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Research Article

Harvesting the Wind: A Study on the Feasibility and Advancements of Wind Energy in Turkey

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Abstract

This research delves into the potential of wind energy, drawing on recent studies to explore its advantages and disadvantages. The study will begin by providing a comprehensive explanation of the concept of wind energy, followed by an in-depth analysis of wind turbines, which are key components of wind power plants. This will involve a discussion of the various types of wind turbines and their individual characteristics. The research will also examine Turkey's wind and wind energy potential, providing valuable insights into the country's renewable energy prospects. In conclusion, the findings of this study will be used to propose recommendations for the development of wind energy in Turkey. Overall, the study aims to highlight the significance of wind energy as a clean, abundant, and sustainable source of power, and to explore ways in which it can be harnessed to meet the energy needs of the future.

Keywords: Wind Energy, Wind Turbines, Wind Technologies, Turkey's Wind Potential, Wind Power.

Rüzgarı Hasat Etmek: Türkiye'de Rüzgar Enerjisinin Fizibilitesi ve Gelişmeleri Üzerine Bir Araştırma

Öz

Konvansiyonel yanıcı (fosil) yakıtların (kömür, madeni yağ ve doğal gaz) rezervleri, bugünkü hızla kullanılması halinde 50 ila 200 yıl içinde tükenecektir. Doğal gaz, petrol, kömür veya nükleer gibi konvansiyonel enerji kaynakları sınırlıyken, rüzgar, güneş, biyogaz/biyokütle, jeotermal vb. gibi yenilenebilir enerji kaynakları temizdir ve doğada bol miktarda mevcuttur. Yenilebilir enerji kaynaklarından olan rüzgar enerjisi temiz, emisyonsuz bir enerji üretim teknolojisidir. Rüzgar enerjisi, üstün özellikleri, yenilenebilir enerji, geniş dağıtım ve sıfır kirlilik nedeniyle "yeşil enerji"nin ana destekçilerinden biridir.
Bu çalışma, son yıllarda yapılan araştırmalara dayanarak rüzgar enerjisinin potansiyelini tartışmaktadır. Çalışmada öncelikle rüzgar enerjisi kavramı kapsamlı bir şekilde anlatılacak, rüzgar enerjisi kullanımının avantaj ve dezavantajlarına değinilecektir. Daha sonra rüzgar enerjisi santrali bileşenlerinden rüzgar türbinleri üzerinde durulacaktır. Rüzgar türbinleri türleri ve özellikleri açıklanacaktır. Son olarak Türkiye'nin rüzgar ve rüzgar enerjisi potansiyeli hakkında bilgi verilecektir. Araştırmanın sonuç kısmında ise araştırmada elde edilen bilgilere dayanılarak, Türkiye'nin rüzgar enerjisi gücünün gelişimine yönelik önerilerde bulunulacaktır.

Anahtar Kelimeler: Rüzgar Enerjisi, Rüzgar Türbinleri, Rüzgar Teknolojileri, Türkiye'nin Rüzgar Potansiyeli, Rüzgar Gücü

1. Introduction

As economies continue to industrialize and develop, the demand for energy becomes increasingly vital for progress. The consumption of energy per capita has become a metric for measuring a country's level of economic development on a global scale. The importance of energy as a crucial component for sustained economic and social development is growing. Energy plays a vital role in ensuring continuous growth and economic prosperity (Rogner and Popescu, 2001). The energy sector is a key factor in addressing current global challenges such as sustainable development and climate change. Several studies have highlighted the rising demand for energy, the role of remaining fossil fuels, and the importance of alternative sources. According to the International Energy Agency (IEA), world energy demand is expected to increase by 90% until 2035 if the annual average increase trend persists (Köktürk & Tokuç, 2017). As a result, significant efforts are being made to ensure the sustainability of both exhaustible and renewable energy sources.

