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OPTIMIZING WIND POWER PLANTS: COMPARATIVE ENHANCEMENT IN LOW WIND SPEED ENVIRONMENTS

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Abstract. *The study aims to optimize wind farm efficiency in low wind speed regions using the HOMER Pro tool to examine the impact of wind turbine ratings on overall efficiency of wind farms. boosting wind farm efficiency is essential for improving economic viability and grid integration. We propose the establishment of three wind farms, each possessing equal capacities but different in individual turbine capacities 1.5 kW, 3.4 kW and 5.1 kW, then optimize their performance in simulation environment. Through employing HOMER Pro optimization algorithm, we assess all wind farms over the period of one year, taking into account wind speed, temperature and geospatial coordinates. Although all wind farms have equal total capacities, simulation results revealed disparities in their generation abilities, reaching up to 22%, favouring the farm with smaller turbines. Furthermore, the results demonstrated that as wind speed decreases, the disparity in power generation between wind farms increases, reaching 51.9% in November, the month with the lowest wind speeds. These findings provide a comprehensive understanding of wind farm behaviour, particularly regarding turbine sizes, and contribute to the research community's efforts to enhance wind farm power production in low wind speed regions. They also help find solutions to enable the embrace of wind energy and decrease fossil fuel consumption in such regions, fulfilling their international sustainability commitments.*

Keywords: wind turbine optimization, wind farms, HOMER, low wind speed regions, wind turbine sizing

OPTYMALIZACJA FARM WIATROWYCH: PORÓWNAWCZE ZWIĘKSZENIE WYDAJNOŚCI W WARUNKACH NISKIEJ PRĘDKOŚCI WIATRU

Streszczenie. *Opracowanie ma na celu optymalizację wydajności farm wiatrowych w regionach o niskiej prędkości wiatru przy użyciu narzędzia HOMER Pro w celu zbadania wpływu mocy turbin wiatrowych na ogólną wydajność farm wiatrowych. Zwiększenie wydajności farm wiatrowych ma zasadnicze znaczenie dla poprawy rentowności i integracji z siecią. Proponujemy utworzenie trzech farm wiatrowych, z których każda ma taką samą moc, ale różni się mocą poszczególnych turbin 1,5 kW, 3,4 kW i 5,1 kW, następnie optymalizujemy ich wydajność w środowisku symulacyjnym. Wykorzystując algorytm optymalizacji HOMER Pro, oceniamy wszystkie farmy wiatrowe przez okres jednego roku, biorąc pod uwagę prędkość wiatru, temperaturę i współrzędne geoprzestrzenne. Chociaż wszystkie farmy wiatrowe mają taką samą moc całkowitą, wyniki symulacji ujawniły różnice w ich zdolnościach generacyjnych, sięgające nawet 22%, faworyzując farmę z mniejszymi turbinami. Co więcej, wyniki wykazały, że wraz ze spadkiem prędkości wiatru wzrasta rozbieżność w wytwarzaniu energii między farmami wiatrowymi, osiągając 51,9% w listopadzie, miesiącu o najniższych prędkościach wiatru. Wyniki te zapewniają kompleksowe zrozumienie zachowania farm wiatrowych, w szczególności w odniesieniu do rozmiarów turbin, i przyczyniają się do wysiłków społeczności badawczej w celu zwiększenia produkcji energii przez farmy wiatrowe w regionach o niskiej prędkości wiatru. Pomagają również znaleźć rozwiązania umożliwiające wykorzystanie energii wiatrowej i zmniejszenie zużycia paliw kopalnych w takich regionach, wypełniając ich międzynarodowe zobowiązania w zakresie zrównoważonego rozwoju.*

Słowa kluczowe: optymalizacja turbin wiatrowych, farmy wiatrowe, HOMER, regiony o niskiej prędkości wiatru, dobór wielkości turbin wiatrowych

1. Problem background

The deployment of wind farms has emerged as a prominent strategy for investing in wind energy but numerous global regions contend with low wind speeds, presenting challenges in the utilization of wind farms for electricity generation; however, the efficacy and success of such installations are notably contingent upon the judicious selection of turbine types. As a result, extensive research endeavors have been undertaken to discern turbines suitable for distinct environments and geographical locations, ensuring optimal efficiency in these systems. This scholarly paper centres on a pivotal aspect of wind farm development, namely, the rate capacity of the turbines deployed.

