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Energy, Economic and Environmental Evaluation of Vertical Axis Wind Turbine for Urban Applications: A Case Study of Dogus University

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Energy analysis,
Economic analysis,
CO_2 emission reduction

Abstract: This study provides a comprehensive energy, economic, and environmental analysis of a commercial vertical-axis wind turbine (VAWT) for urban-scale applications. In accordance with the objective of this study, Doğuş University has been considered as a case study for conducting these analyses. In the analyses, wind speed data obtained from the meteorological station closest to the university, along with the technical specifications of a VAWT with a rated power of 5 kW, were considered as the basis. In the energy analysis, the amount of electricity generated by the turbine is calculated, while the economic analysis determines the revenue from electricity production, the additional revenue from the reduction of greenhouse gas emissions, and the total annual revenue. Additionally, the environmental analysis evaluates the potential for CO_2 emissions reduction. As a result of the study, the power density was calculated as 48.69 W/m² and 49.23 W/m², based on the Weibull distribution and meteorological data. Furthermore, calculations for a single wind turbine indicated that 2468.7 kWh of electricity production and a reduction of 1134.6 kg of CO_2 emissions could be achieved in 2024. From an economic perspective, the total annual revenue is determined to be $271.55, with a Levelized Cost of Energy (LCOE) of 0.161 $/kWh. Based on the findings, it is believed that this study can play a guiding role in the planning and evaluation of wind energy systems for similar buildings and urban areas.

Kentsel Uygulamalar İçin Dikey Eksenli Rüzgâr Türbininin Enerji, Ekonomik ve Çevresel Değerlendirmesi: Doğuş Üniversitesi Örneği

Anahtar Kelimeler
Rüzgâr enerjisi,
Dikey eksenli rüzgâr türbini (VAWT),
Enerji analizi,
Ekonomik analiz,
CO_2 emisyon azaltımı

Öz: Bu çalışma, kentsel ölçekli uygulamalar için ticari bir dikey eksenli rüzgâr türbini (VAWT) üzerinden kapsamlı bir enerji, ekonomik ve çevresel analiz sunmaktadır. Bu çalışmanın amacı doğrultusunda, Doğuş Üniversitesi, bu analizlerin gerçekleştirildiği bir durum çalışması olarak ele alınmıştır. Analizlerde, üniversiteye en yakın meteorolojik istasyondan elde edilen rüzgâr hızı verileri ile 5 kW nominal güce sahip ticari bir dikey eksenli rüzgâr türbininin teknik özellikleri temel alınmıştır. Enerji analizinde, türbinden elde edilen elektrik miktarı hesaplanmış, ekonomik analizde ise elektrik üretiminden sağlanan gelir, sera gazı emisyonlarının azaltılmasından elde edilecek ek gelir ve toplam yıllık gelir belirlenmiştir. Ayrıca, çevresel analizde CO_2 emisyonlarının azaltılma potansiyeli değerlendirilmiştir. Çalışma sonucunda, Weibull dağılımı ve meteorolojik verilere dayanarak güç yoğunluğu sırasıyla 48,69 W/m² ve 49,23 W/m² olarak hesaplanmıştır. Ayrıca, tek bir rüzgâr türbini üzerinden yapılan hesaplamalar, 2024 yılı boyunca 2468,7 kWh elektrik üretimi ve 1134,6 kg CO_2 emisyonu azaltımı sağlanabileceğini göstermektedir. Ekonomik açıdan, toplam yıllık gelir 271,55 $ ve seviyelendirilmiş enerji maliyeti (LCOE) 0,161 $/kWh olarak belirlenmiştir. Elde edilen bulgulara dayalı olarak, bu çalışmanın benzer binalar ve kentsel alanlar için rüzgâr enerjisi sistemlerinin planlanması ve değerlendirilmesinde yol gösterici bir rol üstlenebileceği düşünülmektedir.

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1. Introduction

Increasing energy demand and environmental problems caused by fossil fuels have made interest in renewable energy sources inevitable. Wind energy, which is clean, abundant and has a wide range of uses, stands out among sustainable energy solutions [1]. This energy source, which has the potential to reduce greenhouse gas emissions by decreasing dependence on fossil fuels, is also a cost-competitive alternative [2].

In recent years, there has been a remarkable increase in global investments in wind energy. Based on data provided by the World Wind Energy Association (WWEA), as of 2023, the global installed wind power capacity has attained approximately 1.046 TW, representing a 12.5% growth compared to 2022. China holds the largest share of this total capacity with 470.63 GW, while Turkey's installed wind power capacity stands at around 11.7 GW. Figure 1 illustrates the installed wind power capacities of countries for the years 2022 and 2023 [3].

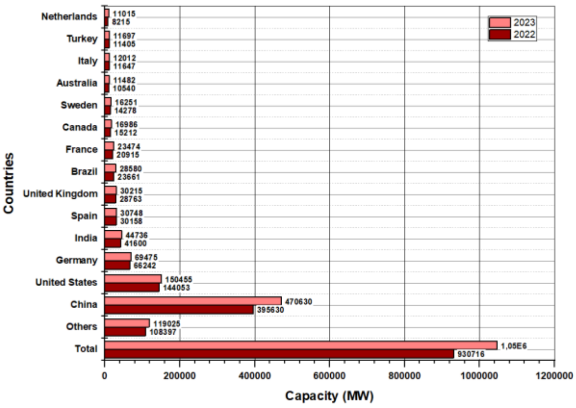

Figure 1. Wind energy installed capacity by country (2022-2023).

Wind turbines are categorized into two main groups based on their axis of rotation: horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs) [4]. Today, various turbine designs have been developed to make the most efficient use of wind energy. Among these, the most commonly used are HAWTs, which feature a rotor shaft and generator mounted on a tower. Their blades rotate on a horizontal axis and must be aligned with the wind direction to achieve maximum efficiency. This alignment can be achieved with a simple wind vane or more advanced systems using sensors and servo motors. Due to their high energy conversion rates, HAWTs capture more wind energy and offer higher efficiency compared to VAWTs. However, the need for an additional mechanism to rotate the turbine toward the wind direction makes the system more complex and increases the overall cost [5].

