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Research Article

Exploring the Contribution of Wind Energy to the Electrical Load at Wadi Alshatti University

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Abstract: In this study, the hourly electrical consumption of the department of mechanical engineering and renewable energies at Wadi Al-Shati University was estimated, along with assessing wind speeds at the site to leverage wind energy to cover part of the electrical load during power outages. The results demonstrated the economic viability of using medium and small-capacity wind turbines at Wadi Al-Shati University due to the presence of suitable wind speeds, allowing for the cost-effective exploitation of wind energy. 6 kW wind turbines coupled with storage batteries can be used to ensure a continuous electricity supply. The annual consumption of the department was found to be 5,993 kilowatt-hours, with an average weekly consumption of about 580 kilowatt-hours. The annual productivity from the turbines reaches 9,171 kilowatt-hours, with a shortfall of 284 kilowatt-hours in electricity. Economically, the capital cost of the project was $7,818, and the Levelized Cost of Electricity (LCOE) was estimated at $0.074 per kilowatt-hour.

Keywords: Wind energy, Levelized cost of energy, Wind turbine, Environmental impact, Electrical load, Brack

1. Introduction

In 2022, wind energy production escalated by an unprecedented 265 TWh, a 14% increase, culminating in over 2,100 TWh. This marked the second-largest expansion among renewable energy technologies, surpassed only by solar photovoltaics [1-4]. Nonetheless, to align with the Net Zero Emissions by 2050 Scenario—which projects wind energy generation to reach approximately 7,400 TWh by 2030—the average annual growth rate must rise to around 17%. Realizing this objective necessitates a substantial augmentation in annual capacity installations, from approximately 75 GW in 2022 to 350 GW by 2030 [5-8]. Such an escalation in capacity growth demands significantly enhanced policy and private sector engagement, particularly in streamlining permitting processes for onshore wind projects and reducing costs for offshore wind developments.

The global trajectory is increasingly oriented towards environmentally friendly energy sources to mitigate global warming and alleviate the adverse effects of climate change [9-13]. In order to fulfill Libya's commitments to the international community as agreed upon during the Paris Conference in December 2015, Libya has unveiled its strategic plan for generating electrical power for the years 2018–2050 [14-19]. This plan stipulates that renewable energy sources will contribute approximately 35% to the energy mix by 2030, with expectations to surpass 50% by 2050. This energy will be derived from solar thermal, photovoltaic, and wind energy. Libya possesses significant potential in wind energy, as evidenced by multiple sources [20-28]. Figure 1 shows average annual wind speeds at an altitude of 100 meters. Figure 2 presents annual total horizontal solar radiation.

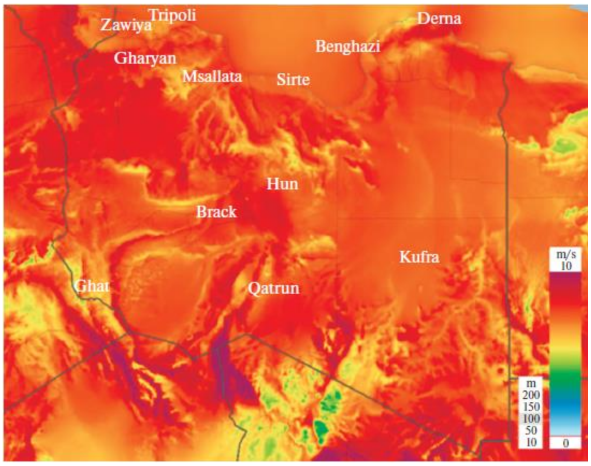

Figure 1. Average annual wind speeds at an altitude of 100 meters [29]

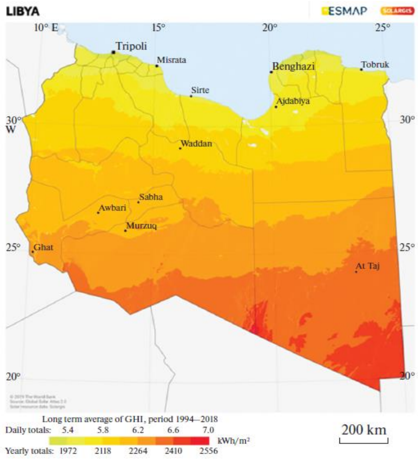

Figure 2. Annual total horizontal solar radiation [29]

Globally, as of 2022, approximately 77.6 gigawatts of wind power were integrated into electrical grids, bringing the total installed capacity to around 906 gigawatts [30-34]. It is anticipated that Africa and the Middle East will add 17 gigawatts of new capacity over the next five years (2023-2027), including 5.3 gigawatts in South Africa, 3.6 gigawatts in Egypt, 2.4 gigawatts in Saudi Arabia, and 2.2 gigawatts in Morocco [35-39]. The significance of wind energy stems from its ability to operate harmoniously with solar energy in hybrid renewable energy systems. Wind energy, characterized by its continuous electricity generation over 24 hours driven by varying wind speeds, complements solar energy, which operates during daylight hours, making it an ideal partner in hybrid systems such as Wind/Grid, PV/Wind, Wind/Diesel, Wind/CSP, and PV/Wind/Battery systems [40-45].

Despite numerous studies confirming the high economic potential of wind energy in various Libyan cities, to the authors' knowledge, there are no installed wind energy capacities in Libya. The research [46] evaluates the economic feasibility of variously scaled wind farms and, for the first time, assesses the wind energy potential across 22 locations in Libya. It employs monthly mean wind data sourced from the NASA power dataset. The analysis encompasses the determination and examination of average wind speeds, frequency distributions, and Weibull distribution's scale and shape factors. The findings highlight Darnah as an optimal site for wind farms, owing to its high wind speeds. Furthermore, RETScreen software is utilized to project energy output and perform economic feasibility studies for the wind farms.

In [47], A life cycle assessment (LCA) was conducted for a proposed wind farm consisting of ten Gamesa wind turbines, each with a capacity of 2 MW. The assessment revealed that the total primary energy consumption of the 20 MW land-based wind farm over its lifetime amounts to 56 GWh, which is significantly less compared to the 2082 GWh of electrical energy it is expected to produce. The economic benefits associated with CO_2 mitigation are substantial, with estimated cost savings of $155 million. Furthermore, the wind farm's operation leads to fuel savings valued at approximately $56.485 billion, funds that could potentially be reinvested into further development of wind energy projects.