Our research team is currently focusing on the remote area in the middle east known as the Aljazeera area, characterized by low wind speeds. Our previous research [13] examined the potential for agricultural reclamation in this region using a novel solar pumping system, and we mentioned this area's significance to both local and global communities. Stretching from the north of Sinjar Mountain to the south valley of Euphrates River and surrounded in Tharthar valley to the east and the Syrian – Iraqi international borders to the west [18], this area spans 29,270 km^2, representing about 6.7% of Iraq's total area [2]. The climate here is hot semi-arid, approaching Mediterranean, with scorching, dry summers, mild shoulder seasons, and moderately wet, relatively cool winters. Average wind speeds in this region do not exceed 5.8 m/s [1], making the establishment of wind farms unviable due to the prevailing low wind speeds.

However, wind energy presents a promising, yet untapped, sustainable resource, necessitating the urgent establishment of wind farms for sustainable electrical energy generation in the Aljazeera area and other regions globally facing similar challenges of low wind speed. Nonetheless, the impact of turbine rating on the efficiency of these farms remains an overlooked aspect.

1.1. Motivation

Iraq, like numerous other nations, has pledged its commitment to the Paris Agreement and has embraced the Sustainable Development Goals outlined by the United Nations [19]. To attain these goals, a comprehensive national strategy has been formulated, emphasizing the growing significance of embracing sustainable energy systems. The shift towards renewable energy solutions is become highly competitive and is anticipated to be a forthcoming imperative. Nevertheless, a thorough scientific inquiry into the impact of turbine size variations on the efficiency of potential wind farms is essential for the future of wind energy in the studied region and other global areas grappling with similar challenges of low wind speeds. Additionally, the finding of this research could assist the research community in overcoming obstacles associated with constructing wind farms in low wind speed environments, such energy generation obstacles, economic viability and grid integration problems, which significantly reducing reliance on fossil fuels and mitigating the associated issues of air pollution and global warming.

1.2. Literature reviews

The literature review will categorize studies into two groups: global and local. In the global category, we'll highlight recent research focusing on enhancing wind farms efficiency. In the local category, we'll cover all studies pertaining to the wind energy sector within the study area.

- Globally:

Arroyo et al. [5] enhancing wind farms efficiency by employing dynamic rating operation of power lines, particularly focusing on a Spanish overhead power line. they analyze different scenarios and demonstrates how dynamic rating operation contributes to more energy generation while decreasing the environmental footprint. Li et al. [16] employing a reinforcement learning based method with multi-agent deep deterministic policy gradient to enhance the yaw maneuver of gathered wind turbines in wind power farms in order to increases power production and significantly improves control efficiency. Sagbansua et al. [20] improve wind farms efficiency by selecting the best wind turbine through expert interviews, literature review, and a decision-making model based on technical, economic, environmental, and customer attributes. Zhu et al. [26] integrate wind farm with a thermodynamic process based on the Kalina cycle and a storage system based on liquid air energy storage technology. the authors achieved a 6.7% improvement in electric round-trip efficiency. Zhang et al. [24] improve wind farms efficiency by proposing a bilevel non-uniform optimization approach for wind farm layout optimization and electrical cable routing simultaneously. The proposed approach is validated through realistic offshore wind farms, showing a decrease in cost of energy by 1.0%. This approach demonstrates potential for improving offshore wind farm efficiency, particularly for turbines of varying power capacities. Da Silva et al. [7] employing a technical and economic analysis of the Interference caused by repowering In neighboring wind farms. they employed PyWake software to analyze wake interference and calculate energy production. Results revealed significant energy deficits in existing wind farms due to repowering activities. Mittal et al. [17] proposed a novel method involving the use of acoustic metamaterials to suppress noise pollution in wind farms while simultaneously enhancing energy output. Zhang et al. [25] enhances wind farm efficiency by proposing a method to accurately Identify the admittance model of wind farms under various operating conditions. By analyzing the frequency-coupling characteristics of wind farms, the authors identify the power-sharing ratio of wind turbine generators as a key factor affecting admittance characteristics. Wang et al. [21] proposed a synchronized optimization method that considers cooperative control of start-stop, yaw, and turbine positions. By employing a three-dimensional wake model and a yaw flow superposition model, the suggested approach enhances the wind farm's power output by 8.85%. Hu et al. [10] proposed a novel hybrid method for wind farm layout optimization In complex terrain. The method combines an elliptical modeling approach with computational fluid dynamics simulations and measured wind data to estimate wind resources. Results demonstrate that the proposed method providing a more favorable wind farm layout in complex terrain, thereby enhancing overall efficiency.

