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ARTICLE

Wind Energy Potential in Turkey's Mediterranean Region: Data-Based Analysis and Sustainable Solutions

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ABSTRACT

This study comprehensively evaluates the wind energy potential of the Mediterranean Region of Turkey and highlights the strategic importance of the area within the context of the country's renewable energy goals. As global energy demands continue to rise and the transition to sustainable energy sources becomes more urgent, identifying and utilizing regional renewable resources is critical. In this regard, the Mediterranean Region stands out with its favorable geographical and climatic characteristics for wind energy generation. Using data from the Global Wind Atlas, the study examines the region's wind speeds and directions across various locations. The analysis reveals that the annual average wind speeds generally range between 5.5 m/s and 7 m/s. These wind speeds are considered technically sufficient for wind energy production, especially along the coastline and in high-altitude mountainous zones where the wind conditions are more stable and intense. The findings suggest that targeted wind energy projects could significantly contribute to both local economic development and national energy sustainability efforts. In addition to emphasizing the technical viability of the region, the study recommends increasing infrastructure investments, deploying advanced and regionally appropriate turbine technologies, and fostering collaboration with local communities to enhance project acceptance and effectiveness. Overall, the research supports the development of informed policies and investment strategies aimed at maximizing the region's wind energy potential. It

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provides a valuable framework for stakeholders interested in leveraging renewable resources to support Turkey's long-term energy transition goals.

Keywords: Environmental Sustainability; Wind Energy; Renewable Energy; Mediterranean Region

1. Introduction

Energy is an indispensable element for the sustainable development and economic growth of modern societies. The environmental impacts of traditional energy sources, the increase in carbon emissions and the limited reserves of fossil fuels have made it necessary to re-evaluate energy production methods worldwide. In this context, renewable energy sources attract attention by offering sustainable and environmentally friendly solutions. Among renewable energy sources such as wind energy, solar, biomass, geothermal and hydroelectric, it stands out as an option based on clean, economical and innovative technologies. Turkey has an advantageous geographical location in terms of renewable energy production. Wind energy, in particular, has significant potential in regions where geographical and climatic conditions are favorable [1]. The Mediterranean Region has a strategic importance in Turkey's renewable energy policies with its wide coastline, high-altitude mountainous areas and wind profile effective throughout the year. The region offers an ideal area for wind energy investments in terms of both economic development and environmental sustainability. Increasing energy demand worldwide requires ensuring energy supply security and minimizing environmental impacts. Energy production based on the use of fossil fuels leads to serious problems such as environmental destruction, climate change and air pollution [2]. For this reason, renewable energy sources offer environmentally friendly alternatives with low-emission energy production processes. Transforming energy production in Turkey also requires greater use of renewable energy sources and energy efficiency. Wind energy is one of the renewable energy sources with high potential in Turkey. The Mediterranean and Aegean regions in particular stand out as areas where annual wind speeds are between 6–8 m/s [3]. The wind energy potential in these regions offers great opportunities to meet both domestic energy demand and increase energy exports. The Mediterranean Region is a strategic area where wind turbines can operate effectively with winds coming from the sea and high mountain areas. Therefore, the Mediterranean Region has the capacity to meet not only Turkey's but also regional energy needs.

The wind energy potential in the provinces of Çanakkale and Istanbul was examined by Arslan et al. (2020) [4]. The average annual wind speed in Çanakkale is 7.3 m/s and 5.8 m/s in Istanbul. Çanakkale is one of the most efficient wind energy regions in Turkey with its high wind speed. Annual wind power generation in Çanakkale has been estimated at 2.5 TWh. Aydin (2009) [5] conducted a GIS-based analysis of wind and solar energy potential in Western Turkey. In the regions recommended for wind energy, annual wind speeds vary between 5 and 7 m/s. The average daily solar radiation for solar energy is around 4–5 kWh/m^2. The solar energy potential has been calculated as 5 kWh/m^2/day. Badger & Jørgensen (2011) [6] created the global wind atlas, which provides a more accurate estimate of wind potential worldwide. At an altitude of 100 m, areas with wind speeds of 7.5 m/s were determined as the regions with the highest energy production capacity. The global wind energy potential is estimated at 50 TWh per annum. Badger, J. et al. (2015) [7] determined wind speeds between 6–8 m/s at a height of 50 m and identified the most suitable areas for wind turbines in the Global Wind Energy Atlas projects. Çapik et al. (2012) [8] examined the renewable energy potential in Turkey and predicted that the country's wind energy capacity could reach 30,000 MW. Turkey's annual solar radiation for solar energy has been determined as 4–5 kWh/m^2/day. Cetin (2023) [9] examined how wind energy resources in Turkey will be affected by climate change. Current projections predict a 5–15% increase in wind energy potential. Durak & Şen (2002) [10] analyzed the wind energy potential in the Akhisar region. The average annual wind speed in Akhisar was measured as 5.5 m/s. At this rate, the efficiency of wind turbines varies between 30–40%.