This study is unique as it utilizes daily measurement data from Az-Zāwiyah, Libya, to evaluate wind and solar energy based on a full year of data collected in 2022. The research [48] aims to explore the viability of wind and solar energy as promising renewable energy sources for coastal agricultural regions in Libya, employing multiple datasets for the first time. In this paper, the suitability, accuracy, and reliability of five satellite products—TerraClimate, ERA5, ERA5-Land, MERRA-2, and CFSR—are assessed and compared against the measured data from January to December 2022.

The article focuses on assessing the practicality of utilizing wind energy to fulfill part of the electricity demands of the Department of Mechanical and Renewable Energy Engineering at Wadi Al-Shati University. To achieve this, the research methodically tests the efficiency and output of various commercially available wind turbines under specific environmental conditions. Key performance metrics such as energy output, reliability, and operational efficiency are measured and analyzed. Additionally, a crucial component of the study is the calculation of the Levelized Cost of Electricity

(LCOE) for each turbine model. LCOE is a comprehensive costing measure that includes all incurred costs over the lifetime of the turbine, divided by the total energy output, allowing for an effective economic comparison. This metric helps in determining which turbine models offer the most cost-effective solution for the department's energy needs. By integrating these approaches, the article aims to provide a thorough analysis of the feasibility of implementing wind energy solutions, considering both technical performance and economic viability, to help guide future energy planning at the university.

2. Methodology

This diagram delineates the step-by-step process employed in conducting the research, providing a clear visual representation of the investigative procedures and analytical methods utilized. Through this structured approach, the study systematically addresses the research objectives, ensuring comprehensive data collection, analysis, and interpretation. The methodology of the study is illustrated by a flowchart in Figure 3.

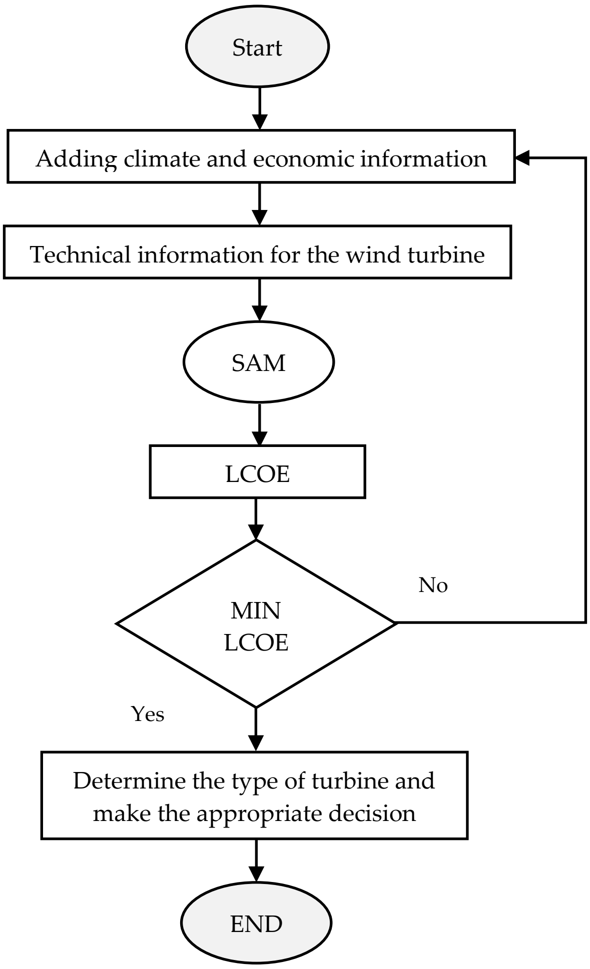

Figure 3. Flow chart illustrating the study methodology.

2.1. Study Location

Figure 4 illustrates the geographical location of the department of mechanical and renewable energy engineering at the faculty of engineering, Wadi Al-Shati University. The city of Brak is situated to the east of Wadi Al-Shati within a chain of cities that extends from Ashkada in the east to Idri in the west. Brak is the largest and most densely populated of these cities and is located between latitudes 34-37° North and longitude 14.16° East.

Figure 4. An image of the study site.

2.2. Climatic Data and Electrical Loads

Wind speed and direction were obtained from the meteorological station installed on the roof of the Department of Mechanical Engineering and Renewable Energies at a height of 15 meters above ground level for a period of three years (2017-2019), with measurements taken every 15 minutes. Figure 5 displays the wind speed and direction for the studied location. Figure 6 illustrates the hourly air temperatures for Barak City. Table 1 presents the electrical appliances, their power ratings, and the average number of weekly operating hours.

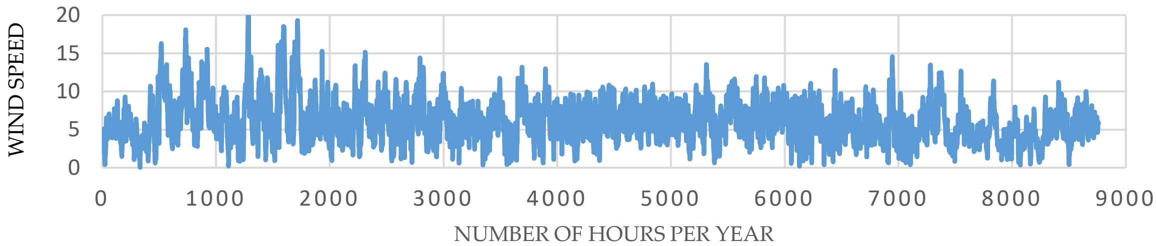

Figure 5. Wind speed and direction for the studied site.