- Locally:

There is a scarcity of research focused on wind energy within the study area. The following compilation highlights selected studies conducted either in the study region or its vicinity. Al-Taai et al. [3] conducted a study on the feasibility of utilizing wind energy for electricity generation in Iraq. They collected daily average wind speed data from fifteen different stations in various regions of Iraq for the period from April 1, 2011, to April 1, 2012. The study considered three different heights (12, 50, and 100 meters) and applied a 3 kW wind turbine. The authors calculated wind energy and wind density for the particular locations, Discovering the peak values in Basrah, moderate values in Baghdad, and the lowest values in the northern area of Mosul. The authors depend graphical method to calculate the Weibull distribution, they observed highest values for Weibull parameters at Basrah while the medium and lowest values in Baghdad and Mosul respectively. Finaly the study estimates the potential of wind power in Iraq by examine wind speed data for different sites and heights. Al-ubeidi et al. [4] conduct research at the Technical Institute in Mosul, they aimed to assess wind speed for electricity generation, focusing on laboratory usage. They designed and fabricated a windmill positioned on a 30 m turret above sea level. They measured wind speed every 20 seconds using an Anemometer device and averaged over 10 minutes, which was then further averaged over one hour. The Weibull Possibility Density Function for wind potential is estimated from the mean wind speed information, revealing a connection between average wind speed (V) and the scale factor (c) as $c = 1.495\,V$. Results indicated average wind speed of 6.2 m/s for large parts of March, suggesting sufficient wind power for generating electricity at this month. The study demonstrated efficiency and compatibility between measured wind speed and the Weibull Probability Density Function, affirming the potential for electricity generation at the Technical Institute in Mosul. The paper of Hassoon, A. F [9] addresses the significance of wind energy as a renewable and environmentally friendly resource, crucial for various applications. Despite its potential, the absence of a dependable Iraq Wind Atlas necessitates additional studies on wind energy evaluation. The primary focus is on investigating the wind energy prospects in the north part of Iraq. Over nearly three decades, wind data from five different locations were collected and examined utilizing the two-parameters Weibull possibility distribution function. Tuz and Tikrit stations exhibited the highest probability frequency wind speeds, with Tuz showing dominance in the range of 2.5-3.0 m/s. Tikrit displayed high frequency in the ranges of 3.5-4.0 m/s and 4.0-4.5 m/s. Conversely, Biji, Kirkuk, and Mosul demonstrated high frequency in low wind speeds. The study advocates for wind energy in northern Iraq and aims to contribute to the creation of a comprehensive Wind Atlas for the country. Dihrab, S. S. et al. [8] address Iraq's growing energy demand and insufficient power generation by proposing a hybrid system utilizing solar and wind energies. They simulate the system's feasibility in three Iraqi cities Basrah, Mosul, and Baghdad using MATLAB solver with meteorological data. The hybrid system, comprising PV modules and wind turbines, proves effective for grid-connected applications. The simulation indicates that Basrah is the optimal location for the hybrid system, generating the highest power output from both PV modules and wind turbines. They emphasize the significance of plant location, as relocating to Mosul instead of Basrah could result in a more than 15% decrease in total power output. Kazem H. A. et al. [15] address Iraq's current electricity shortages and the challenges in meeting future demands. They highlight underutilization of solar, wind, and biomass energy sources, emphasizing their potential role in Iraq's renewable energy future. The investigation calls for a thorough examination of wind energy potential in Iraq. The authors discuss the government's attempts at incorporating renewable energy and review the current status of solar, wind, and biomass usage. The paper concludes with recommendations, emphasizing the need for increased investment of these clean energy sources to address Iraq's energy challenges and pave the way for a more sustainable future.

1.3. State of the art and limitations

As indicated in existing literature, there is no studies highlights the influence of wind turbine rating on wind farms efficiency, especially in low wind speed environment. Additionally, in local aspect all previous studies indicate that Mosul, the closest region to the study area "Aljazira desert", encounters the least average wind speed, presenting a considerable challenge for the advancement of wind energy. Notably, there have been no suggestions to establish wind farms or improve wind energy investment in the region. This research seeks to fill this research gap by examining how variations in turbine rating size affect the efficiency of prospective wind farms in low wind speed environment.