Emeksiz & Demirci (2019)[11] predicted that Turkey's non-offshore wind energy potential could reach an annual energy production of 50 TWh. It has been determined that the offshore wind potential is increasing in the Aegean and Mediterranean regions. Genç et al. (2021)[12] selected suitable sites for non-offshore wind energy in Turkey. In the Mediterranean and Aegean Seas, the wind speed was determined to be between 6–8 m/s. Gördü et al. (2022)[13] studied the efficiency of different types of turbines in the Mediterranean region. In regions with an average wind speed of 6.5 m/s, the electricity generation capacity of wind turbines can be up to 2.5 MW. Güngör-Demirci (2015)[14] conducted a map-based analysis of renewable energy potential in Turkey. The regions where renewable energy sources are most efficient are the Aegean and the Mediterranean, with wind speeds ranging from 5–9 m/s in these regions. İlkiliç (2012)[15] calculated Turkey's wind energy potential as 48,000 MW. In western coastal regions such as Izmir and Çanakkale, the wind speed is 7–9 m/s. İlkiliç & Türkbay (2010)[16] conducted a site selection analysis for wind energy potential in Turkey. In western Turkey, the highest productivity is achieved in the Izmir and Manisa regions with a wind speed of 8 m/s. Jahangiri et al. (2016)[17] suggested wind speeds of 6–8 m/s in studies for the optimal locations of solar and wind power plants in the Middle East. Kaplan (2015)[18] stated that Turkey's current wind energy capacity is 8,000 MW, and as of 2020, 10–15% of this capacity can be supplied by non-offshore wind energy. Kaygusuz (2004)[19] discussed the role and future of renewable energy sources in Turkey. It is estimated that renewable sources can meet 25% of Turkey's total energy needs. Keleş & Bilgen (2012)[20] emphasized the importance of using renewable energy sources in Turkey to combat climate change and calculated the solar energy potential as 4.5 $kWh/m^2/day$. Michalena et al. (2009)[21] conducted a renewable energy analysis for the Mediterranean Islands. The solar energy potential was found to be 4.2 $kWh/m^2/day$ and wind energy was found to be between 6–8 m/s. Nassar et al. (2023)[22] created an atlas of solar and wind energy for Libya. Libya's solar energy potential is 5–6 $kWh/m^2/day$ and wind energy is 7–9 m/s. Sánchez-del Rey et al. (2022)[23] assessed the wind energy potential in Spain. Spain's wind potential is around 7 m/s, with an annual production of 15 TWh expected. Soukissian et al. (2017)[24] examined the potential for non-marine renewable energy in the Mediterranean. An annual potential of 3.2 TWh for wind energy in the Mediterranean Sea has been estimated. Şahin & Türkeş (2020)[25] analyzed Turkey's wind energy potential using wind speed maps. The regions with the highest wind speed are Western Turkey, with speeds between 7–8 m/s. Tekin et al. (2021)[26] calculated wind speeds of 6–8 m/s for assessing wind energy potential in the Eastern Mediterranean region. This region is noted for its high productivity. Yılmaz et al. (2014)[27] conducted a comprehensive study on Turkey's renewable energy potential. The Yildiz, Mediterranean region, is quite high in terms of solar energy potential. Zhao et al. (2019)[28] created a map of wind energy potential in China. It is predicted that the wind energy capacity can reach 200 TWh with annual speeds of 6–8 m/s. Zhou, M., & Zhang, L. (2020)[29] conducted an assessment of the wind energy potential in China. The wind speed in southeast China is around 7–8 m/s, and the annual output is around 100 TWh.

Turkey's renewable energy potential is quite high, especially in terms of wind energy, and the correct evaluation of this potential is of great importance in terms of both environmental sustainability and economic development. The Mediterranean Region has suitable geographical and climatic characteristics for wind energy investments and plays a strategic role in Turkey's wind energy policies. A more effective use of the wind energy potential of the Mediterranean Region will be an important step to increase Turkey's energy independence and achieve its sustainable development goals.

2. Methodology

This study examines the wind energy potential of Turkey's Mediterranean Region using data derived from the Global Wind Atlas (GWA), version 3.1, developed by the Technical University of Denmark (DTU) in collaboration with the World Bank. The analysis focuses on wind speed and direction data at an altitude of 100 meters above ground level (AGL), which aligns with the hub height of standard utility-scale wind turbines.

The data analysis process includes several stages: organizing and cleaning the raw datasets, extracting region-specific wind characteristics, and conducting spatial and statistical evaluations. Wind speed distribution, mean annual wind speeds, and directional patterns were assessed to identify zones with high generation potential.