VAWTs have a significant advantage as they can operate without being dependent on wind direction. Unlike traditional HAWT, VAWTs can generate energy regardless of the direction from which the wind blows. This feature provides a major advantage, especially in areas where wind flows are variable and turbulent. On the other hand, VAWTs have a simpler design, which results in lower production and maintenance costs. With fewer moving parts compared to HAWTs, they tend to have a longer lifespan and require less maintenance. Moreover, VAWTs are preferred in urban and coastal areas because they can operate at low speeds and are quiet. Thanks to these advantages, their use for energy production has increased in both inland and coastal regions in recent years [6].

Among VAWTs, the most notable designs are the Darrieus and Savonius turbines. These two turbines have different operating principles and efficiencies. The Savonius VAWT has two or more scoops that capture the wind and cause the rotor to spin, working on the principle of aerodynamic drag. Its simple design makes it effective at low wind speeds. However, since it operates based on drag, its efficiency is lower compared to systems that rely on lift force [7]. Furthermore, Darrieus VAWT operates on lift force. The lift force on its blades causes the turbine to rotate and efficiently convert mechanical energy into electricity. The Darrieus VAWT can reach higher speeds, but it lacks self-starting capability. This means it doesn't begin rotating at low wind speeds and requires sufficient wind force to operate efficiently. Figure 2 depicts the general types of wind turbines [8].

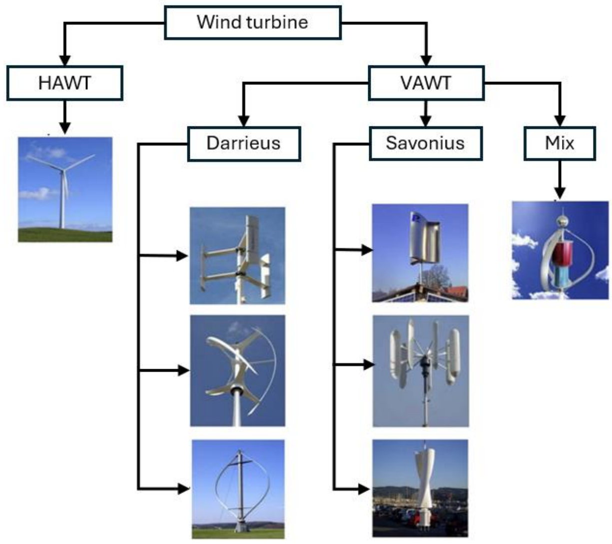

Figure 2. The types of wind turbine [8].

Recent research indicates that VAWTs may perform better than HAWTs, especially in urban and semi-urban areas. The advantages of VAWTs, such as lower costs, less noise, resistance to wind direction changes, and minimal visual disruption, make them more attractive in areas where HAWTs are less suitable [6]. VAWTs are versatile devices that can be used in many different fields. These types of wind turbines are particularly effective in meeting essential needs such as electricity generation, water pumping, and water treatment. Moreover, they play an important role in heating and cooling systems, particularly in hot water supply and high-pressure heat pumps. These features contribute to the use of VAWTs as sustainable energy solutions, supporting their applications across various sectors [9].

In recent years, numerous studies have been carried out on the use of VAWTs in buildings. These studies generally provide analyses from various perspectives, including technical performance, economic feasibility, and environmental impacts. Balduzzi et al. examined the feasibility of installing a Darrieus VAWT on the roof of a building. In their study, they highlighted that these turbines stand out in urban applications due to their low visual impact and high performance. In this context, the energy efficiency of a Darrieus VAWT installed on the roof of a building in a European city was thoroughly evaluated through numerical analyses [10]. Lee et al. studied the power output of a small VAWT installed on a building's roof. The study found that in an environment with turbulence intensity greater than 30%, when the vertical angle was 45° or smaller, 90% of the power generation occurred [11]. Basack et al. analysed and numerically modelled the performance of the mechanical and electrical components of a rooftop VAWT. Their research revealed that the VAWT installed on the roof operates efficiently at wind speeds ranging from 0.5 to 6 m/s. Vibration measurements indicated that the variations in parameters were not constant. Both experimental and numerical findings were found to be consistent, proving that the turbine is suitable for urban applications [12]. Loganathan et al. conducted a study on the design of micro wind turbines for electricity generation in residential areas and their economic feasibility analysis. The study aims to design a small VAWT for large cities in Australia and assess its economic viability. The study specifies that a turbine suitable in terms of size and cost would have a diameter of 2.4 meters, a height of 1.2 meters, and a blade radius of 0.32 meters, capable of generating 10 W of power [13]. Akhan performed a technical and economic evaluation of a photovoltaic (PV) and wind hybrid energy system for two electric vehicle charging stations in a shopping centre in Edirne. In the optimization carried out using HOMER software, the most efficient system was found to consist of 50 kW VAWT, a 50 kW PV system, and 52.1 kW power converters. As a result of the study, the total system cost was calculated to be $145,961, with an annual operating cost of $1,881 and a levelized cost of energy (LCOE) of $0.0193/kWh [14]. Saleh et al. investigated two different types of small-scale VAWTs aimed at reducing energy consumption in a three-story residential building located in the Karaburun district of İzmir, where annual wind speeds range between 6-8 m/s. Simulations were performed using ANSYS Fluent and Design Builder software. The study found that installing 15 Ice-Wind VAWTs reduced energy consumption by 22.5%, with each turbine costing $2,000 and a payback period of 14.57 years. On the other hand, 15 Savonius VAWTs led to a 36% reduction in energy consumption, with each turbine priced at around $2,300 and a payback period of 8.93 years. These results suggest that the Savonius turbine provides a quicker return on investment [15]. Rosato et al. conducted simulations to assess the energy, environmental, and economic effects of various vertical-axis micro wind turbines for a standard residential building in Italy. Four turbines with power outputs ranging from 1100 to 6300 W were studied in five Italian cities. The results showed that the use of wind turbines significantly reduced energy consumption, CO_2 emissions, and costs, with the best results achieved with the 2200 W turbine [16]. Chong et al. examined the performance of a VAWT integrated with an omni-directional guidance vane (ODGV) for urban applications through simulations and wind tunnel tests. The integration of the ODGV reduced the cut-in speed of the turbine, allowing it to operate at lower wind speeds. At a wind speed of 6 m/s, the rotor speed increased by 182%, and the power output increased by 3.48 times. The results indicate that this ODGV-supported system offers a strong alternative for efficient wind energy production in urban areas [17]. Casini et al. explored how VAWTs can enhance the incorporation of renewable energy within building systems. The potential for small-scale wind turbines (ranging from 200 W to 10 kW) to generate energy even at low wind speeds, their minimal visual impact, and their ability to work in harmony with photovoltaic systems were highlighted. Additionally, the study discussed how these turbines can be integrated into buildings as Building-Integrated Wind Turbines (BIWTs) and compared their energy production advantages to photovoltaic systems. These turbines can be used either in standalone or grid-connected systems and can also be integrated into urban infrastructure, such as smart lighting [18]. Turhan and Saleh carried out a study investigating the energy savings that can be achieved through the integration of small-scale VAWTs into buildings. In the study, three-blade IceWind turbines with a 112-degree pitch angle and a 0.38 aspect ratio were integrated into a guardhouse at Istanbul Airport. The analysis, conducted using dynamic building energy simulations, revealed that the integration of 40 IceWind turbines reduced the building's total energy consumption by 9.3%. This study highlights the potential of different designs of small-scale vertical wind turbines to enhance energy efficiency in buildings [19]. Ali et al. executed an in-depth experimental and simulation-based performance study of a VAWT integrated into a rooftop. In tests conducted in the Tabuk region of Saudi Arabia, it was observed that the turbine began generating power at wind speeds of 3 m/s and reached its nominal power at 9 m/s. The maximum power coefficient obtained was 0.45, and the tip speed ratio was 1.94. CFD simulations revealed that the equivalent force applied to each blade was approximately 2.8 N, with the total force being 8.5 N. These results successfully confirm the turbine's durability and efficiency at higher wind speeds [20]. Saeidi et al. examined the aerodynamic design and economic feasibility of small-scale VAWTs tailored for local use in a specific region. In the design process, the blade element momentum theory (BEM) and dual-multiple flow tube model were used, and a 1.5 kW H-rotor type VAWT with a NACA4415 airfoil was selected. An economic analysis, considering the renewable energy costs in Iran, calculated the annual electricity production with a cost of 12 cents per kWh. It was concluded that a profit of 6 cents per kWh produced could be achieved. The study highlights the economic efficiency of VAWTs in areas with low wind speeds and turbulence [21].