In addition to concerns about the sustainability of energy sources, the role of carbon dioxide (CO_2) emissions from fossil fuels in contributing to global warming has been a significant driver for renewable energy. Among the various forms of renewable energy, wind energy has emerged as a widely utilized alternative. The widespread availability of wind resources and the relative convenience of wind energy technology when compared to other renewable energy sources are considered key factors behind this trend (Esteban, Diez, López, & Negro, 2011).

This research focuses on exploring the potential of wind energy based on recent studies. Firstly, the concept of wind energy is comprehensively discussed, highlighting its advantages and disadvantages. Additionally, the role of wind turbines as a crucial component of wind power plants is emphasized, with a detailed analysis of various types of wind turbines and their specific characteristics. The study also provides an overview of Turkey's wind resources and the potential for wind energy development in the country. The research concludes by providing recommendations based on the findings, to promote the sustainable development of wind energy in Turkey.

2. Material and Method

2.1. Wind Energy Concept

Wind is the movement of atmospheric air, and it is formed due to uneven heating caused by the sun's rays hitting the earth's surface, including bodies of water. Wind is a fundamental element of the environment that is present everywhere (Mustafakulov & Arzikulov, 2020). The speed of wind determines its strength, which can range from barely noticeable to powerful and destructive. When wind is strong, it can carry debris and become visible. The power of wind is directly related to its kinetic energy, which increases as the speed of air movement increases. Therefore, the faster the wind is, the more energy it carries, and the more powerful it becomes (Kalmikov, 2017). Wind power as a form of renewable energy that is gaining global attention. It is a clean and widely available source of energy. Wind energy has the potential to generate electricity continuously, making it suitable for systems that require continuous energy supply (Demolli, Dokuz, Ecemis, & Gokcek, 2019). The energy content of wind is referred to as kinetic energy, which is a function of the mass and velocity of the air flow. As the air moves faster, it has more kinetic energy and can generate more power. Therefore, wind energy can be harnessed by wind turbines to produce electricity that can power homes, businesses, and industries (Kalmikov, 2017).

$$KE = \frac{1}{2} \cdot m \cdot U^2$$

The basic equation of wind energy and the difference between power and energy. The basic equation of wind energy determines how much energy is present in the wind. The concepts of power and energy are distinguished, where power is the ratio of energy to time, and it expresses how much energy can be produced per unit time. For instance, in wind energy, power expresses the amount of energy a wind turbine can generate in a given time. The power of the wind is the speed of the energy flow through an open window. This means that the faster the wind, the more energy it carries, and the more power it can generate. Therefore, understanding the basic equation of wind energy is crucial for designing wind turbines and optimizing wind energy production (Kalmikov, 2017). Wind energy is generated based on the movement of air, and it depends on several factors. The amount of air or the volume of considered air is one of the significant factors that influence wind energy production. The velocity of the air, which is the magnitude of its velocity, is also an important factor. The higher the velocity of the air, the more energy can be harnessed from the wind. The air mass, which depends on the volume of air via density, is another factor that affects wind energy (Kalmikov, 2017). The higher the density of the air, the more energy it carries. Wind turbines are used to convert the kinetic energy of wind into electrical energy. The amount of power that can be harnessed from the wind by a wind turbine depends on several factors. These factors include the air density, the swept area of the turbine blades, and the cube of the wind speed along the rotor plane. This means that a wind turbine can generate more power if it has larger blades that capture more wind energy and if the wind speed is high. The air density also affects wind energy production, as it determines how much energy the wind carries (Pryor, Barthelmie, Bukovsky, Leung & Sakaguchi, 2020). Table 1 includes Wind Energy Classes Measured at 50 m Above Ground According to NREL (United States National Renewable Energy Laboratory) Wind Energy Intensity Based Classification (Kalmikov, 2017). Wind energy depends on the amount of air, velocity of the air, and air mass. The power that can be harnessed by a wind turbine is a function of air density, swept area of the blades, and the cube of wind speed along the rotor plane. Table 1 presents typical values of wind power classes with power densities and average wind speeds (Kalmikov, 2017). The average wind power density has advantages over average wind speed for comparing sites with different probability distribution skewness. Wind speed varies with altitude, and wind turbines are typically placed in open plains, hill areas, and coastlines where wind speeds can be high. The power produced by wind turbines is proportional to the cube of the wind speed, meaning that doubling wind speeds results in an eightfold increase in energy production. Wind turbines placed in hilly areas can collect an appropriate amount of wind, and the tunnel effect can increase wind speed by up to 40% (Begeç, 2022). Modern wind turbines are designed to be relatively quiet, and the noise they produce is typically drowned out by the sound of the wind itself on a windy day. In fact, many studies have found that wind turbines do not significantly impact human health or well-being due to noise. Additionally, because wind energy does not rely on the combustion of fossil fuels, it produces no air or water pollution, and it does not generate hazardous waste or contribute to climate change. Overall, wind energy is a relatively clean and sustainable source of electricity that has many environmental benefits. In addition to these benefits, there are some obstacles to large-scale application of wind energy. The barriers (Archer & Jacobson, 2005), there are several other obstacles to large-scale application of wind energy:

-Grid Integration: One of the major challenges associated with wind energy is the intermittent nature of wind. Wind turbines generate power only when wind is blowing, and the power output fluctuates with changes in wind speed. This poses a challenge for integrating wind energy into the grid, as the grid requires a stable and reliable supply of electricity. Solutions to this challenge include energy storage systems, demand-side management, and advanced grid management systems.

-Infrastructure and Transmission: Wind farms are typically located in remote areas, which can pose challenges for infrastructure and transmission. Building the necessary infrastructure, including access roads, electrical substations, and transmission lines, can be costly and time-consuming. In addition, transmission capacity may be limited, which can limit the amount of wind energy that can be delivered to the grid.

-Environmental Concerns: While wind energy is generally considered to be a clean source of energy, there are some environmental concerns associated with wind farms. These include the impact on bird and bat populations, noise pollution, and visual impacts. Addressing these concerns requires careful site selection, technology improvements, and ongoing monitoring and mitigation measures.

-Public Acceptance: Finally, wind energy projects can face opposition from local communities, which may have concerns about the impact on property values, scenic views, and local wildlife. Effective engagement and communication with local communities can help to address these concerns and build support for wind energy projects. In addition to estimating future wind speed values, there are several other ways to assess wind energy resources and design viable wind energy infrastructures:

-Site Selection: The first step in assessing wind energy resources is to identify potential sites with high wind speeds and low turbulence. This requires a detailed analysis of wind patterns, terrain, and other factors that affect wind energy production. Site selection can be aided by advanced modeling tools, such as computational fluid dynamics (CFD) simulations, which can provide detailed information about wind patterns and turbulence.

-Resource Assessment: Once potential sites have been identified, a detailed resource assessment is needed to determine the expected energy output of a wind energy project. This involves installing wind measurement equipment, such as anemometers and wind vanes, to collect data on wind speed, direction, and other variables. Resource assessment can also be aided by remote sensing technologies, such as lidar and satellite imaging, which can provide detailed information on wind patterns and turbulence.

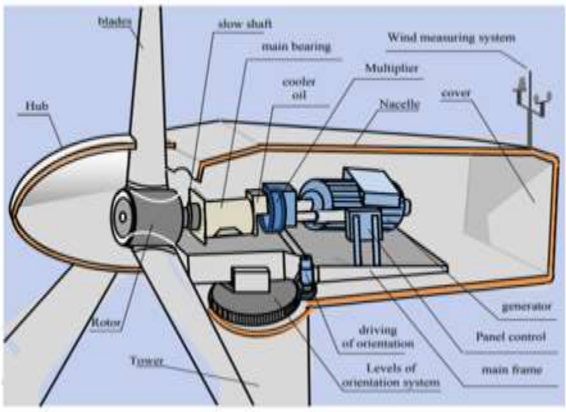
-Technology Selection: Wind energy projects require careful selection of wind turbines and other equipment to ensure optimal performance and reliability. This involves consideration of factors such as turbine size, rotor diameter, and tower height, as well as maintenance and repair requirements.