To ensure methodological rigor and reproducibility, the analysis was carried out using Python programming language, with libraries such as Pandas, NumPy, Matplotlib, and GeoPandas for data preprocessing, visualization, and spatial analysis. The GWA platform was used as the primary data source, and its online GIS interface helped refine the spatial boundaries of the Mediterranean Region in Turkey.

What distinguishes this study methodologically is its integration of high-resolution GWA data with open-source computational tools to perform a reproducible and region-specific wind energy assessment. Unlike previous generalized evaluations, this study emphasizes site-specific turbine planning by correlating wind behavior with geographic and topographic conditions, offering a more actionable framework for regional stakeholders and energy planners.

2.1. Mediterranean Region Wind Energy Profile

The Mediterranean Region stands out as a very important region in terms of Turkey's wind energy potential. The wind speeds and directions of the region are factors that directly affect the energy production capacity. In particular, high-altitude mountainous areas and wide coastlines offer favorable conditions for wind power generation in **Figure 1**.

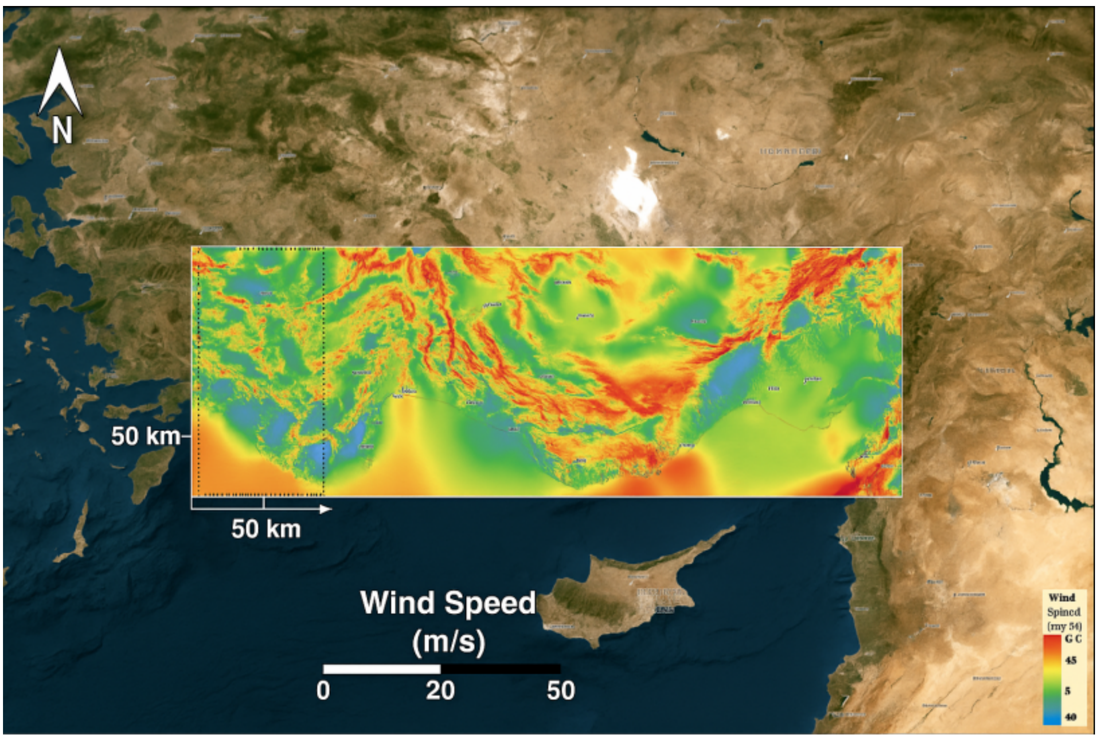

Figure 1. Global Wind Atlas Mean Wind Speed at 100 m Medıterrenıan [30].

2.2. Wind Speeds and Directions

Annual average wind speeds in the Mediterranean Region generally vary between 5.5 m/s and 7 m/s. Observational data from specific locations such as the Gibraltar–Tangier–Tétouan corridor indicate mean wind speeds ranging from approximately 5.2 to 5.5 m/s, with seasonal peaks (Levante winds) reaching up to 8.7 m/s. Similarly, climatological analyses show that coastal and strait regions—including parts of the Aegean and the Gulf of Lion—exhibit higher average wind speeds, often exceeding 6 m/s, while the broader Mediterranean basin typically experiences annual averages between 5.5 and 7 m/s [31,32]. These speeds are highly conducive to wind power generation, as efficient energy production for wind turbines usually occurs at speeds of 4 m/s and above. The highest wind speeds in the region are observed especially in settlements and high mountainous areas on the Mediterranean coast. These areas draw attention as ideal regions for the efficient operation of wind turbines.