In light of the discussions and findings presented above, this study aims to provide a comprehensive energy, economic, and environmental analysis of a commercial VAWT for urban-scale applications. In accordance with the objectives of this study, Doğuş University has been chosen as a case study. Using real meteorological data, the energy output of the turbine will be calculated based on wind speeds, and its performance will be assessed. From an economic perspective, LCOE (Levelized Cost of Energy) calculations will be performed to determine the electricity production cost of the turbine, considering installation and maintenance costs. The environmental impacts will be evaluated based on the reduction in carbon emissions achieved during energy production and the turbine's capacity to generate eco-friendly energy. This study provides a novel assessment of a commercial VAWT's performance on a university rooftop using actual wind data. This study aims to highlight the potential of commercial VAWTs to provide energy efficiency, economic benefits, and environmental contributions in confined spaces such as university roofs, contributing to the implementation of sustainable energy solutions. Furthermore, such applications could assist in diversifying local energy production systems and reducing carbon footprints. The findings will guide the applicability of similar turbines in other buildings within the same region, facilitating the widespread adoption of sustainable energy production.

2. Materials and Methods

In this chapter, the methodology and materials used for energy, economic, and environmental analyses of a commercial VAWT planned for installation on the roof of Doğuş University for urban applications are provided in detail. Figure 3 represents a flowchart that outlines the methodology used in this study.

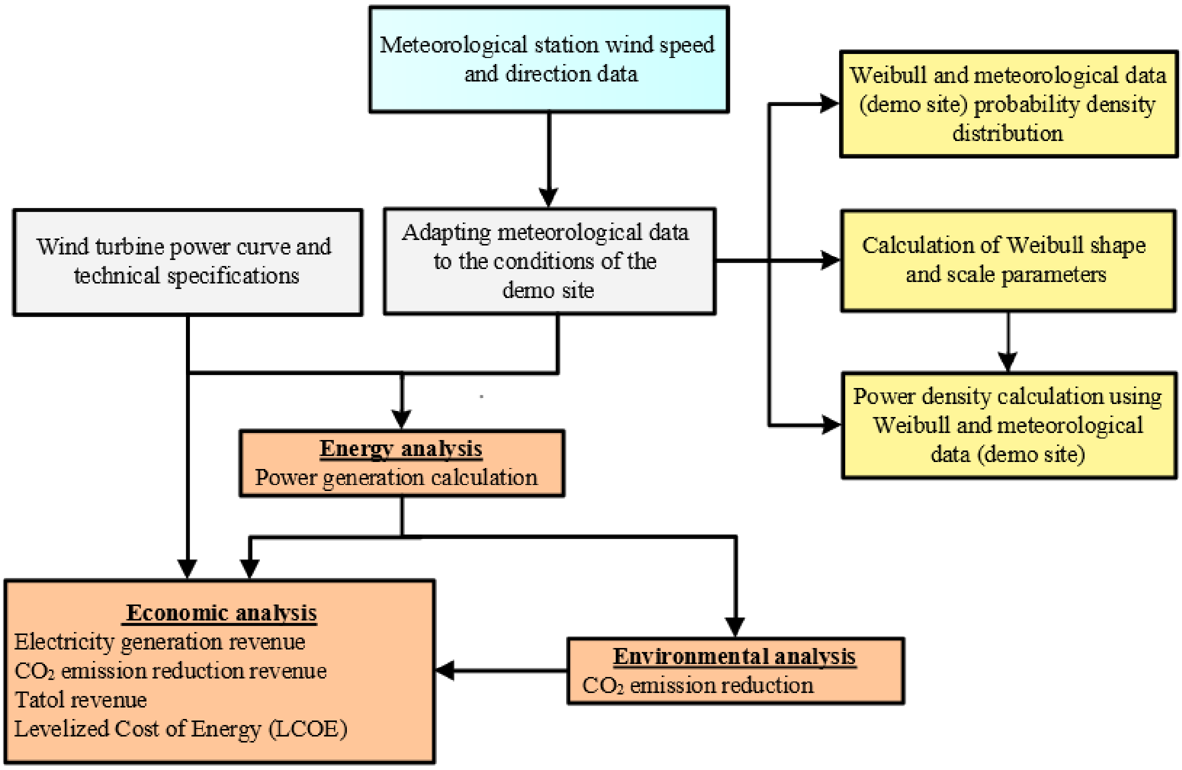

Figure 3. Systematic approach and methodological process flow.

