, it is essential to optimize the spacing between them. Although this distance may vary depending on factors such as terrain, wind conditions, and turbine design, it is generally established that the distance between turbines should be 6 to 10 times the blade diameter (D) [57], as represented in Figure 9.

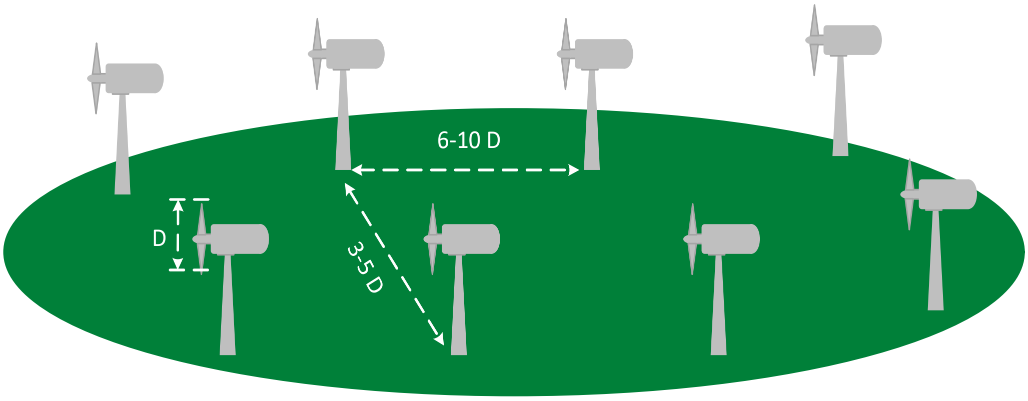


Figure 9. Spacing between wind turbines.

4. Discussion

The site selection for wind farms is a multifaceted process, where several factors must be carefully evaluated to ensure optimal performance and sustainability. Based on the investigations on site selection for wind farms, four groups of factors containing social, economic, terrain, and ecological variables are concerned, as represented in Figure 10.

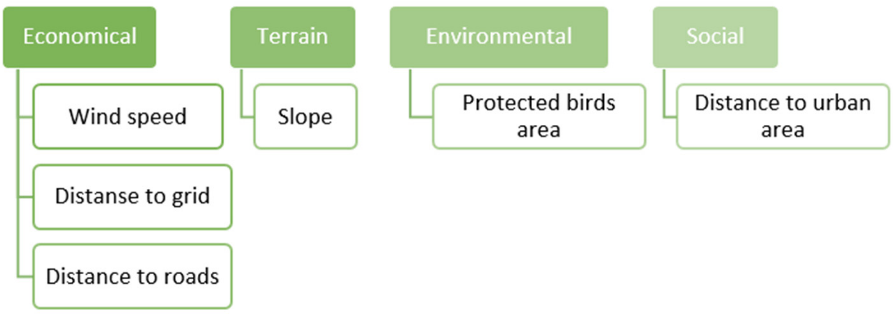


Figure 10. Factors affecting wind turbine site selection.

The relationship between these factors is integral to the successful implementation of wind energy projects, ensuring they operate at maximum efficiency while minimizing ecological disruption. In addition, the success of a wind energy project significantly depends on the stages involved, starting from early planning and extending to pre-investment analysis. Figure 11 shows the phases of a wind energy project before investment [58].

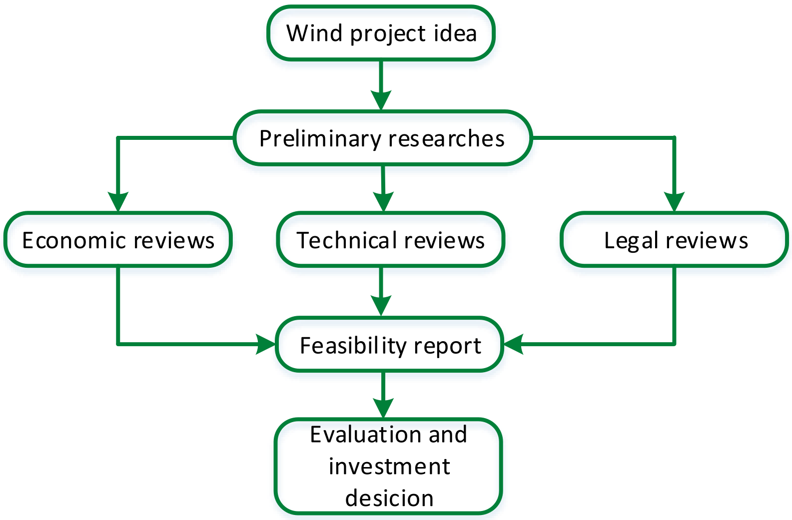


Figure 11. Wind energy project stages.

5. Conclusions

In an era marked by increasing energy demands and the looming threats of globalization, the reliance on renewable energy sources has become crucial for ensuring environmental sustainability and energy security. This paper has addressed significant challenges, such as the depletion of fossil fuels and the consequent urgency for sustainable alternatives. The shift toward renewable energy sources, particularly wind energy, is essential not only for environmental protection but also for enhancing energy independence. Wind energy, as a clean and renewable source, plays a pivotal role in the global energy transition, providing a viable solution to mitigate climate change and reduce greenhouse gas emissions.

This study highlights the critical importance of site selection in wind energy projects, emphasizing its profound impact on project efficiency, sustainability, and environmental compatibility. Key factors such as wind potential, topographical features, environmental sensitivities, community interactions, legal permits, and available infrastructure must be meticulously evaluated to optimize the performance of wind turbines.

Moreover, the findings underscore that proper site selection is not merely a logistical consideration but a fundamental component of the strategic planning necessary for the success of wind energy initiatives. By carefully analyzing and selecting appropriate locations for wind turbines, stakeholders can enhance energy production, foster community support, and ensure compliance with environmental standards.

To meet the energy needs of the planet while protecting its ecological integrity, the transition to renewable energy sources must be prioritized. This study reinforces the necessity of thorough and informed site selection processes in wind energy projects, ultimately contributing to the global energy transformation. It calls for collective action from governments, industries, and communities to embrace sustainable energy practices and prioritize the careful planning of wind energy projects for a greener, more resilient future.

Future studies can be carried out focusing on developing advanced site assessment tools that integrate real-time data, climate modeling, and machine learning to optimize wind turbine placement. Collaborative efforts should also be essential among policymakers, engineers, and local communities to align siting strategies with global sustainable energy goals, particularly in the face of evolving environmental challenges and energy demands.

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Data Availability Statement: The data presented in this study are openly available in Wind Turbine Models, reference number [46].

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