Wind directions in the region generally blow from the northeast (Meltem winds), but changes in wind directions can be seen according to local conditions. The winds on the northern coast of the Mediterranean become more pronounced, especially in summer. These directional winds offer a significant advantage for wind energy projects in the region.

2.3. Mountainous Areas and Coastline

The mountainous nature of the Mediterranean Region is an important factor for wind energy production. High altitude areas can cause wind to accelerate and create stronger wind currents. These mountainous areas allow installation at suitable heights for wind turbines. In addition, large areas along the coast are also advantageous for the efficient operation of wind turbines.

The coastline in the area also allows the wind to constantly change direction and offer variable speeds in different areas. This allows different wind turbines to operate more efficiently in different areas.

2.4. Wind Energy Potential and Investment Opportunities

The wind energy potential of the Mediterranean Region is at very high levels compared to other regions in Turkey. Annual wind energy production in the Mediterranean can be an important source of energy under current conditions. Wind farms located in the coastal areas of the Mediterranean offer great opportunities to meet the increasing energy demand, especially in the summer months. In addition, wind power projects in mountainous areas can significantly increase the power generation capacity in the region.

In order to further increase the potential in the region, it is necessary to increase the investments made for the installation of wind power plants. In particular, investing in technologies that will increase the efficiency of wind turbines can make energy production in the Mediterranean Region more efficient.

The Mediterranean Region is a very suitable area for wind energy production with the advantages of high wind speed and directions. Investments and projects to be made in the region can play an important role in meeting Turkey's energy needs. In particular, the potential offered by mountainous areas and coastlines makes the Mediterranean Region attractive for wind energy projects.

The novelty of this study lies in its region-specific application of Global Wind Atlas data to assess wind energy potential in Turkey's Mediterranean Region, an area that has been underrepresented in detailed analyses. Unlike broader national-level studies, this work highlights localized wind patterns and strategic sites using percentile, seasonal, and diurnal analyses. While it employs standard visualization and data tools, the study offers a unique interpretive approach by proposing differentiated turbine applications—horizontal and vertical axis—based on site-specific wind behavior. Furthermore, it integrates a social dimension by emphasizing the role of community engagement in wind project planning, a perspective rarely addressed in prior Turkish energy studies.

3. Results

Figure 2 illustrates the variation in wind speed values (denoted as "val") across increasing percentile levels ("perc"). The graph reveals a distinctly negative correlation, indicating that wind speed values tend to decrease as percentile values increase. This inverse relationship is particularly pronounced in the lower percentiles, where the decline in wind speed is steeper. As the percentile value exceeds 50%, the rate of decrease becomes more gradual and stabilizes, suggesting a diminishing marginal change in wind speed.

The wind speed values begin at approximately 8.84 m/s and decrease steadily to 4.9 m/s, reflecting a total reduction of nearly 4 units over the percentile range. The use of point markers (marker = ‘o’) enhances the clarity of individual data points and underscores the continuity and regularity of the dataset. This distribution pattern highlights a log-linear decline and can be particularly valuable for researchers analyzing wind speed trends in disciplines such as meteorology, renewable energy planning, and environmental sciences.

Understanding how wind speed varies across percentiles provides critical insights for applications such as wind energy potential assessments, where the frequency and intensity of wind events influence both site selection and turbine efficiency. The observed trend in **Figure 2** thus offers a robust foundation for evaluating wind behavior and its implications on environmental or technical systems.

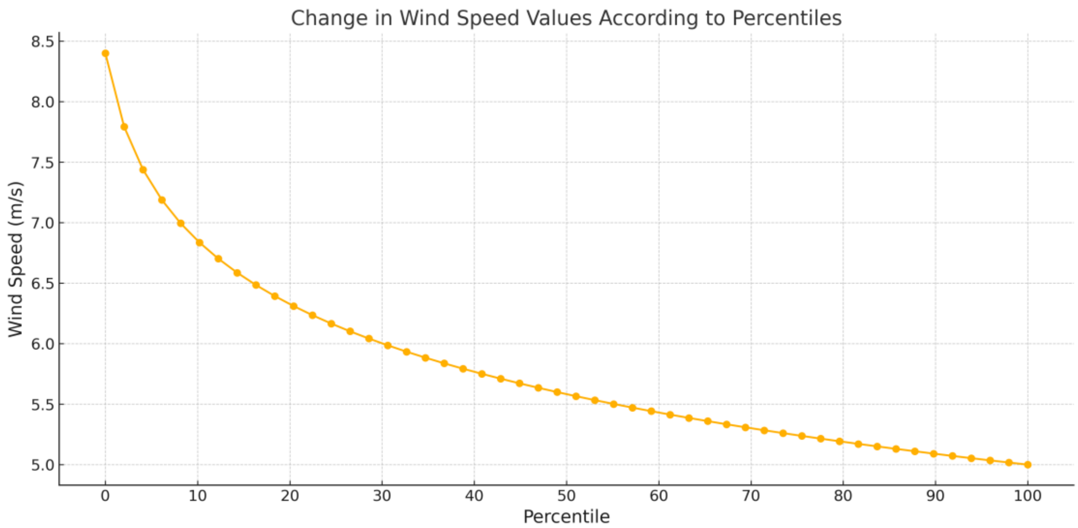

Figure 2. Trend of changes in wind speed by percentiles.