The study is based on real meteorological data for the region and the technical specifications of the turbine to be used. Wind speed and direction data were obtained from a nearby meteorological station for the year 2024, with hourly long-term data used as the primary source for determining wind energy production potential. First, these data were processed using standard wind energy equations, and the potential for the region was calculated. Then, using the turbine's power curve, the amount of electricity that could be generated based on wind speed was determined. These calculations were made considering the turbine's actual performance and energy production near its maximum capacity. In the economic analysis, the installation cost, annual maintenance and operational costs, and revenue from electricity production were calculated. Additionally, the Levelized Cost of Energy (LCOE) was determined. In the environmental analysis, the potential for reducing CO_2 emissions through the application was examined, and the resulting greenhouse gas emission reduction revenue was calculated.

2.1. Meteorological data

In this study, the meteorological data required for assessing the wind energy potential of Doğuş University and conducting the necessary calculations were obtained from Station No. 18403, operated by the General Directorate of Meteorology (referred to as MGM in Türkiye) and located in the Ümraniye district. The station is located at 41°01'46.0"N 29°08'18.0"E and includes wind speed and direction data measured hourly throughout 2024. Figure 4 presents the hourly wind speed data measured from the meteorological station during 2024.

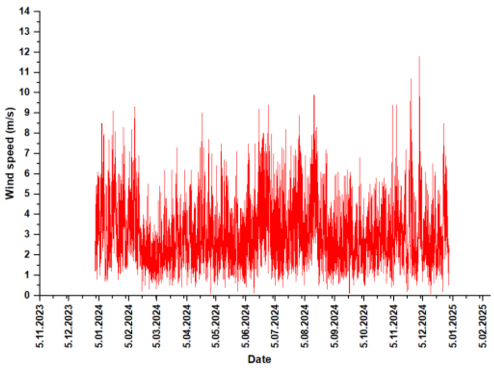

Figure 4. Hourly wind speed data measured in 2024.

Figure 5 depicts the wind rose illustrating the distribution of wind speed and direction data obtained from the meteorological station. The chart demonstrates that the wind predominantly blows from the northeast, with the most frequent wind speeds falling within the ranges of 2–4 m/s and 4–6 m/s, respectively.

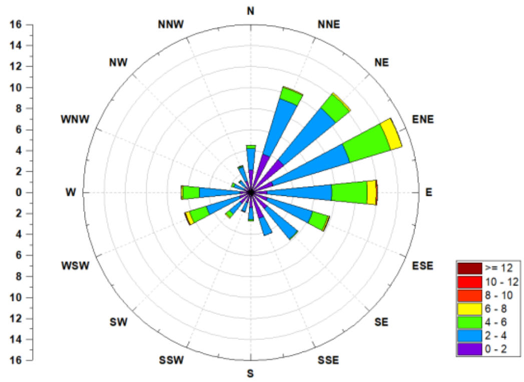

Figure 5. Wind rose of wind speed and direction.

Doğuş University, the proposed application site, is located at 41°00'06.3"N 29°10'34.0"E. In this study, the meteorological station is located close to the university rooftop. Therefore, the wind speed data were directly taken from the station measurements, and all analyses were carried out based on these data. Within the scope of this study, this wind speed data provide an important basis not only for energy analyses but also for economic and environmental assessments.

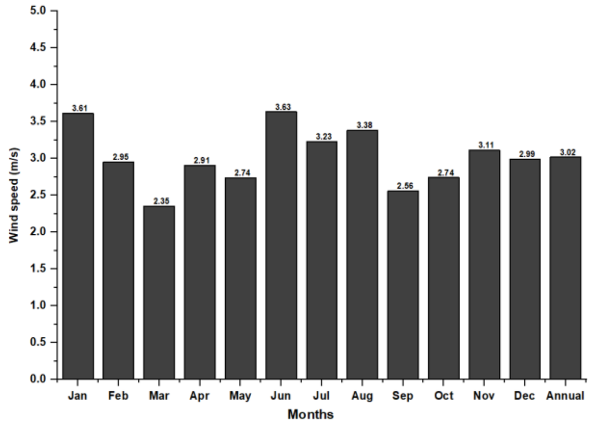

Figure 6. Monthly average wind speed in 2024.

Figure 6 illustrates the monthly mean wind speed measured at the meteorological station throughout 2024. The highest monthly mean wind speed was detected in June, reaching 3.63 m/s, while the lowest occurred in March, with a value of 2.35 m/s, as shown in Figure 6. The annual mean wind speed for 2024 was determined to be 3.02 m/s. In this study, these measurements enable a clear overview of the time-based variations in wind conditions at the station, which serve as the basis for subsequent analyses.

2.2. Wind turbine specifications and power curve

In this section, the technical specifications of the commercial wind turbine used and its power curve reflecting the energy production capacity are presented. The turbine's technical details are given in Table 1 [22]. Based on these parameters, the turbine's overall performance is outlined. In addition, the relationship between wind speed and power is depicted in Figure 7 through the power curve [22]. This curve has been used as a fundamental tool to determine the turbine's electricity generation based on the wind potential at the application site.

Table 1. Wind turbine technical parameters.