1.4. The research contribution

The research breaks new ground in enhancing wind farm efficiency in regions with low wind speeds by investigating the impact of varying the rated capacity of the wind farm turbines on overall wind farm efficiency. The study proposes the establishment of three distinct wind farms, each possessing a capacity of 51 kW as shown in Fig. 1. Wind Farm-A will be composed of 34 small turbine units, each with a capacity of 1.5 kW, Wind Farm-B will be composed of 15 Medium turbine units, each with a capacity of 3.4 kW, while Wind Farm-C will incorporate 10 large turbine units, each with a capacity of 5.1 kW. It is imperative to note that all turbines utilized in this study will be sourced from the same manufacturer.

Subsequently, these wind farms will undergo operation for a complete annual cycle within a simulated software environment resembling the geographical conditions of the target region. The HOMER Pro will be employed for this simulation, incorporating considerations for temperature and wind speeds prevalent in the specified region as well as turbines models. The primary objective of this investigation is to assess the energy output of each farm, ultimately determining the impact of turbines capacity for wind farms performance within the designated environmental parameters. The research hypothesis anticipates that the results will reveal disparities in energy production among wind farms, despite their equal total capacities.

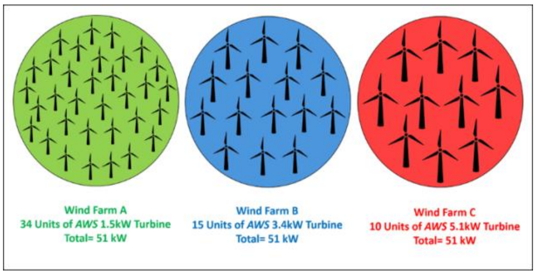

Fig. 1. Visual illustration showing the construction of each proposed wind farm

1.5. Justification

The proposed system seeks to fill a significant knowledge gap concerning the effects of rated capacity variations among wind farm on the overall efficiency of wind farms. Given the growing importance of renewable energy, especially wind power, there is a pressing need to enhance the performance of wind farms. The research aims to play a crucial role in this field by conducting a comprehensive examination for three distinct wind farms. The considered decision to exam A, B and C wind farms with a range of turbine capacities, from small to large, enable deep insight of the impact of different turbine sizes on the total efficiency of wind farms. In addition, it is worth noting that using turbines from the same manufacturer ensures uniformity and eliminates potential confounding variables associated with different turbine systems or designs.

The decision to utilize HOMER Pro, we can effectively replicate real-world scenarios with precision. Because HOMER Pro is advanced simulated environment, is hold up by its powerful and intelligence abilities in modeling complex renewable energy plants and has sophisticated capability of simulating the environmental factors of the target area, such as temperature, wind speed and geospatial coordinates. The duration of the simulation, spanning a complete one-year cycle, holds significant importance in capturing seasonal fluctuations and long-term trends in energy production. This extended timeframe allows us to assess the performance of each wind farm under diverse weather conditions and operational scenarios.

Through including real turbines parameters and variables in the simulation process among with all environmental and other geographic factors then quantifying energy outputs and scrutinizing efficiency metrics, we enable valuable insights to wind farm operators, policymakers, and stakeholders in renewable energy. Eventually, this study holds the potential to guide decision-making processes, optimize resource allocation, and bolster the sustainability and efficiency of wind energy production. By addressing the challenges associated with low wind speeds and improving turbine selection, our research can significantly enhance the reliability and cost-effectiveness of wind farms. This, in turn, can contribute to a more stable and sustainable energy grid, reduce reliance on fossil fuels, and promote the broader adoption of renewable energy sources.