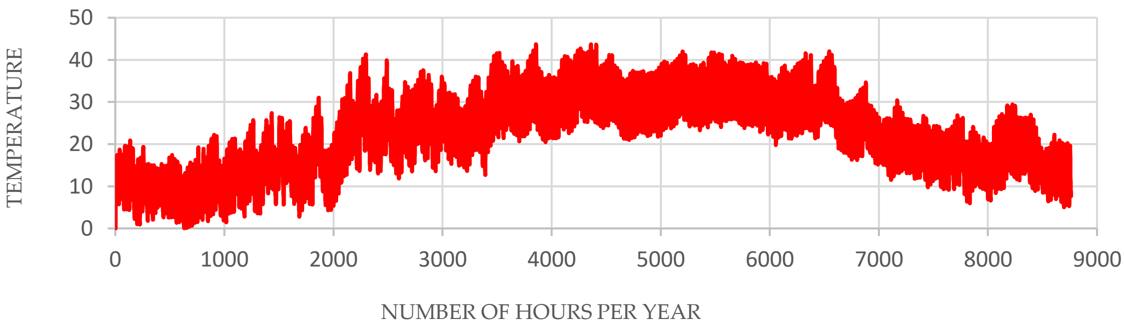

Figure 6. Annual air temperature for the city of Barak.

Table 1. Electrical appliances, power ratings, average weekly operating hours, and electrical load.

Device type	Device capacity	Number of devices	Number of operating hours h\week	Consumption
Electrical load	Power (watt)	-	Number of weekly operating hours, h/wk	Weekly consumption, Wh/wk
Long lighting	66	10	48	31680
Short lighting	12	15	36	6480
Air conditioner	1800	8	36	518400
Desktop computer	100	4	30	12000
Laptop devices	70	3	18	3780
Phone charging	7.75	4	6	186
Data Show	52	2	36	3744
The Printer	107	1	30	3210
Other Devices	500	10	1	500
Total weekly load consumption				579980
Total daily consumption				82855
Total daily ampere hours Amph/day				6905
Multiplied by the temperature correction factor for the battery (1.1)				7595

2.3. Estimation of Energy Generated by the Turbine

To estimate the annual energy production from the turbine, it is necessary to know the performance curve of the turbine, which represents the relationship between wind speed ($V_{Z,t}$) and the generated electrical power (P_t). The turbine begins generating power at a specific wind speed known as the cut-in speed (V_{cut-in}), approximately 3 m/s. The amount of energy produced increases as the wind speed rises until it reaches the rated speed for the turbine's nominal power (V_{rat}). Beyond this speed, the turbine produces a constant amount of energy equal to the nominal power of the turbine (P_{rat}) until the wind speed exceeds the cut-off speed ($V_{cut-off}$), at which point the turbine ceases to rotate. With knowledge of the technical specifications of the tested wind turbines, the instantaneous energy quantity ($P_{WT(t)}$) and the annual production ($P_{WT,a}$)generated by the turbine can be calculated as following Eq. (1).

$$P_{WT}(t) = \begin{cases} P_{rat}\left(\frac{V_{Z,t} - V_{cut-in}}{V_{rat} - V_{cut-in}}\right) & V_{cut-in} < V_{Z,t} < V_{cut-off} \\ 0 & V_{Z,t} \leq V_{cut-in} \; OR \; V_{Z,t} \geq V_{cut-off} \end{cases} \quad (1)$$

Where the subscript Z represents the height of the turbine tower, while the symbol t denotes time. Additionally, wind speeds at different heights than those measured can be calculated using the power law from the Eq. (2).

$$V_{Z,t} = V_{0,t}\left(\frac{h_Z}{h_0}\right)^{\propto} \quad (2)$$

Where $V_{0,t}$ and $V_{Z,t}$ represent the wind speed at time t at the height of the wind speed measurement device and at the height of the wind turbine tower (m/s), respectively. The symbols h_0 and h_Z denote the height of the measurement device and the height of the turbine tower above the ground surface (m), respectively. The symbol α represents the wind shear stress coefficient, which varies according to the roughness, terrain, and atmospheric stability of the studied area. In this research, α has been considered as 1/7, based on the recommendations of several local studies. Consequently, the estimated average annual energy production ($P_{WT,a}$) is calculated as following Eq. (3).

$$P_{WT,a} = \frac{1}{n}\int_{1}^{35040\times n} P_t dt \quad (3)$$

Where the number 35040 represents the count of data points every 15 minutes throughout the year, and n denotes the number of years.

2.4. Storage Battery Capacity

The capacity of storage batteries can be calculated from the following Eq. (4):

$$SOC(t) = SOC(t-1).(1-\sigma) + \left(\left(P_{WT}(t)\right) - \frac{P_L(t) + P_{EV_{Dem}}}{\eta_{inv}} \right) \times \eta_b$$
$$SOC(t) = SOC(t-1).(1-\sigma) + \left(\frac{P_L(t) + P_{EV_{Dem}}}{\eta_{inv}}) - P_{WT}(t) \right) \times \eta_b \quad (4)$$

2.5. Levelized Cost of Electricity (LCOE)

The levelized cost of electricity for an onshore wind farm is determined by the total installation costs, the capacity factor over the lifespan, operational and maintenance costs, the economic lifetime of the project, and the cost of capital. While all these factors are important in determining the levelized cost for a project, some components have a greater impact than others. For example, the cost of turbines (including towers) is the most significant element in the total installation costs for an onshore wind energy project. With no fuel costs, the capacity factor and capital cost also have a significant impact on the LCOE. It can be calculated from the following Eq. (5).

$$\text{LCOE} = \frac{\frac{i(i+1)^n}{(i+1)^n - 1} \times c.c + O\&M - Cco2}{\text{E pro}} \quad (5)$$

Where:
n = Turbine lifespan (30 years).
i = Annual interest rate (8%).
C.C = Capital cost ($).
O&M = Operating and maintenance costs ($/year).
$Cco2$ = Environmental damage cost ($/year).
E pro = Annual energy production (KWh/year)."

2.6. System Advisor Model (SAM):

SAM is considered a dynamic program for simulating the performance of a wide range of renewable energies, through which an economic study can be conducted to calculate various economic and energy indicators such as: annual production, capacity factor, Levelized Cost of Electricity (LCOE), as well as capital costs and Net Present Value (NPV). LCOE has been adopted as an indicator to choose the best technology for a specific location. The program's suitability for use in Libya has been verified by several local researchers.