Parameters	Value	Unit
Model	SM-5000 WT	
Rated power	5	kW
Maximum power	5.6	kW
Rated voltage	12V/24V/48V/120V/220V	
Start-up wind speed	2	m/s
Rated wind speed	12	m/s
Survival wind speed	50	m/s
Number of blades	3	unit
Blade length	2.1	m
Blade Materials	High strength fiberglass reinforce polymer	-
Working temperature	-40/80	ºC
Design life	20	years

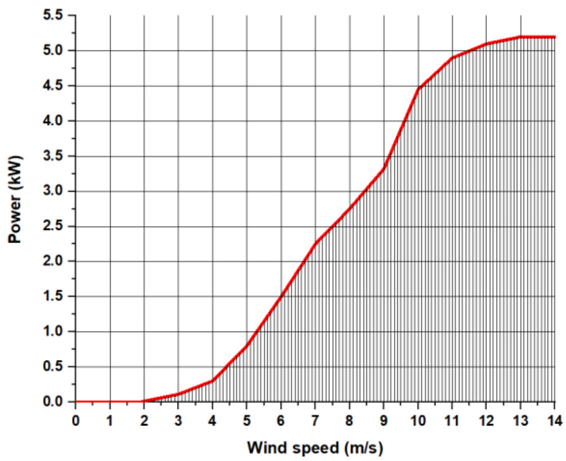

Figure 7. Wind turbine power curve.

3. Analysis

3.1. Energy analysis

The electrical power generated by the wind turbine is directly dependent on the wind conditions in the region where the turbine is located. Considering the meteorological conditions, wind speed continuously fluctuates. This variability can be described using distribution functions. The most suitable model for the wind speed distribution is the Weibull probability density function (PDF), which is defined as the following equation [23].

$$f(v) = \frac{k}{C}\left(\frac{v}{C}\right)^{k-1} exp\left(\left(-\frac{v}{C}\right)^{k}\right) \tag{1}$$

where k and C (m/s) express the shape and scale parameters, respectively. In addition, v (m/s) is the wind speed. The Weibull scale parameter can be presented as follows [24]:

$$C = \frac{v_{ort}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{2}$$

where Γ denotes the gamma function. The gamma function is defined using the following equations [25]:

$$\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt \tag{3}$$

The expanded form of Eq. 3 is presented in the following equation [26]:

$$\Gamma(x) = \sqrt{2\pi x}(x^{x-1})e^{x}\left(1+\frac{1}{12x}+\frac{1}{288x^2} - \frac{139}{51840x^x}+\cdots\right) \tag{4}$$

The shape parameter can be determined using the following equation [27]:

$$k = \left(\frac{\sigma}{v_{avg}}\right)^{-1.086} \tag{5}$$

where σ and v_{avg} depict the standard deviation and the average wind speed, respectively. The average power density can be calculated using the following equation for the Weibull distribution [28]:

$$P_w = \frac{1}{2}\rho C^3\Gamma\left(1+\frac{3}{k}\right) \tag{6}$$

The following equation is utilized to estimate the wind power per unit area [29]:

$$P_{wt} = \frac{1}{2}\rho V^3 \tag{7}$$

where, ρ refers the density of air.
The capacity factor, an important indicator of performance for vertical axis wind turbines, is determined using the following equation [30].

$$CF = \frac{P_p}{P_{rated}} \tag{8}$$

where P_p denotes the average power output generated by the wind turbine during a certain duration, while P_{rated} indicates the nominal (rated) power of the turbine. The energy output from the turbine (E_p) can be computed by the following equation [31] :

$$P_p = \sum_{i=0}^{n} P_i(v)t \quad (9)$$

where n is the total number of hours in the selected time period (year, season, or month), and t denotes a one-hour time interval.

3.2. Economic analysis

This section provides the economic analysis of the VAWT selected for the application site. Within the scope of the analysis, the cost of producing 1 kWh of electricity has been calculated, and the findings are discussed in detail in the results and discussions section. The unit energy cost of the proposed turbine is computed using the following equation [21]:

$$LCOE_{wt} = \frac{NPW_{OC}}{En_{tot}} = \frac{C_{inv.}}{En_{tot}n}\left[1 + m\left(\frac{(1+I)^n - 1}{I(1+I)^n}\right)\right] \quad (10)$$

where NPW_{OC} represents the net present value of the turbine's annual operating costs, while En_{tot} represents the total annual electricity production. m, I, and n represent the percentage of operating and maintenance costs relative to the turbine's investment cost, the real interest rate, and the turbine's economic lifespan, respectively. In this study, the values of m and n are taken to be 6% and 20 years, respectively. Furthermore, according to data from the Central Bank of the Republic of Turkey for 2024, the real interest rate is assumed to be 42.5%.

The following equation can be used to calculate the net present value of all costs, including operating, maintenance, and initial investment [21]:

$$NPW_{OM-I} = C_{inv.}\left[1 + m\left(\frac{(1+I)^n - 1}{I(1+I)^n}\right)\right] \quad (11)$$

where $C_{inv.}$ represents the initial investment cost of the VAWT project under consideration and can be calculated using the following equation:

$$C_{inv.} = CO_{wt}(1 + IC) \quad (12)$$

where CO_{wt} denotes the cost per kW of a VAWT, which is taken as 1000$/kW in this study [21]. IC refers to the initial installation cost, including expenses such as grid connection, transportation, and installation, and is assumed to be 40% of the turbine cost [21].