1.6. Thesis statement

The effectiveness of wind farms depends significantly on the careful selection of turbine types. Therefore, this research piece focuses on a critical side of wind farm development: the influence of turbine rated capacity on overall wind farm efficiency in low wind speed environments. For investigate this aspect, the research proposes the creation of three distinct wind farms, each with a capacity of 51 kW but vary in individual turbine rating. These wind farms will undergo operation for a full annual cycle within a robust simulated environment reflects the geographical conditions of the target area and real operation of the turbines. Using the HOMER Pro simulator, the study will take into account the region's prevailing temperature and wind speeds, as well as various turbine models. The main aim is to evaluate how different turbine capacities affect wind farm efficiency while adhering to specific environmental constraints. This will be accomplished through evaluating the energy output of each farm independently. The research hypothesis anticipates that the results will reveal disparities in energy production among wind farms, despite their equal total capacities. This behavior expected to contribute to the development and improvement of wind farm efficiency in low wind speed environments and offer valuable perspectives to wind farm operators, policymakers, and stakeholders within the wind energy industry.

2. Methods

2.1. Study methodology

The present study utilized two methodologies: simulation and data analysis. Initially, computer simulation was employed to construct a virtual model of the wind farms and simulate its operation in an environment mirroring reality to yield results. This procedure describes the connection between the turbine capacities and the performance of the whole wind farm. These findings were subsequently analyzed to formulate a precise understanding and interpretation of the system's behavior. In summary, the integration of computer simulation and data analysis methodologies facilitated a thorough examination of the research problem. Subsequent sections will delve deeper into the simulation's design and outcomes for a more in-depth analysis.

2.2. Optimizing tool

The proposed model of three wind farms, A, B, and C, is simulated using HOMER Pro, it is an abbreviation of (Hybrid Optimization of Multiple Electric Renewables) a computer simulation model developed by the National Renewable Energy Laboratory in the United States (NREL) as specialized platform for control and optimizing numerous clean energy systems such as solar, wind, hydro, and biomass energy systems. HOMER has built-in capability that allows it to create a strong linking between the virtual model and the physical functions of the real equipment's by offering a wide range of input's variables, parameters, optimization algorithms and control strategies. This facilitates the simulation of the wind turbine systems, enabling our team to compare outcomes and produce realistic projections of power production capacity for each wind turbine [14, 23].

2.3. Model description

The proposed system comprises three wind farms, with each farm composed of a cluster of horizontal turbines whose quantity varies based on the turbine size, as previously mentioned in the introduction section (see Fig. 1). A separate model was constructed for each farm within the HOMER pro as illustrated in Fig. 2., the wind farms models connected to infinite grid and ensuring that the combined capacity of the three farms remained constant at 51 kilowatts. This approach facilitated the examination of how variations in turbine sizes impact farm power production.

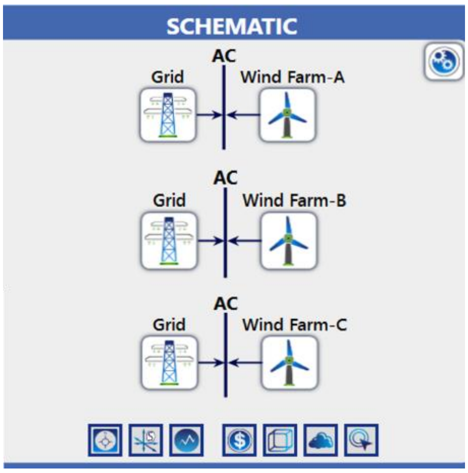

Fig. 2. The proposed system as showing in HOMER Pro

All wind turbines utilized in the simulation models were sourced from AWS Manufacturing (Australian Wind and Solar). These turbines are equipped with Horizontal Control and they claim the lowest startup speed within their class, along with the highest efficiency and excellent construct quality. They feature a carbon-fiber blades, cast body, and comprehensive passive pitch control across the entire structure.

Wind Farm-A comprises 34 units, each rated at 1.5 kW. Wind Farm-B consists of 15 units, each with a rating of 3.4 kW, while Wind Farm-C comprises 10 units, each with a rating of 5.1 kW. The process of generating electricity begins for wind turbines once they reach their cut-in speed, after which power production gradually escalates until the turbine hits its rated speed. It's important to highlight that the power curve of wind turbines is a crucial characteristic, outlining the correlation between the power generated and the rotational speed [11]. The total annual power (W_E) generated by a wind turbine, measured in kilowatt-hours (kWh), can be expressed using equation (1) as follows:

$$W_E = \sum_{t=1}^{N_h} N_{tr}\, P_{tr}\,(v_t) \tag{1}$$

In this equation, (N_h) represents the total number of hours in a year, (t) denotes the specific hour within the year, (P_{tr}) stands for the output power in kilowatts as determined by the average wind rate during that hour, and (N_{tr}) indicates the quantity of turbines situated at the site. [6]