Figure 3 shows the distribution of values in the heat map and data set. In the data, since the color scale is “coolwarm”, low values are expressed as cooler (blue) and high values are expressed as warmer (red) colors. When we look at the heatmap, we see that the red tones are generally concentrated in the top rows (the first few columns and rows), while the blue tones gain weight as you move towards the bottom rows and the columns on the right. This indicates that the data generally has higher values in the first rows and lower values in the following rows and columns. When evaluated on a row-by-line basis, more reddish colors are seen, especially in the first lines (for example, lines 0–10). This indicates that the data in these rows has higher values. It means that in subsequent rows (for example, lines 20–23) the colors shift toward blue, with blue channel intensity values increasing to above 150 (on a 0–255 scale), and the data values decrease overall. Between the columns, especially in the first few columns (for example, columns 1–3), the red channel intensity predominantly exceeds 180 (on a 0–255 scale). This indicates that these columns have high values. In columns 9–12, blue tones predominate; This means that there are lower values in these columns. It is observed that the data reaches the highest values at some points, such as the intersection of column 1 and row 10. In some areas, especially near the lower-right corner (for example, rows 22–23 and columns 10–12), the lowest values are found. There is no obvious trend or symmetrical structure in the data; This indicates that the data may be randomly distributed. Color gradients do not clearly indicate that values increase or decrease in an orderly manner across both rows and columns.

As a result, this heat map visualizes the distribution of values in the data set, allowing us to easily understand which regions have high (red) and low (blue) densities. Especially in time- or area-based analysis, such shapes are very useful for quickly detecting trends and anomalies.

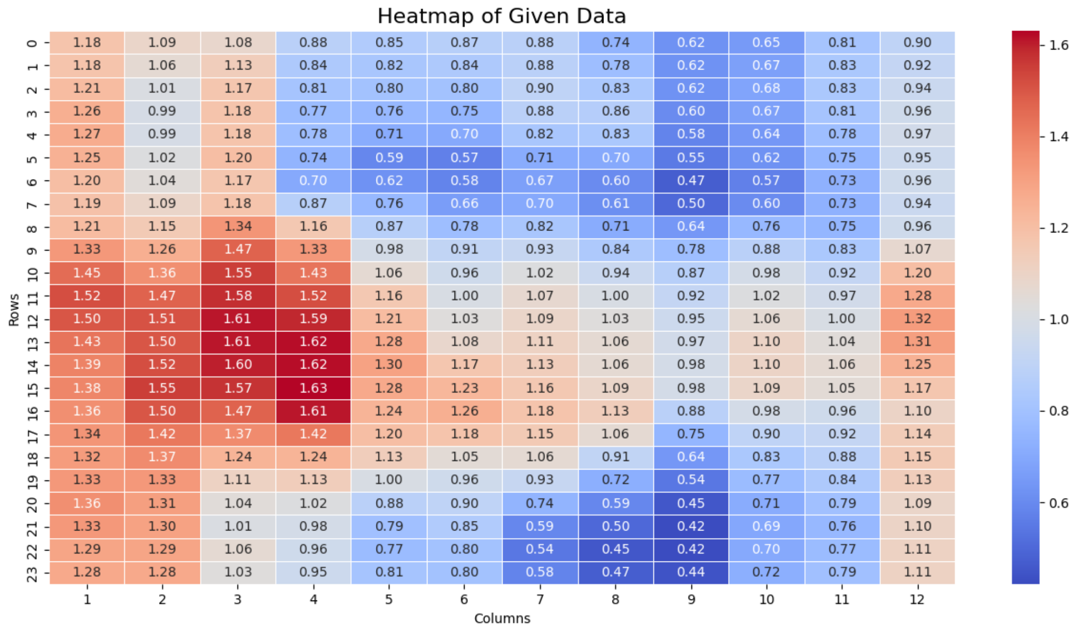

Figure 3. The heat map shows the distribution of values in the data set.