The following equation can be used to calculate the net present value of the turbine's yearly operating costs [21]:

$$NPW_{OC} = \frac{NPW_{OM-I}}{n} = \frac{C_{inv.}}{n}\left[1 + m\left(\frac{(1+I)^n - 1}{I(1+I)^n}\right)\right] \quad (13)$$

3.3. Environmental analysis

Environmental analysis includes evaluating the CO_2 reduction over the project's lifetime, which is calculated using the following equation:

$$CO_{2,reduction,tot} = nCO_{2,reduction} \quad (14)$$

where $CO_{2,reduction}$ represents the project's annual CO_2 reduction amount, which is determined using the following equations:

$$CO_{2,reduction} = En_{tot}emi_{CO_2} \quad (15)$$

where emi_{CO_2} refers to the grid emission factor, which is assumed to be 0.4596 tCO_2/MWh in this study [14]. Additionally, for calculating the greenhouse gas (GHG) reduction revenue, it is assumed that sustainable emission reductions will be achieved over 20 years, generating $15 in revenue for each ton of CO_2 reduced [32]. In this context, the revenue from GHG reduction can be calculated using the following equation.

$$Rev_{CO_2,reduction} = CO_{2,reduction,tot}Rev_{CO_2} \quad (16)$$

4. Results and Discussions

In this section, the energy, economic, and environmental of a commercial VAWT, planned for installation on the university's roof, were carried out. Prior to the analyses, preliminary evaluations were performed based on wind speed for the application area. These preliminary analyses involved examining the changes in the Weibull shape (k) and scale (c, m/s) parameters, and variations in power density, all using monthly wind speed data. Following the preliminary analysis, taking into account the power density chart and other technical characteristics of the proposed commercial VAWT for the application area, the generated power, total revenue, unit electricity production cost (LCOE), CO_2 reduction potential, and greenhouse gas (GHG) emission reduction revenue were thoroughly analysed. The results obtained were extensively discussed.

Figure 8 presents a comparative view of the probability density functions of the meteorological data and the Weibull distribution. Weibull probability density functions are commonly used to model the distribution of wind speeds over a specific time period. The peak points of these distribution curves represent the most frequent wind speed ranges. The analysis shows that the values obtained from the distribution of the meteorological wind data are very close to those derived from the Weibull function. As shown in Figure 8, the probability density for the Weibull distribution ranges from 0.090 to 0.276, while for the distribution based on meteorological data, this range is between 0.114 and 0.300. The shape (k) and scale (c) parameters used in the Weibull function calculations were directly determined based on the 2024 meteorological wind data and were calculated to be 2.203 and 3.314 m/s, respectively.

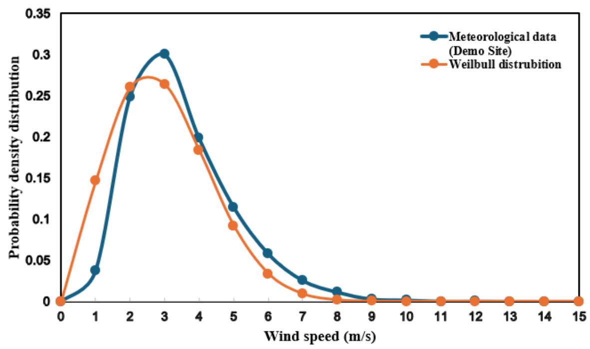

Figure 8. Wind speed frequency distributions based on meteorological data and the Weibull model.

Figure 9 indicates the variation of the Weibull shape (k) and scale (c) parameters on a monthly basis throughout the year 2024. Over the course of the year, the shape parameter ranged from 1.68 to 2.69, while the scale parameter fluctuated between 2.54 m/s and 4.00 m/s. Both parameters reached their highest values in June, with the shape parameter at 2.69 and the scale parameter at 4.00 m/s. The average Weibull shape and scale parameters calculated for the year were 2.31 and 3.31 m/s, respectively.

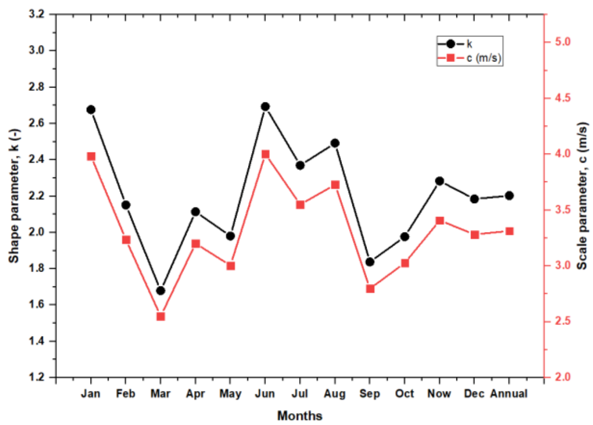

Figure 9. Monthly changes in Weibull shape and scale parameters in 2024.

In Figure 10, the monthly variations in power density based on the Weibull distribution and meteorological data are given. The analysis revealed that the calculations from both data sources yielded very similar results. The highest power density values were determined in June, with values of 48.69 W/m^2 (Weibull) and 49.23 W/m^2 (meteorological data). In contrast, the lowest power density occurred in March, with values of 13.01 W/m^2 (Weibull) and 13.49 W/m^2 (meteorological data).

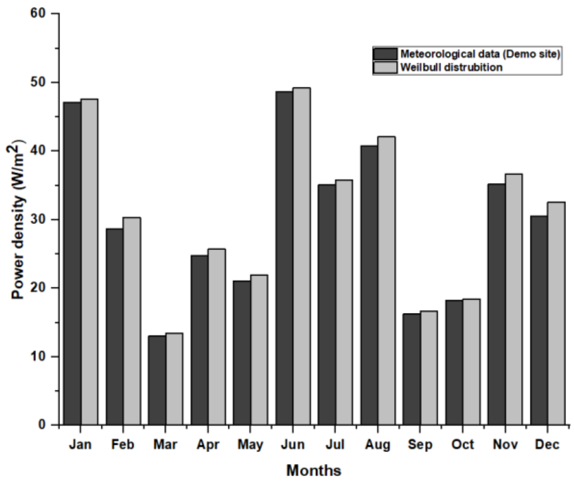

Figure 10. Monthly variation of power density in 2024.

The results presented in Figure 11 show that the wind turbine's capacity factor varied between 2.07% and 9.52% throughout 2024. On the other hand, the annual average capacity factor is calculated to be 5.62%. These values indicate that the capacity factor remains limited, particularly during periods of low wind speeds. This may be attributed to the wind regime observed at the study site not reaching sufficient levels during certain periods of the year. Nevertheless, the relatively high capacity factor obtained in June reveals that the turbine performance can attain high-level under favorable wind conditions.