2.7. Assumptions, Limitations, and Sources of Uncertainty in the Study

To facilitate calculations, this study adopts the following assumptions:

- Wind speed and direction are constant over 15 minutes.
- Stable electrical consumption in the department.
- Technical specifications of wind turbines as provided by the manufacturer are not affected by weather factors such as heat, dust, and rain.
- There are no losses in electrical connections between the generation system, storage system, and consumption system.

- Degradation in turbine performance over time is not accounted for.
- Standard specifications of atmospheric air

Data of all types—climatic, technical, economic, and environmental—represent one of the main sources of uncertainty in the study results. Another area of uncertainty is the cost of wind energy equipment. Nassar and Alsadi [49,50] observed a variance in the prices of renewable energy technology equipment exceeding 360%. Significant variations in air emission coefficients were also observed.

3. Results and Discussion

This section provides a detailed analysis centered on three key aspects: estimating energy consumption patterns, examining the productivity of small-scale wind energy systems, and determining the capacity factor. This section aims to evaluate how effectively these small wind systems perform under various conditions and their potential contribution to sustainable energy goals. Additionally, it discusses the implications of these findings for optimizing wind energy utilization and improving system designs for enhanced efficiency.

3.1 Estimation of Consumption

To estimate the electrical consumption of the management office of the Department of Mechanical Engineering and Renewable Energies, data on electrical consumption were collected over a specific time period during peak hours, and then the consumed energy was measured using electricity meters. The load curve is graphically represented in Figure 7.

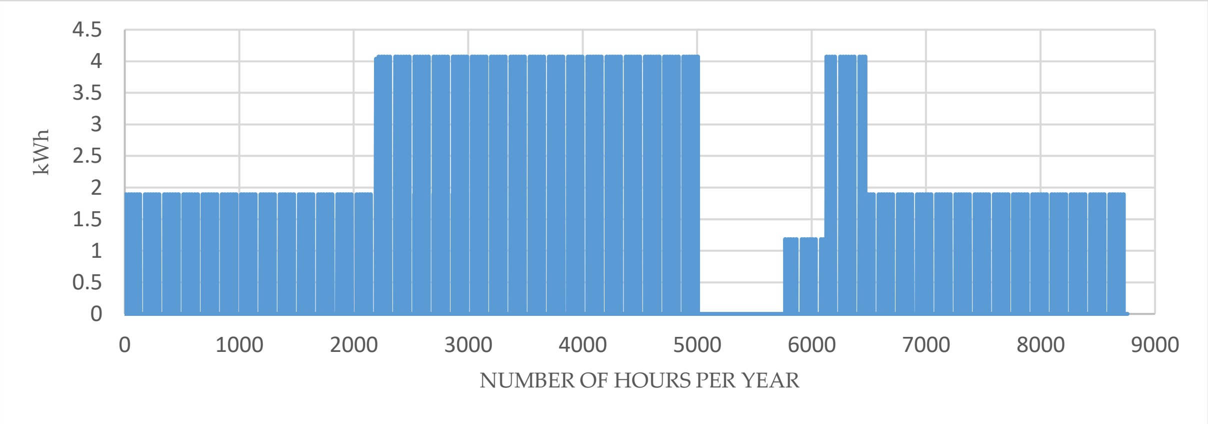

Figure 7. Electrical load of the management office of the department of mechanical engineering and renewable energies.

The method begins by importing data which includes meteorological data and data necessary for economic analysis such as extracted power and economic calculations for wind energy, computed using the SAM program. Afterward, the data were processed using Microsoft Excel to optimize the design and size of the wind energy system.

3.2 Productivity of Small Wind Energy

The energy production is obtained through the SAM program from the renewable energy laboratory, which produces productivity for wind turbine farms with capacities of 4 kW, 5 kW, 6 kW, and two turbines of 3 kW each. The productivity illustrates the power output diagrams from a wind turbine farm for the types of turbines used in energy generation (Anelion Sw3.5 GT 3.5m, Kestrel e400i, Evance R9000, Eoltec Scirocco E5.6-6). The technical specifications of the wind turbines are listed in Table 2. Figure 8 represents the power curve of a 3-kW wind turbine. Meanwhile, Figure 9 displays the electrical power produced by two turbines with a load capacity of 6-kW each.

Table 2. Wind Turbine Specifications.

Specifications	3KW	4kW	5kW	6kW
Maximum power	3300	3500	5000	6000
Initial speed of operation	m/s 2.5	m/s3.5	m/s3	m/s 2.7
Maximum operating speed	m/s11	m/s17.5	m/s60	m/s60
Number of feathers	3	3	3	2
Feather diameter	m4	m3.5	m5.5	m5.6
Tower height	m-15 m12	m10	80m–m10	12m15-m
Rotational speed	rpm520	rpm145	rpm200	rpm 245

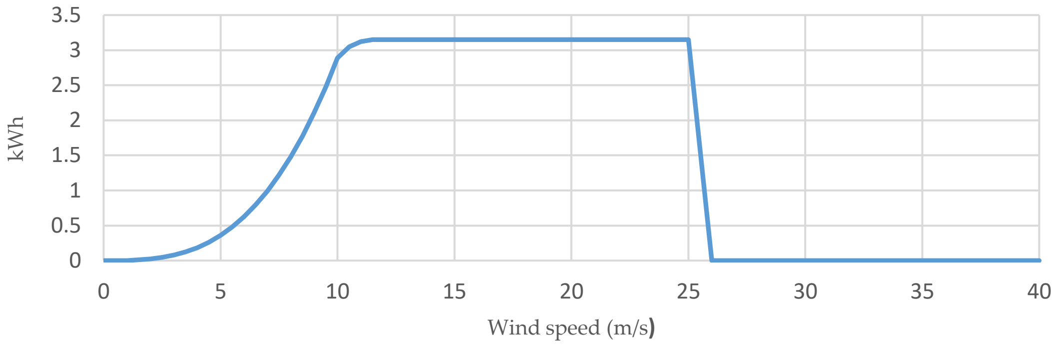

Figure 8. Power curve of a 3-kW turbine.