Figure 4 shows the change in values as a function of time (months) over a indicate this year. In the first three months, when the values are around 1.3, a downward trend is observed in the middle of the year (between 4 and 9 months). The dashed line represent the annual average value (0.99). Especially in the first quarter (1–3 months) and the last quarter (10–12 months) of the year, the values remained above average. Between 4 and 9 months, values were generally below average, indicating a period of decline in the middle of the year. A more detailed analysis of the data shows that mid-year lows may be due to a seasonal effect. For example, environmental conditions or economic factors may have caused a drop in values in the middle of the year.

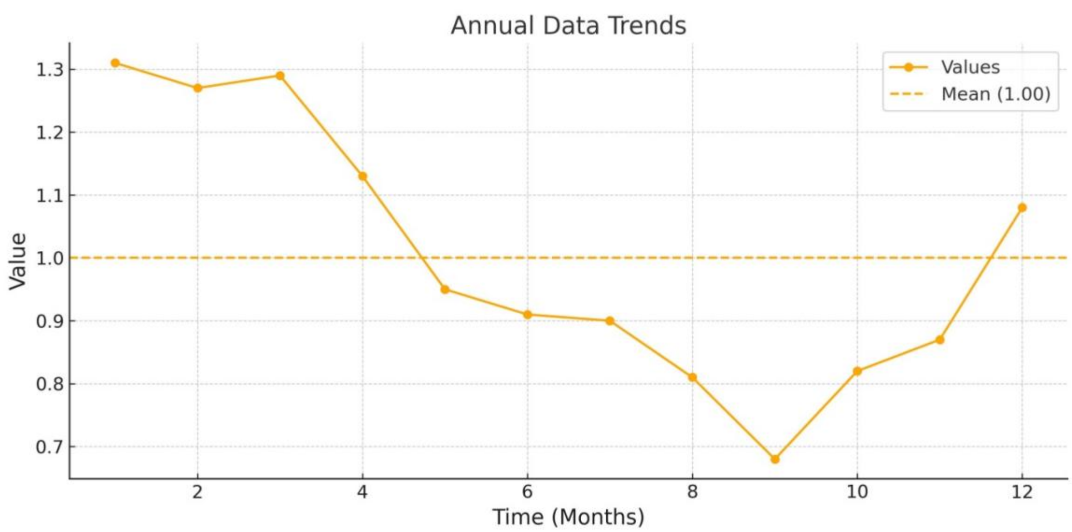

Figure 4. Change of values over time (months) in a one-year period.

Figure 5 shows the change in the measured values between 2008 and 2017. The data are randomly distributed around the mean value (1.01), varaing between 0.94 and 1.04. No trend was observed as a function of time. The dashed line represents the average of all years. The average value is around 1.01, and most data is centered around this value. The highest and lowest values were recorded in 2009 of 1.05 and in 2011 of 0.93, respectively.

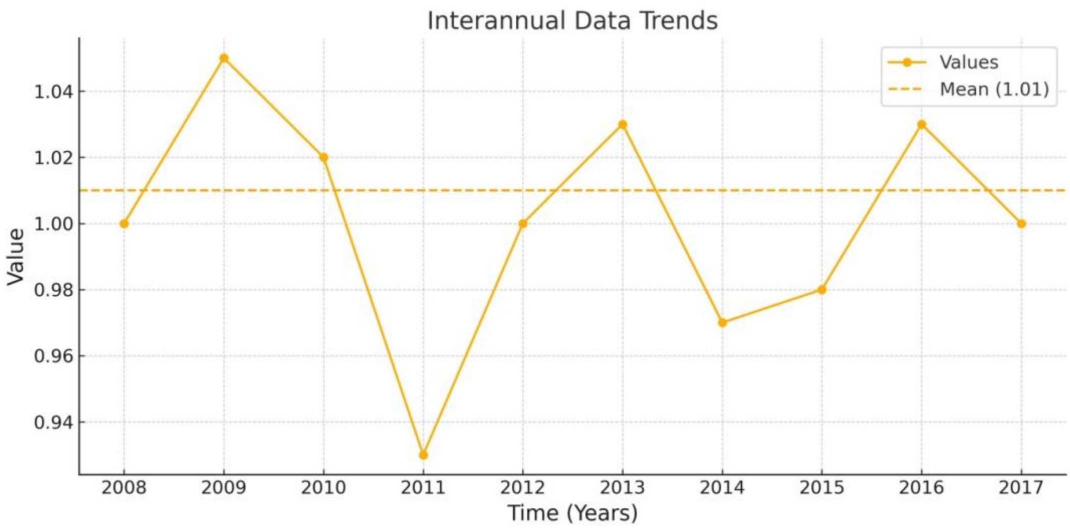

Figure 5. Annual changes measured between 2008 and 2017 and their deviations with the general mean.