-Grid Integration: Finally, wind energy projects must be integrated into the electricity grid in a way that ensures stable and reliable power supply. This requires careful planning and coordination with grid operators, as well as the installation of advanced grid management systems and energy storage technologies to mitigate the intermittent nature of wind energy production (Sharifian et al., 2018; Ammar et al., 2018). To assess wind energy resources and design wind energy infrastructures, high-quality and comprehensive wind speed data are required. However, such observational datasets are often rare, insufficient or nonexistent in potential areas for wind energy development. Therefore, modeling approaches are used to overcome these barriers and create useful wind resource guidance. Accurate estimation of wind speed is critical to increase the safety, reliability and profitability of wind farms. Modeling can help to estimate future wind speed values, assess wind patterns and turbulence, select appropriate wind turbine technology, and integrate wind energy projects into the electricity grid. Overall, a comprehensive approach that considers a range of factors is necessary to assess wind energy resources and design viable wind energy infrastructures. In addition to the barriers to implementing wind energy, there are also several disadvantages associated with wind turbines (Demolli, Dokuz, Ecemis, & Gokcek, 2019; Atılgan, 2022). These include their potential to affect electromagnetic waves, the requirement for high hilly areas to generate yield, risks to birds, the risk of overturning and burning, dependence on optimal wind conditions, high initial investment costs, environmental noise, and aesthetic pollution. In addition, wind energy potential is often located in remote areas, requiring extensive transmission lines to connect to the national grid. However, these disadvantages can be mitigated through careful site selection, advanced technology, and effective grid integration. Despite these challenges, wind energy remains a promising source of renewable energy with the potential to contribute significantly to global energy needs. Wind power is an intermittent power supply due to the high stochasticity and low predictability of wind. This intermittency greatly affects the safety and stability of large-scale grid-integrated renewable energy systems, and wind power is also affected by transmission and distribution losses. Planning, management and optimization are the main challenges for the high penetration of renewable energy sources, including wind and solar, in grids of different scales. To overcome these challenges, advanced grid management systems and energy storage technologies can be used to mitigate the intermittency of wind power, and effective planning and management strategies can be developed to optimize renewable energy integration into the grid. Overall, careful planning and effective management are necessary to ensure the safe and stable integration of wind power into the electricity grid (Wang, Zou, Liu, Zhang & Liu, 2021). A wind power plant consists of several basic components including a tower, 2 or 3 bladed wind turbine, mechanism to adjust the direction of the blades/turbine based on wind direction, mechanical gear unit, electric generator, speed sensors and speed control unit, power-electronic unit and control, energy storage systems (especially for off-grid operation), transformer, transmission line and breaker for connection to the local power grid. These components work together to convert wind energy into electricity and transmit it to the grid for distribution.

2.2. Wind turbine

The wind turbine is the most important part of a wind energy system, as it converts wind energy into mechanical and electrical energy. The use of wind energy dates back to AD 644 when windmills were used to lift water. In 1891, Danish inventor Poul La Cour produced electricity in DC form for the first time from a wind turbine, demonstrating the potential of wind energy as a source of electricity. Although wind energy is often considered a new energy source, it has a long history and has been used for centuries to perform various tasks. The development of wind energy technology has significantly advanced over time, and modern wind turbines are highly efficient in converting wind energy into electrical energy (Beig & Muyeen, 2015).