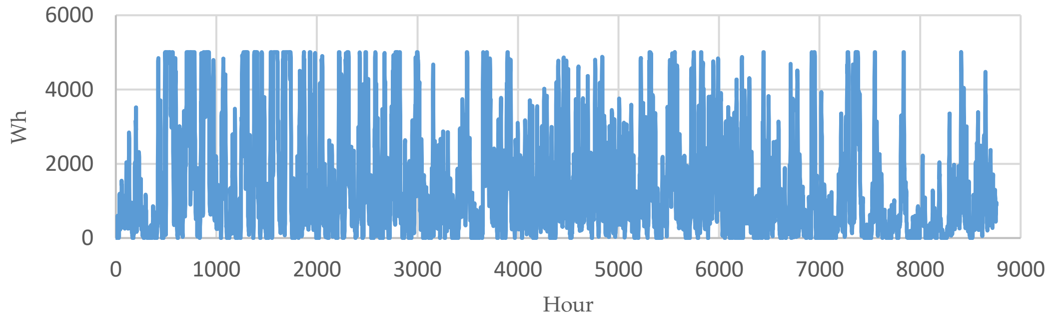

Figure 9. The energy produced from a 6-kW wind farm.

Based on the simulation using the SAM program for a 2x3 kW wind turbine, which starts generating energy at a wind speed of approximately 2.5 m/s, and as the wind speed increases, so does the productivity. Figure 10 represents the power curve of a 4-kW wind turbine. Meanwhile, Figure 11 displays the electrical energy produced by a 4-kW turbine.

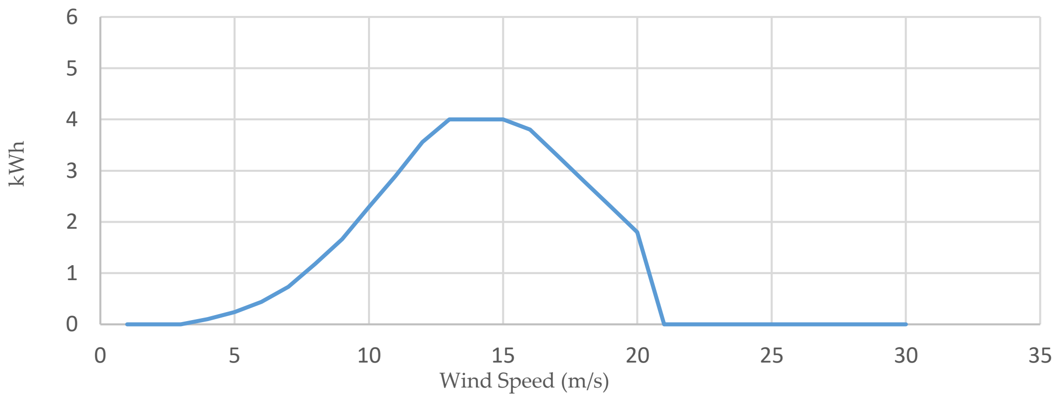

Figure 10. The power curve for a 4-kW turbine.

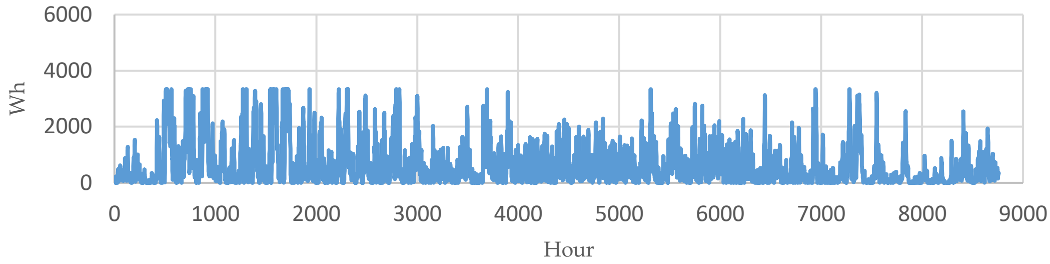

Figure 11. The energy produced from a 4-kW wind farm.

It is observed through simulation using the SAM program for a 4-kW wind turbine that it starts generating energy at a wind speed of approximately 3.5 m/s, and thereafter, as the wind speed increases, so does the productivity. Figure 12 represents the power curve of a 5-kW wind turbine. Meanwhile, Figure 13 displays the electrical energy produced by a turbine with a capacity of 4-kW.

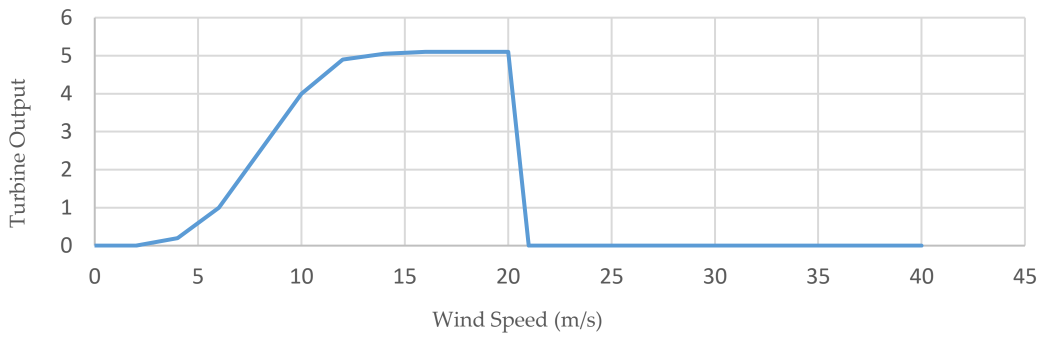

Figure 12. Power curve for a 5-kW turbine.

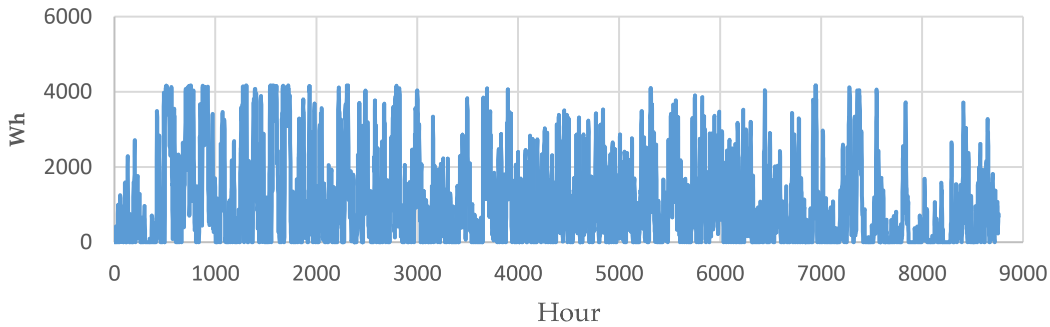

Figure 13. The energy produced from a 5-kW wind turbine.