Figure 6 shows the relationship between values and time in hours of the day (day/month/year). The results show fluctuations in the data points indicating a certain upward and downward trend throughout the day. The average value, shown by the orange dashed line represents the general trends of the day. The maximum value indicated by the green dashed line represents the highest value in the data set (1.27) occurs at 14th hour, while the minimum indicated by the red dashed line (0.78) is recorded at 6th hour, indicating a typical daily pattern with lower values in the morning and higher values in the evening. This suggests that the influence of environmental factors, such as temperature changes, on such data. When interpreting this graph and data, it is important to consider that values that vary according to the time of day may be related to environmental variables.

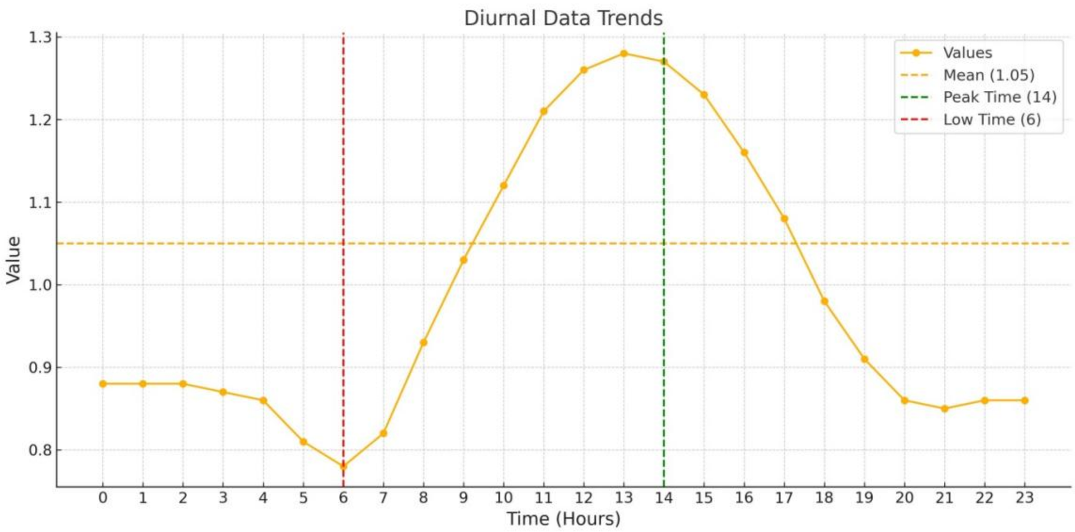

Figure 6. Diurnal variations in wind speed suggest potential influence of environmental factors such as temperature.

Figure 7 shows the variations of power density (val) as a function of percentage (perc). The results shows an inverse relationship between percentage increase (perc) and power density (val). Initially, the percentage increase is low (about 2%), while the power density is very high (about 1054.44), represent the highest power density. However, as the percentage increase (up to about 100%), the power density decreases from

249.98, 1054.44), represent the lowest power density. The average power density is 522.58, which represents the average level of the overall power in the figure. This can mean that the efficiency of the system decreases as the load increases, or that the power density decreases when more energy is demanded. The shape can be useful for energy efficiency analyses or power distribution studies.

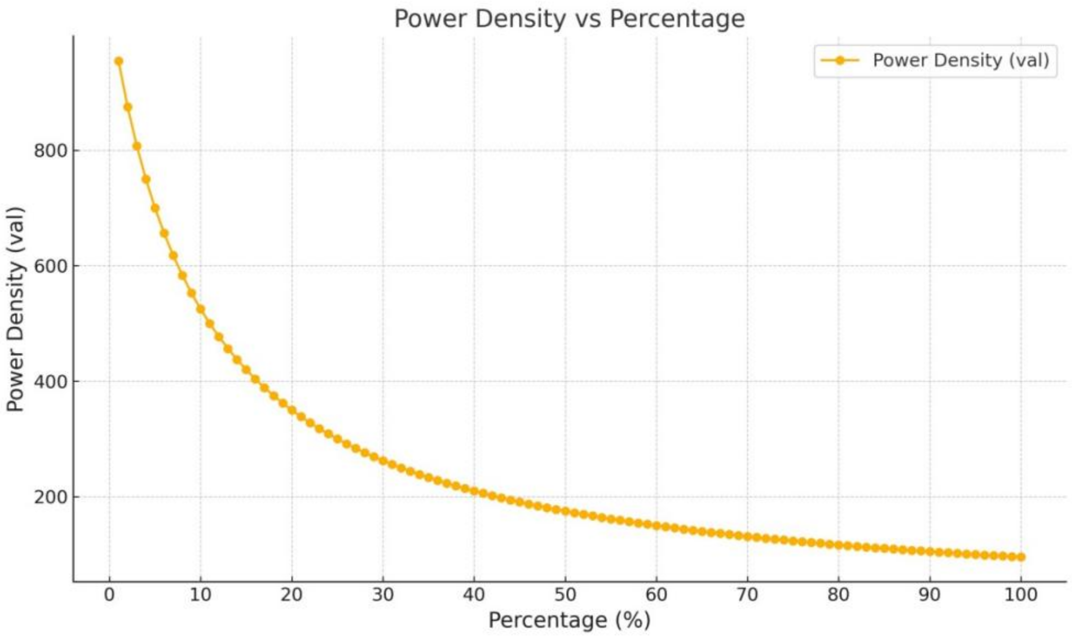

Figure 7. How power density changes with respect to percentage increase.