$$P_w = \frac{1}{2}\, P_\alpha\, C_p\, V_r^3\, A\, n_t\, n_g \tag{2}$$

The power output of the wind turbine (P_w) in kilowatts is determined by the formula described in equation (2), where (p_α) represents the density of the air (approximately 1.22 kilograms per cubic meter), (A) correspond to the area swept by the wind turbine rotor. measured in m^2, (V_r) stands for the wind velocity in meters per second, (C_p) signifies the wind turbine power coefficient, (n_g) reflects the wind generator efficiency, and (n_t) indicates the efficiency of the wind turbine [22].

Moving to Fig. 3 which presents the turbines power curves. Upon examining the three curves, a similarity emerges in how wind speed impacts the generating capacity across all turbines. This similarity motivated our decision to select turbines from the same factory. Despite varying in size, these turbines exhibit comparable responses to wind conditions, thus enhancing the precision of study and the authenticity of simulation outcomes as we investigate the influence of turbine size on wind farm performance.

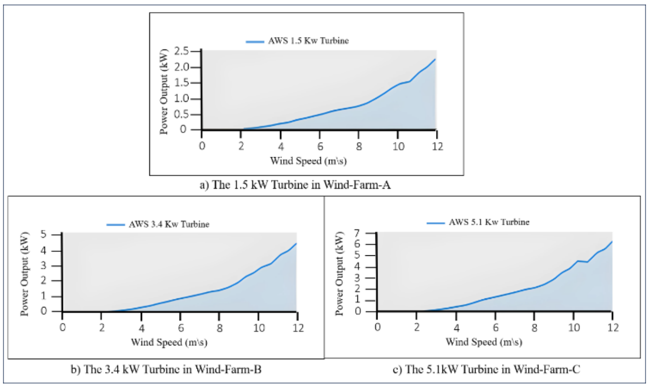

Fig. 3. The Power curves for turbines utilized in each wind farm; showing similarity emerges in how wind speed impacts the generation capacity across turbines

2.4. Inputs parameters

The simulation model incorporates a variety of technical input parameters, as detailed in Table 1. The primary sources for obtaining this input data were the Homer software website and the manufacturer's data sheets for the wind turbines.

Table 1. Technical parameters of simulation model

Parameter	Wind farm-A	Wind farm-B	Wind farm-C
Electrical bus	AC	AC	AC
Number of turbines	34	15	10
Turbine Rated Output	1500 W	3400 W	5100 W
Hub height	12 m	12 m	12 m
Running life	20 years	20 years	20 years
Rotor diameter	3.2 m	4.65 m	5.24 m
Wake effect losses	10%	15%	18%
Rated Wind Speed	10.5 meter per second	10.5 meter per second	11 meter per second
Peak output	1700 W	3650W	5700 W
Cut in	2.7 meter per second	2.7 meter per second	2.7 meter per second
Yaw control system	Tail Fin	Tail Fin	Tail Fin
Generator	Permant magnet 3-phase generator (variable speed)	Permant magnet 3-phase generator (variable speed)	Permant magnet 3-phase generator (variable speed)
Number of blades	3	3	3
Swept area	9.2 m^2	16.4 m^2	21.4 m^2
Lateral thrust (max)	1200 nts	3200 nts	4200 nts
Unit weight (Tower Top)	34 kg	77 kg	99 kg
Voltage options	12 to 48 low voltages / 60 to 140 high voltages	12 to 48 low voltages / 60 to 140 high voltages	48 low voltages / 60 to 240 high voltages
Survival wind speed	55 m/s	55 m/s	55 m/s

2.5. Boundary conditions

In the field of simulation modeling, it's crucial to recognize some external factors that impact the model's operation, factors out of control the modeler. Noteworthy among these are temperature, wind speed, and spatial coordinates. Our focus lies on the Aljazera area, positioned at latitude 36°7.1' N with longitude 41°47.6' E, at altitude of 223 meters. This location experiences an average wind speed of 5.88m/s [1]. Additionally, Fig. 4 visually represents the ambient temperature data, showcasing the daily average temperatures for each month. Fig. 5 displays the average wind speed in the region, indicating a significant decrease, particularly during colder months.