It is also noted from the simulation using the SAM program for a 5-kW wind turbine that it starts generating energy at a wind speed of approximately 3 m/s, and as the wind speed increases, so does the productivity. Figure 14 represents the power curve of a 4-kW wind turbine. Meanwhile, Figure 15 displays the electrical energy produced by a turbine with a capacity of 6 kW.

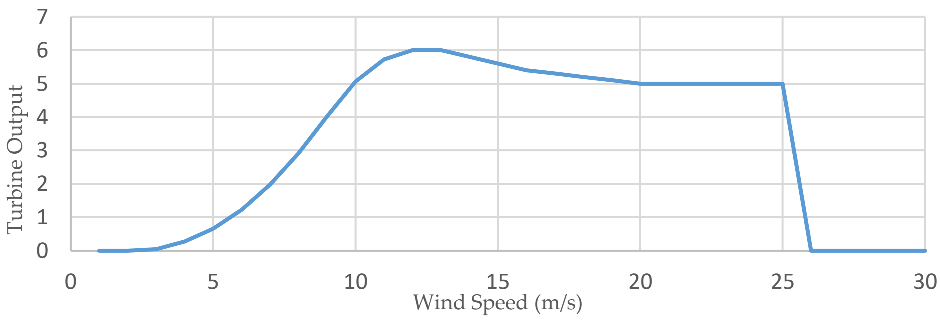

Figure 14. The power curve of a 4-kW wind turbine.

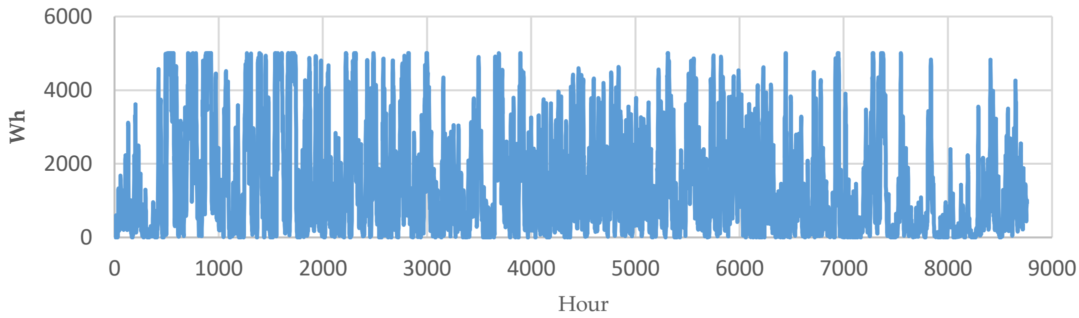

Figure 15. The electrical energy produced by a turbine with a capacity of 6 kW.

It is also observed through the simulation using the SAM program for a 6-kW wind turbine that it begins generating energy at a wind speed of approximately 2.7 m/s, and as the wind speed increases, so does the productivity.

3.3. Capacity Factor

There are many energy indicators for wind farms, and the Capacity Factor is one of the most important. It is defined as the ratio of the annual energy produced by the farm to the energy that should be produced throughout the year. It is expressed as following Eq. (6):

$$CF = \frac{E_{pro}}{P \times 8760} \tag{6}$$

Where:
E_{pro} is the annual energy produced (kWh/year).
P is the capacity of the farm (kW).

3.4 Environmental Analysis CO2

Calculating the environmental damage caused by CO2 emissions from the smokestacks of power plants provides a fair opportunity for renewable and clean energies to compete in the energy market, even in oil-producing countries and those that subsidize electricity as illustrated in Eq. (7) and (8).

$$M_{CO2} = EF_{CO2} \times E_{pro} \tag{7}$$

$$C_{CO2} = M_{CO2} \times \emptyset_{CO2} \tag{8}$$

Where:
E_{pro} is the annual energy produced (kWh/year).
EF_{CO2} is the CO2 emission factor, which equals 0.967 kgCO2/kWh.
M_{CO2} is the annual environmental damage in terms of CO2.
C_{CO2} represents the environmental damage.
$\emptyset_{CO2}$ is the cost of environmental damage, estimated at approximately $75 per ton of CO2.

4. Results

The study was conducted on four different types of small wind energy systems, consisting of wind turbine farms of varying capacities, to assess their ability to provide sufficient energy supplies. Most of them failed to achieve the energy balance required for the desired load and also failed to cover the consumption adequately, as shown in Figure 16 and Figure 17 However, the results of the remaining wind turbine farms demonstrated that they could adequately cover the consumed loads, with the capability to generate energy at an 80% rate as illustrated in Figures 18 and Figures 19, thereby meeting the energy needs of the studied region.

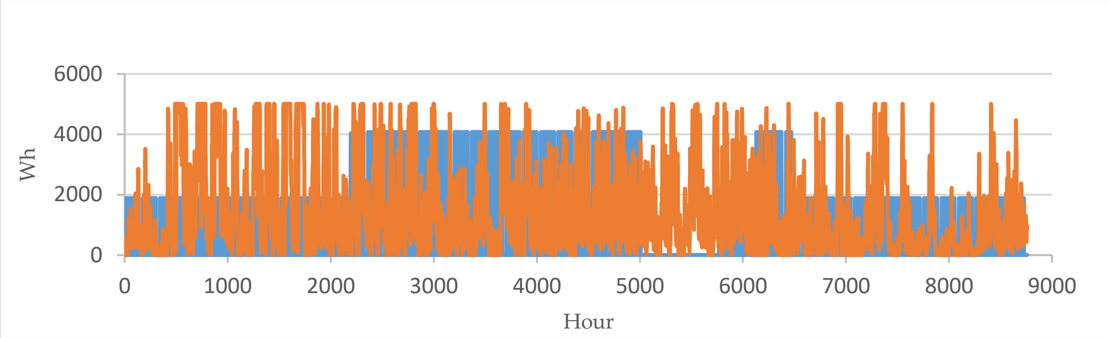

Figure 16. Productivity of a 3-kW wind farm with consumption.