4. Discussion

The Mediterranean Region's favorable wind conditions present a significant opportunity to support Turkey's transition to renewable energy. The potential to reduce carbon emissions by utilizing wind power aligns with both national climate strategies and global sustainability goals.

This study emphasizes the importance of selecting appropriate turbine technologies based on the region's wind characteristics. The distinction between horizontal- and vertical-axis turbines underscores the need for region-specific analysis during turbine selection and site planning.

To fully harness the region's wind energy potential, a series of strategic actions are proposed:

- Infrastructure Development: Comprehensive feasibility studies should be conducted to identify optimal installation sites, particularly along coastlines and elevated terrains.
- Turbine Technology Adaptation: Turbine models must be selected based on localized wind speed and direction data to maximize energy output.
- Community Engagement: Involving local communities in project planning and implementation will foster public support. Addressing concerns related to noise, aesthetics, and environmental impact is essential.
- Economic Incentives: Policy frameworks such as tax incentives, subsidies, and accessible long-term financing are necessary to accelerate wind energy deployment.
- Research and Development: Investing in R&D will promote innovation in turbine and energy storage technologies, reducing costs and improving efficiency.
- Policy and Climate Integration: Energy policies must incorporate climate change projections to adapt to future changes in wind patterns and ensure the long-term viability of wind energy infrastructure.

5. Conclusions

This study has demonstrated that Turkey's Mediterranean Region holds significant and underutilized potential for wind energy generation. By analyzing wind speed distributions through the Global Wind Atlas and reviewing current literature, the research identifies both coastal and elevated inland areas as viable zones for wind farm development, with average wind speeds ranging from 5.5 m/s to 7.0 m/s. These wind conditions meet international standards for commercial-scale energy generation, particularly in areas exceeding 6.0 m/s, positioning the region as a promising frontier for renewable energy investment.

In addition to providing a scientific assessment of wind potential, the study offers a framework for strategic action to unlock this capacity. Recommendations include the expansion of energy infrastructure, site-specific turbine technology adaptation, stronger policy incentives, enhanced community engagement, and increased investment in research and innovation. These components are interdependent and must be implemented in an integrated manner to ensure long-term energy sustainability and system resilience.

Importantly, this research underlines the necessity of tailoring wind energy solutions to local conditions. The identification of suitable turbine types—horizontal-axis turbines for high-consistency coastal winds and vertical-axis turbines for variable inland wind profiles—demonstrates that a one-size-fits-all approach is not viable in wind energy development. Instead, location-specific planning and design are essential for maximizing energy output and economic returns.

The broader implications of the study are also noteworthy. The successful integration of wind energy in the Mediterranean Region can contribute to:

- Reducing Turkey's dependence on imported fossil fuels, thus enhancing energy security.
- Lowering greenhouse gas emissions, supporting national and international climate targets.
- Stimulating regional economic development through job creation, local investments, and technological innovation.
- Promoting social acceptance of renewable energy projects through inclusive, transparent planning processes.

Ultimately, the findings of this study provide a roadmap for evidence-based policy formulation and investment prioritization in the context of Turkey's green energy transition. Policymakers, energy developers, and investors are encouraged to use these insights in identifying high-potential zones, conducting pre-feasibility assessments, and designing data-driven deployment strategies.

In conclusion, with strategic coordination and long-term commitment, the Mediterranean Region can evolve into a national hub for wind energy production, playing a vital role in achieving Turkey's sustainable energy future.

Author Contributions

Conceptualization, A.E. and M.E.Ş.; methodology, A.E. and M.E.Ş.; software, A.E. and M.E.Ş.; validation, A.E. and M.E.Ş.; formal analysis, A.E. and M.E.Ş.; investigation, A.E. and M.E.Ş.; resources, A.E. and M.E.Ş.; data curation, A.E. and M.E.Ş.; writing—original draft preparation, A.E. and M.E.Ş.; writing—review and editing, A.E. and M.E.Ş.; visualization, A.E. and M.E.Ş. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The author declare that data supporting the findings of this study are available in the article. If a raw data file in another format is required, it is available from the corresponding author upon reasonable request. The dataset corresponds to GWA version 3.0 at 100 m hub height. Python scripts used for plotting are available upon request for reproducibility.

Conflicts of Interest

The authors declare no conflict of interest.

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