Figure 1. Cross-section view of a horizontal axis wind türbine



There are two main types of wind turbines used to implement wind power systems:

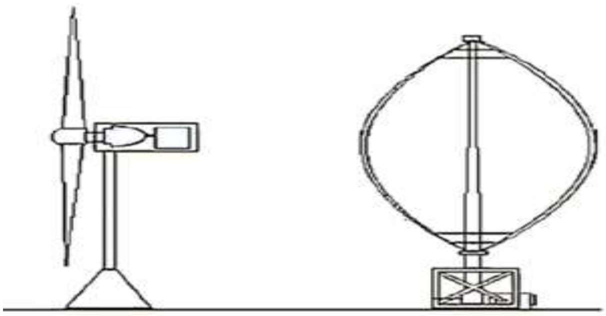
-horizontal axis wind turbines (HAWTs) and

-vertical axis wind turbines (VAWTs).

-HAWTs are the most common.

Horizontal Axis Wind Turbine has horizontal shaft while Vertical Axis Wind Turbine has vertical shaft (Günhan, 2020).

Figure 2. Horizontal and Vertical Axis Wind Turbines



Horizontal Axis Wind Turbine rotation axis is parallel to the ground. These wind turbines are used for large wind farms located both offshore and on land (Günhan, 2020).

Figure 3. Horizontal Axis Wind Turbine

In these wind turbines can be designed with different numbers of blades, with the rotor rotating faster as the number of blades decreases. Fewer blades can theoretically reduce costs, but can also lead to uneven torque. The difference in torque between tri-wing and biplane configurations is approximately 5%. Wind turbines can be manufactured with a single, two, or three blades, with three-bladed turbines being the most commonly used. Three-bladed turbines are preferred due to their ability to generate more uniform torque. In Horizontal Axis wind turbines, the blades of the propeller rotate, the shaft connected to the hub rotates. Opposite the shaft is a gearbox to adjust the speed. The shaft rotating at the specified speed drives the generator. The ratio obtained by dividing the wind speed by the rotor blade tip speed is called the blade tip speed ratio (λ). If; λ= 1–5 multi-bladed rotor, λ=6–8 three-bladed rotor, λ= 9–15 two-bladed rotor, λ>15 single-bladed rotor are used. An important variable of wind turbines is the swept area. In reality wing cost changes with increasing length and power output increases with large swept area. Then it is aimed to maximize the ratio of the swept area according to the wing length.

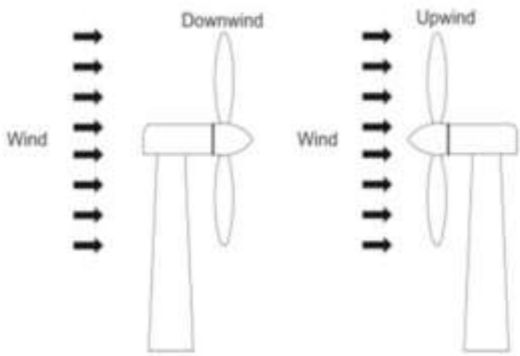
Rotor swept area for horizontal axis turbine;

$$A = \frac{\pi}{4}D^2$$

The wind power generated by a horizontal axis turbine is proportional to the square of the blade diameter, and larger wind turbines are more economical. Turbines with more blades operate at low speeds and have a higher initial power coefficient, but the coefficient decreases rapidly as the speed increases. Turbines with fewer blades operate at high speeds, and the power coefficient takes large values initially, but gradually decreases as the speed increases (Boulouiha, Allali, & Denai, 2017).

The turbine can be in front (downwind) or behind (downwind) the engine compartment.

Figure 4. Turbine wind direction



Horizontal axis wind turbines (HAWTs) can be divided into two categories: lift type and drag type.

Wind wheels driven by drag force

1. Savonius type wind impellers (a.Single blade b.Multi bladed)

2. Lafond type wind impellers

3. Panemone type wind impellers

Wind turbines powered by buoyancy

1. Darrieus type wind impellers

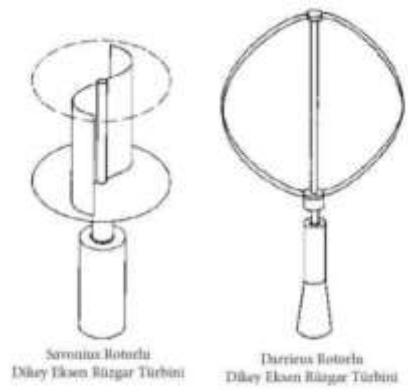
(a. Cylindrical type b. Conical type c. Mixer type)