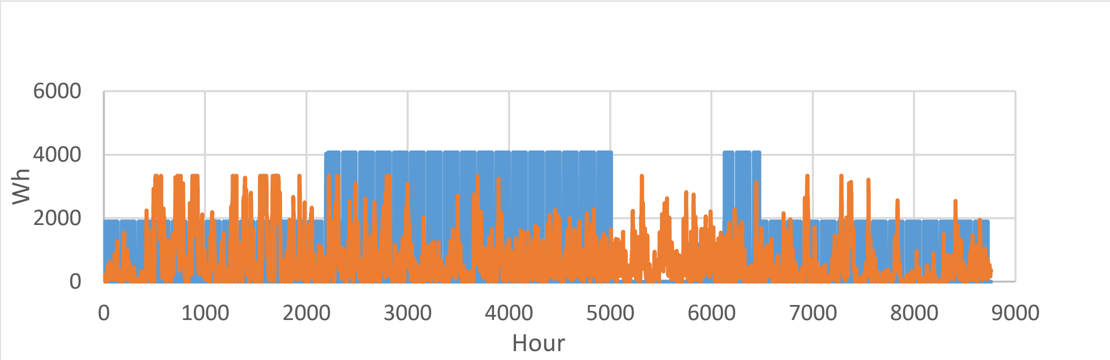

Figure 17. Productivity of a 4-kW wind farm with consumption.

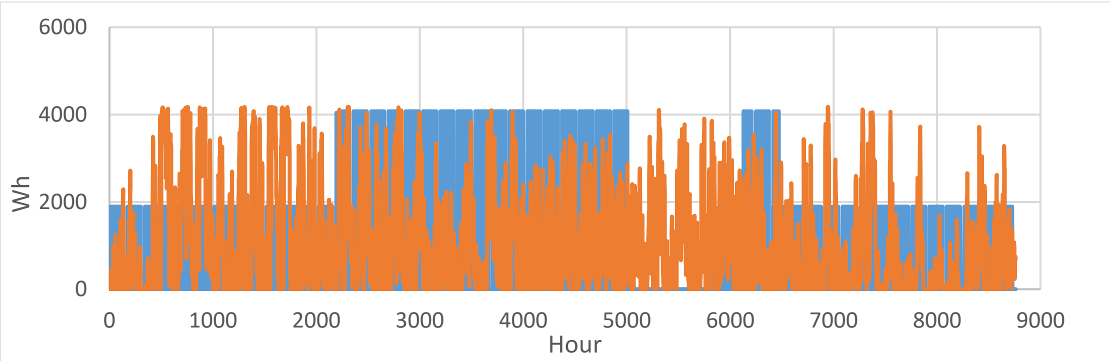

Figure 18. Productivity of a 5-kW wind farm with consumption.

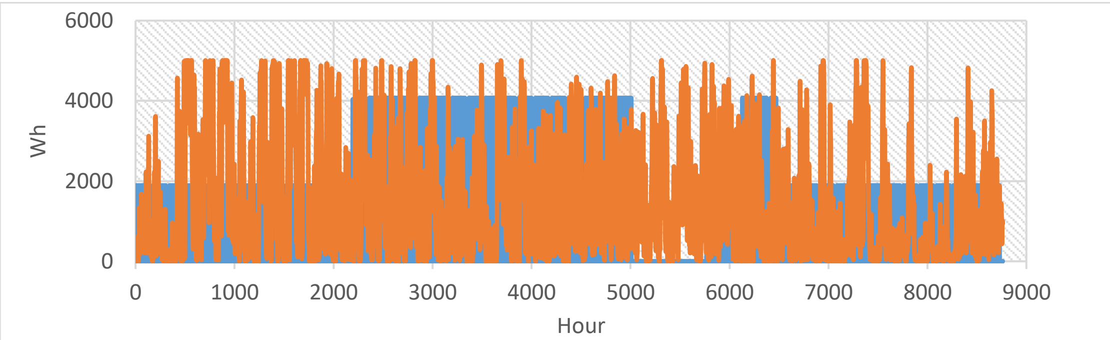

Figure 19. Productivity of a 6-kW wind farm with consumption.

From the study presented, which discussed the productivity of several turbines with varying capacities ranging between (3, 4, 5, 6) kilowatts per hour, it became apparent that productivity differences depend on the type of turbine, the number of blades, the size of the turbine, and the wind speed per hour. It was also evident that using a 3-kilowatt turbine is the best option during the winter, when electrical loads decrease. Meanwhile, a 6-kilowatt turbine can cover the electrical loads during the summer, when loads increase due to the operation of air conditioning units within the department. Additionally, it proved to be the least costly option compared to other systems, with the levelized cost of electricity being approximately 0.35 Libyan dinar. Figures 20 to 23. illustrate the energy balance for several wind power generation systems with capacities of 3, 4, 5, and 6 kW respectively. Table 3 shows the results of economic calculations and the cost of producing a unit of energy (LCOE).