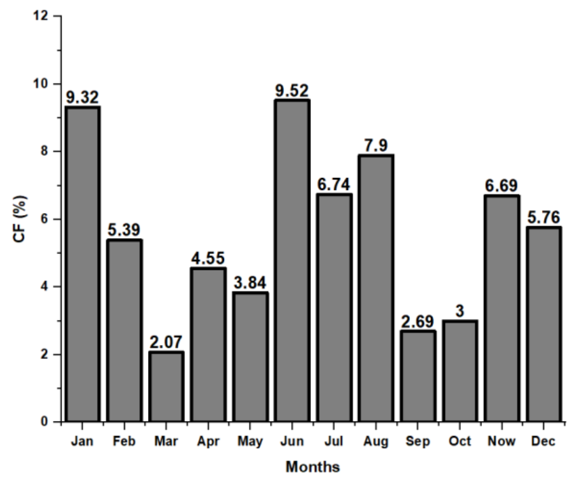

Figure 11. Monthly change of wind turbine capacity factor in 2024.

Figure 12 illustrates the monthly variation in hourly electricity production for 2024. These results are based on the amount of power that the commercially planned VAWT can generate, depending on the wind speed values. According to the analysis, electricity production varied throughout the year, with the highest production occurring in June and the lowest in March. This clearly demonstrates the impact of seasonal fluctuations in wind speed on electricity generation.

Figure 13 depicts a detailed overview of the monthly electricity production, unit electricity production cost (LCOE), and CO_2 emission reduction for the planned VAWT on the university roof. These calculations are based on the power generation curve derived from wind speed data shown in Figure 7 and meteorological data from the application area. The analysis demonstrates that the turbine's highest electricity production occurs in January, at 346.6 kWh, while the lowest production is in March, at 76.9 kWh. These findings indicate that a single VAWT will produce a total of 2468.7 kWh of electricity in 2024, resulting in a CO_2 emission reduction of 1134.6 $kgCO_2$/kWh. Regarding energy costs, the highest cost is observed in March, at 0.432 $/kWh, while the lowest cost is calculated in January and June, at approximately 0.096 $/kWh. Furthermore, the energy production cost over the turbine's lifetime is determined to be 0.161 $/kWh in this study.

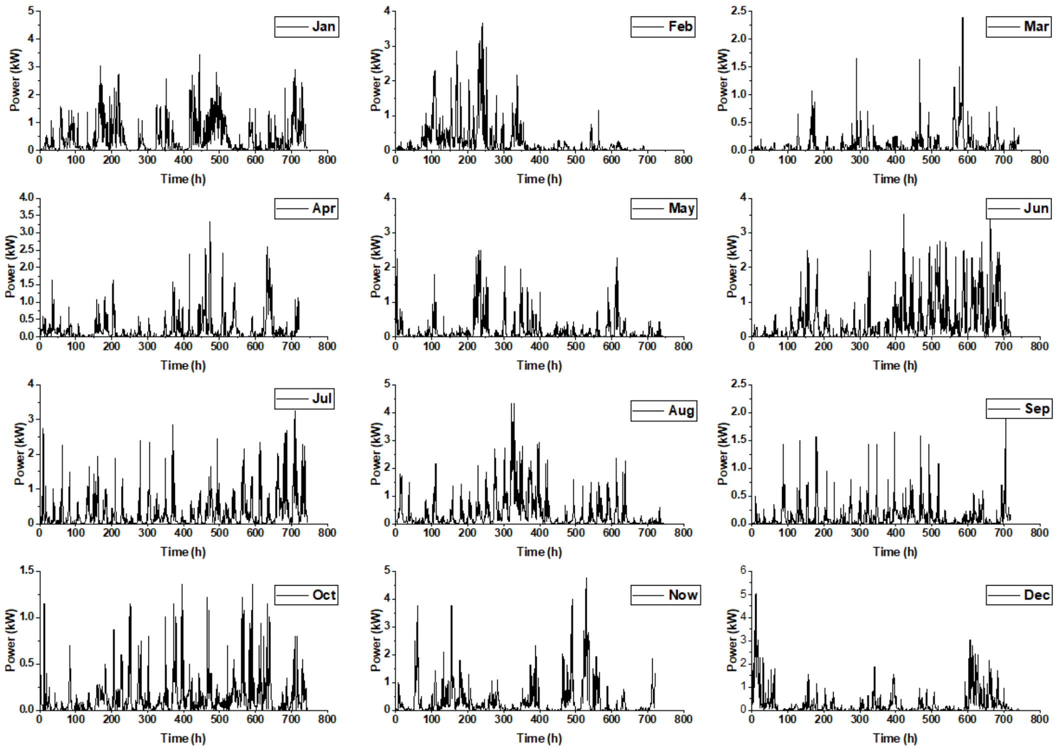

Figure 12. Hourly electricity generation variations for each month of the year.

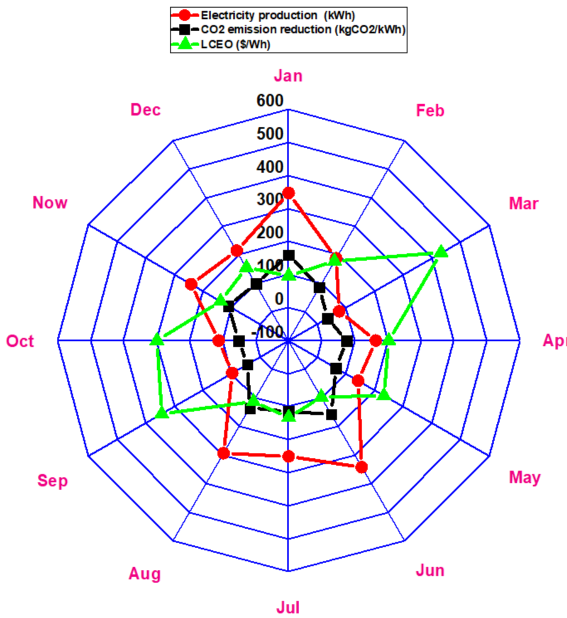

Figure 13. Monthly values of electricity generation, LCOE, and CO_2 emission reduction.