(c1. Chain Curve (catenary) c2. Parabolic c3. Troposkien c4. Sandia)

2. Cross Flow Wind Wheels

There are different types of wind turbines, including horizontal axis wind turbines with reverse blade designs or swirling features, and vertical axis wind turbines like Darrieus and Savonius. Vertical axis turbines are more complex to manufacture due to their blade structure, but Savonius turbines have lower power efficiency and are suitable for low-power wind energy systems. The main drawback of horizontal axis turbines with swirling features is increased fatigue from wind fluctuations (Yılmaz, 2022).

Figure 5. Vertical axis wind türbine



Some vertical axis wind turbines do not start by themselves and require an external power source. Another type of vertical axis turbine is known as Musgrove blades with H-shaped rotors. For high wind speeds, the rotor blades are rotated around a horizontal point caused by centrifugal force. This eliminates the risk of higher aerodynamic forces on the wings.

Since the area swept by the vertical axis wind turbine (rotor) is not fully circular, it presents a more complex structure. This area is approximately;

$$A = \frac{2}{3} D.H$$

Here;

D: Maximum width of rotor blades

H: Vertical maximum height of rotor blades One of the most important points in wind turbines is the amount of energy to be captured at different wind speeds.

In the design phase of wind power plants, estimates of operating (or outside) conditions are used, including a range of wind parameters (such as wind storm, 50-year rotation period continuous wind speed, and turbulence intensity) to identify fatigue and mechanical overloads. It guides the selection of an appropriate WT class for a particular location (Pryor, Barthelmie, Bukovsky, Leung & Sakaguchi, 2020).

2.3. Wind Energy in Turkey

Turkey's best wind source areas are the Aegean and Marmara coasts, with high wind speeds in the northeast of the Aegean Sea and an area near Antakya. Central Turkey has moderate wind speeds, while the coastal regions of the Central Black Sea and the central part of the Mediterranean Sea also have suitable wind speeds for energy investments (Malkoç, 2008).

According to a report, Turkey has a wind potential of 37.83 MW on land and 10.01 MW at sea, for a total of 47.84 MW at an altitude of 50 m. In the first half of 2020, Turkey produced 11,506,233 kW of electrical energy from wind power, representing 8.5% of the total electricity produced in the country (Özkan, Uslu & Gedikli, 2022).

To evaluate wind energy potential, reliable wind resource data must be obtained through meteorological measurements. In Turkey, wind measurements are made by the General Directorate of Meteorology using Wind Energy Observation Stations at a height of 10-30 m, in one hour and 10-minute intervals, and processed and archived in software programs (Şenel & Koç, 2015).

To effectively invest in wind energy, it is crucial to identify the wind energy potential and prioritize the most suitable wind resource areas. The Wind Energy Potential Atlas (REPA) was developed to provide wind resource information. REPA utilizes medium-scale numerical weather forecast models and micro-scale wind flow models to produce wind resource information. These atlases can be integrated with geographic information systems (GIS), meteorological models, and computer software to provide valuable information about the wind regime on hourly, daily, monthly, seasonal, and annual time scales, helping to determine the most suitable wind resource areas(Malkoç, 2008).