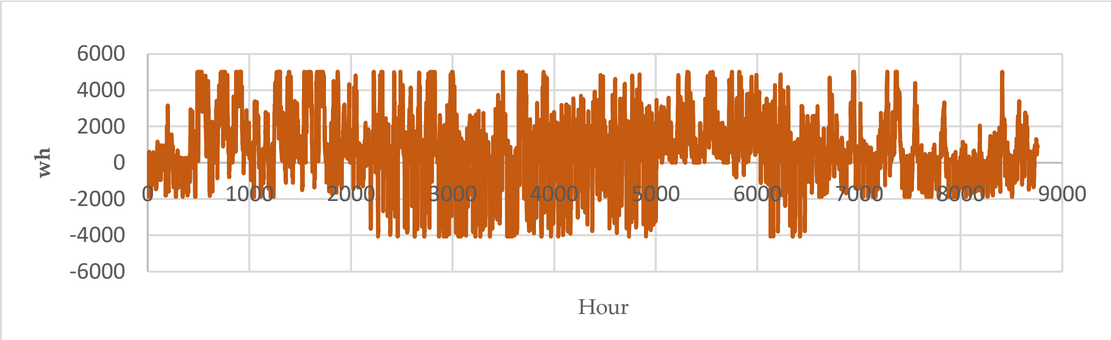

Figure 20. Energy balance for the 3-kW system

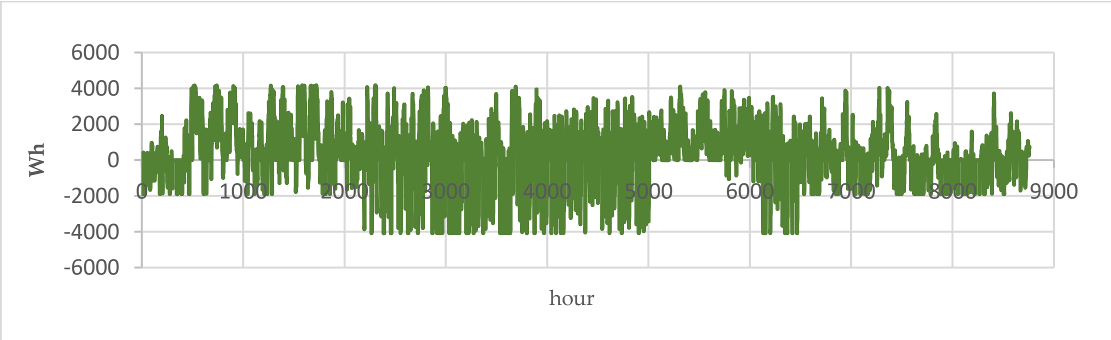

Figure 21. Energy balance for the 4-kW system.

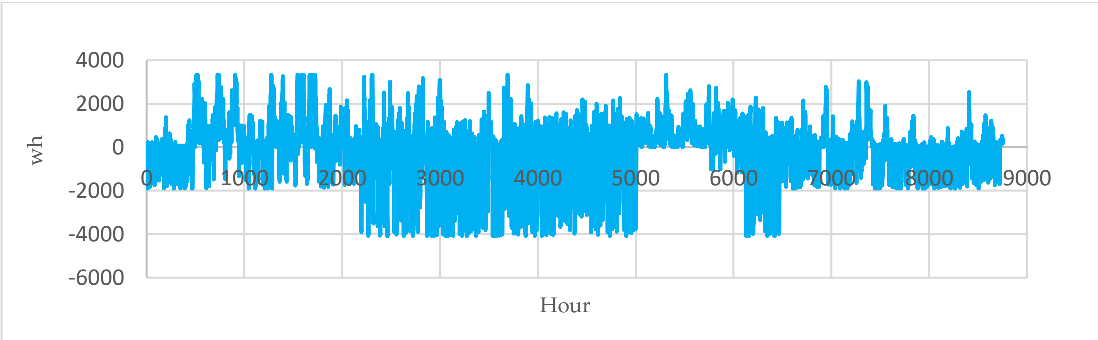

Figure 22. Energy balance for the 5-kW system.

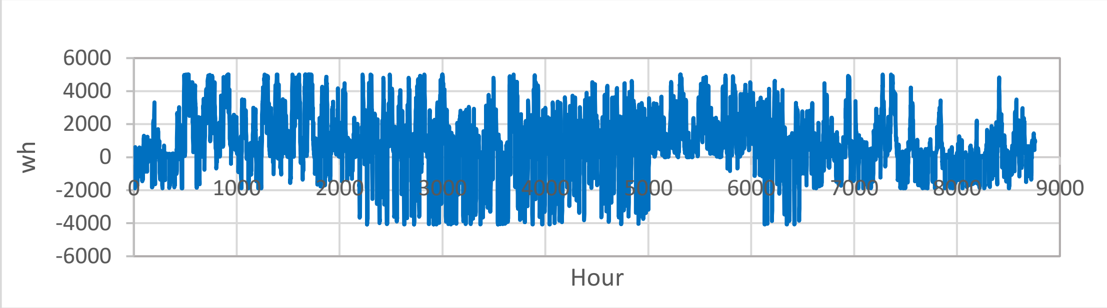

Figure 23. Energy balance for the 6-kW system.

Table 3. Economic Costs of the SAM Program for the Turbines Used.

Turbine	Turbine type	Cost of capital $/kW	Maintenance and operation cost year/$	LCOE $/kWh
3-kW	Kestrel e400i	3909	126	0.078
4-kW	Anelion Sw3.5 GT 3.5m	5212	168	0.12
5-kW	Evance R9000	6515	210	0.091
6-kW	Eoltec Scirocco E5.6-6	7818	252	0.074

5. Conclusions

Wind turbines with medium and small capacities are found to be highly effective for use at the University of Wadi Al-Shati, specifically due to the prevailing wind speeds that range from 2 meters per second (m/s) to 20 m/s. This range is optimal for maximizing the operational efficiency of wind turbines, allowing them to produce energy most effectively throughout the year. The Department of Mechanical Engineering and Renewable Energies can significantly benefit from these turbines. By harnessing wind energy, the department can fully cover its electrical demands throughout the different seasons — winter and summer. This self-sufficiency not only reduces reliance on traditional power sources but also supports environmental sustainability efforts. In scenarios where the turbines generate more electricity than the university consumes, the excess power can potentially be fed into the public electrical grid. This not only ensures a continuous supply of power during times when there are no disruptions to the main power supply but also positions the university as a contributor to the local energy market. The annual output from these turbines is estimated to be approximately 9,171,070.52 kilowatt-hours (kWh), which leads to an excess of 6,329,888 watts that could potentially be redirected or stored. Economic analysis reveals that the Levelized Cost of Electricity (LCOE) is approximately $0.074 per kWh. This low cost of energy production makes the project economically viable and sustainable. The favorable LCOE underscores the project's potential for cost recovery and profitability, making it an attractive investment in terms of both economic and environmental returns. By further developing and optimizing these systems, the university not only enhances its operational sustainability but also contributes to broader goals of energy independence and environmental stewardship.

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