Figure 14 demonstrates the variation in annual electricity production, CO_2 emission reduction, and the corresponding economic benefits based on the number of VAWTs. As the number of turbines increases, both energy production and environmental and economic returns rise linearly. According to the analysis, with the installation of 20 turbines, annual electricity production reaches approximately 49.37 MWh, CO_2 emission reduction totals 22.69 tons, and this production generates around $5,431.06 in electricity revenue and $340.37 in greenhouse gas reduction revenue. As a result, the total annual income reaches $5,771.44.

Table 2 presents a comparison between the LCOE and capacity factor values obtained in this study and those reported in the literature. The comparison indicates that the results for both parameters are consistent with the ranges presented in previous studies. Accordingly, the LCOE and capacity factor values obtained in this study can be considered to align with those reported in the literature.

Table 2. Comparison with similar studies in literature for present study.

Parameter	Present study	Ref. [33]	Ref. [21]	Ref. [34]	Ref. [35]	Ref. [36]	Ref. [37]
Annual average wind speed (m/s)	3.02	3.81-4.22	6.3	4.72	2.57	3.5-5.5	4.88
Wind turbine rated power (kW)	5	7.5	1.5	10	10	3	10
LCOE ($/kWh)	0.161	0.228-0.265	0.058	0.18	0.54	-	20.5
CF (%)	5.62	14-17	-	-	1.76	7-16	9.49

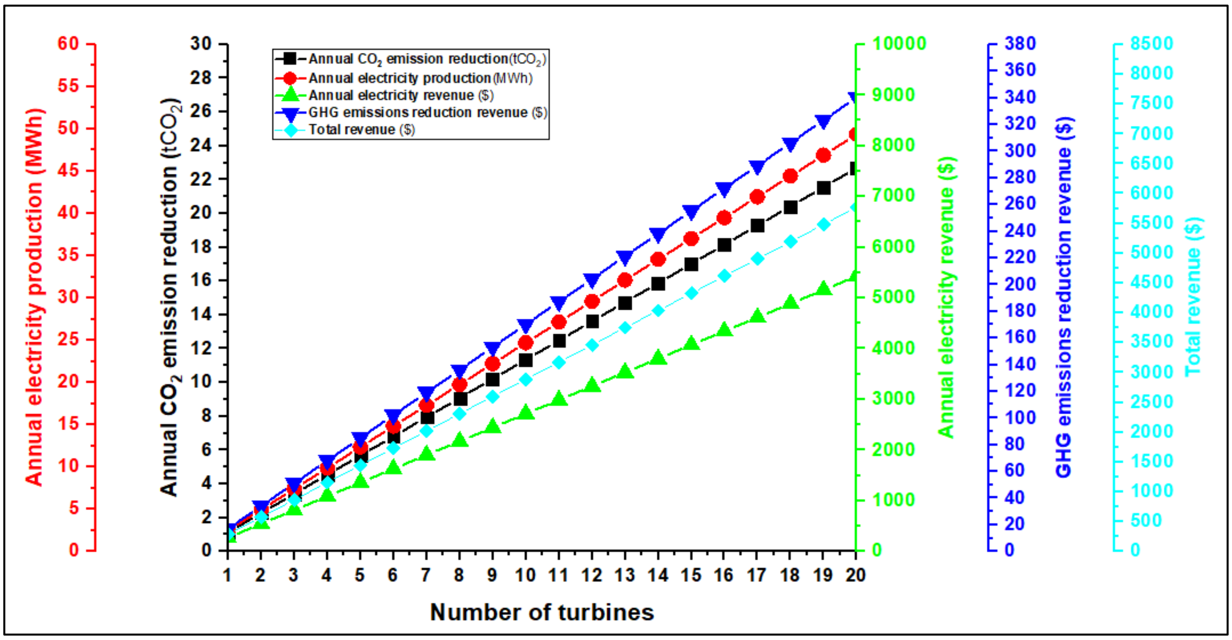

Figure 14. Variation of annual electricity generation, CO_2 emission reduction, and economic revenue depending on the number of turbines.

5. Conclusions

In this study, the energy production potential, economic benefits, and environmental impacts of a commercial VAWT planned for installation on the roof of Doğuş University have been comprehensively evaluated. The findings related to energy, economics, and the environment are summarized below:

- Based on the analysis using real meteorological data, the average Weibull shape parameter was calculated as 2.31, and the scale parameter was determined as 3.31 m/s. The highest power density values, according to both the Weibull distribution and meteorological data, were obtained in June, with values of 48.69 W/m^2 and 49.23 W/m^2, respectively.
- As a result of the energy analysis, the turbine's highest electricity production was determined to be 346.6 kWh in January, while the lowest production occurred in March at 76.9 kWh. A total of 2468.7 kWh of electricity production is projected for the year 2024.
- In the economic assessment, the revenue from annual electricity sales was calculated at $271.55, and the additional gain from reducing greenhouse gas emissions was estimated at $17.01. Therefore, the total annual revenue reaches $288.57. On a monthly basis, the lowest energy cost was approximately 0.096 $/kWh in January and June, while the levelized cost of energy (LCOE) over the turbine's lifetime was determined to be 0.161 $/kWh.
- Environmentally, the system can prevent about 1134.59 kg of CO_2 emissions annually. This clearly highlights the positive impact of the wind turbine on the environment.

In conclusion, this study shows the potential of using renewable energy in urban areas, with Doğuş University as an example. The results give useful information for urban planning and policy decisions and can help guide future sustainable energy projects. The study also points to opportunities for further research, such as improving system performance, combining different renewable technologies, and examining the energy, environmental, and economic aspects of similar systems. In general, the findings help to understand how renewable energy can be applied in cities and provide a reference for future studies and applications.

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Etik Beyanı/Declaration of Ethical Code

Bu çalışmada, "Yükseköğretim Kurumları Bilimsel Araştırma ve Yayın Etiği Yönergesi" kapsamında uyulması gerekli tüm kurallara uyulduğunu, bahsi geçen yönergenin "Bilimsel Araştırma ve Yayın Etiğine Aykırı Eylemler" başlığı altında belirtilen eylemlerden hiçbirinin gerçekleştirilmediğini taahhüt ederiz.

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