The Wind Energy Potential Atlas (REPA) provides various types of data related to wind resources, which include:

-Annual, seasonal, monthly, and daily wind speed averages at -0, 50, 70, and 100 m altitudes

-Annual, seasonal, and monthly wind power densities at -50 and 100 m altitudes

-Annual capacity factor at 50 m height for a reference wind turbine

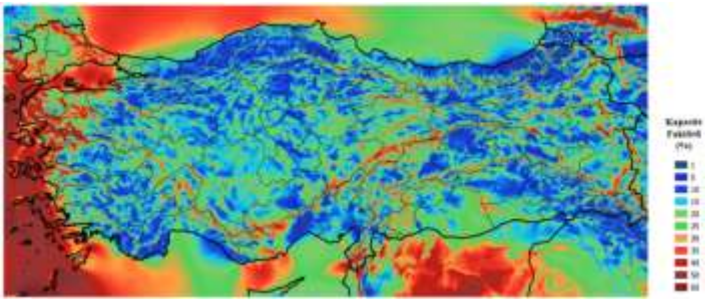
-50 m high annual wind classes

-Monthly temperature values at -2 and 50 m altitudes

-Monthly pressure values at sea level and 50 m altitude

This information is crucial for accurately assessing the wind energy potential of a particular area and determining the feasibility of wind energy investments. With the REPA maps, the areas where wind power plants can be installed have become easily identifiable (Çalışkan, 2019). The Capacity factor distribution map prepared by REPA, taking into account the technical values of a 3 MW wind turbine, is given in Figure 6.

Figure 6. Capacity Factor Distribution (100m) (Source: www.repa.enerji.gov.tr



A capacity factor of 35% or more is required for economic WPP investment. The Distribution of Wind Power Plants in Operation and Under Construction as of 2020 by Regions is given in Table 2.

Table 2. Distribution of Wind Power Plants as of 2020 (Source: Özkan, Uslu & Gedikli, 2022).

Bölgeler	İşletmede Bulunan Santraller		İnşa Halindeki Santraller	
	Kurulu Güç (MW)	Kurulu Güç (%)	Güç (MW)	Güç (%)
Ege	3.511,00	37,73	165,90	8,86
Marmara	3.290,72	35,36	1.487,43	79,45
Akdeniz	1.120,20	12,04	19,20	1,03
İç Anadolu	921,05	9,90	110,40	5,90
Karadeniz	353,80	3,80	7,20	1,92
Güneydoğu Anadolu	93,05	1,00	-	-
Doğu Anadolu	15,20	0,16	53,20	2,84

Table 1. Wind energy classes (Source: Kalmikov, 2017)

Wind power classification			
Wind power class	Source	Wind power Intensity /W.m^{-2}	Wind speed /m.s^{-1}
1	Potential	0-200	0.0-5.9
2	Bad	200-300	5.9-6.7
3	Marginal (borderline)	300-400	6.7-7.4
4	Middle	500-600	7.4-7.9
5	Good	500-600	7.9-8.4
6	Perfect	600-800	8.4-9.3
7	Extraordinary	>800	>9.3

3. Results and Discussion

Wind energy is a clean and renewable source of energy that does not produce any harmful emissions, unlike fossil fuels which are responsible for a significant amount of greenhouse gas emissions. As such, wind energy is seen as a key solution in the global effort to reduce carbon emissions and combat climate change. Many countries have set ambitious targets to increase the share of renewable energy in their energy mix, including wind energy, in order to reach the goal of zero emissions by 2050. Increasing the number of wind measurement stations in Turkey can definitely provide more accurate and reliable data, which will help to better determine the potential of wind energy in the country. The Wind Energy Potential Atlas of Turkey can be updated with this new data and provide a better understanding of the country's wind energy potential. This, in turn, can attract more companies to invest in the sector and promote the use of renewable energy sources, which is a critical step towards achieving zero emissions by 2050. It is important to continue efforts to expand the wind energy infrastructure and encourage the development of more efficient wind turbines to increase the efficiency of wind energy production (Şenel, & Koç, 2015). wind energy has a variable character, meaning that wind speed and direction can fluctuate over time. However, with the help of modern wind turbine technologies and energy storage systems, wind energy can be integrated into the power grid and provide a reliable source of electricity. Additionally, as you mentioned, diversifying energy sources is important to ensure a stable and sustainable energy supply. Wind energy can play an important role in this diversification, along with other renewable energy sources such as solar, hydro, and geothermal (Malkoç, 2008).

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