It is crucial to emphasize that Table 2 presents essential parameters concerning the simulation process. The accuracy of constructing the wind data model hinges on these parameters, as they provide the simulation model with a real understanding of the wind speed values at the turbine's hub height.

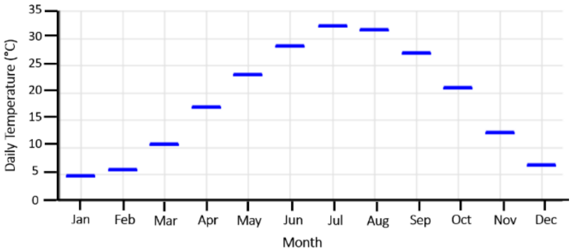

Fig. 4. The daily average ambient temperatures in the study site for each month

Fig. 5. The daily average wind speed in the study site for each month

Table 2. The simulation process parameters for the simulation model

No.	Parameters	Value
1	Altitude above sea level	223 m
2	Anemometer Hight	50 m
3	Surface roughness length	0.01 m
4	Weibull K	2
5	Houre of peak wind speed	15
6	1 hr autocorrection factor	0.85
7	Diurnal pattern strength	0.25

2.6. Additional settings

It is vital to delineate the complex simulation parameters governing the behavior and operation of the model. These parameters encompass various conformations and conditions directly mirroring real world settings. Table 3 offers a comprehensive overview of the primary simulation parameters, facilitating a fundamental comprehension of our study's precise depiction of wind power dynamics.

Table 3. The simulation setting parameters

No.	Setting parameters	Value
1	Project life time	1 yr
2	Load at present time step	10%
3	Minutes per each time step	60
4	Max. simulation per optimization	10,000
5	System precision	0.01

These parameters play a crucial role in simulating wind power dynamics. They determine simulation duration, impacting long-term strategies, and influence immediate response to demand, crucial for efficiency. They also define temporal resolution, affecting prediction accuracy, and limit computational resources, impacting optimization thoroughness. Moreover, they govern model detail, ensuring simulations accurately reflect real-world conditions. Together, these parameters enhance decision-making and operational strategies in wind power systems.

2.7. Simulation procedure

HOMER Pro holds a meticulous analytical approach to model various aspects of energy systems, including wind power systems.

The process begins with defining input data, which includes technical parameters, model settings, restraints, and the election of objective functions. By default, HOMER Pro focuses on minimaizing the total Net Present Cost (NPC). The restraints of the system are rigorously verified during this process to compute system outputs. HOMER Pro simulates the system scheme by conducting energy poise computation at all time steps of the year. It assesses the electric demand in each time step regarding to the system's energy provision capacity [12]. The entire procedural sequence, encompassing simulation and analysis steps, is depicted in an easily understandable flowchart, as shown in Fig. 6.

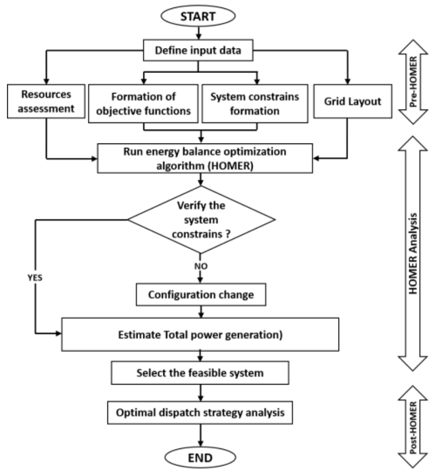

Fig. 6. Illustration flowchart showing the simulation process

3. Results and discussion

Although all three wind farms have equal total capacities, simulation results revealed disparities in their generation capacities. Wind farm B generated 71,124 kWh/year during an annual cycle, surpassing the output of wind farm C, which yielded only 68,132 kWh/year. Conversely, Wind Farm A exhibited considerable superiority over Farms B and C by 19% and 22%, respectively, with a generating capacity of 86,775 kWh/year. This advantage is due to its turbines experiencing fewer wake effect losses, which were 10% compared to 15% and 18% for Farms B and C, respectively, where smaller turbines create smaller, less turbulent wakes compared to larger ones, which minimizes wake losses within the farm. The illustrative chart depicted in Fig. 7 illustrates the variations in generating capacities among the three wind farms for each month over single annual cycle.

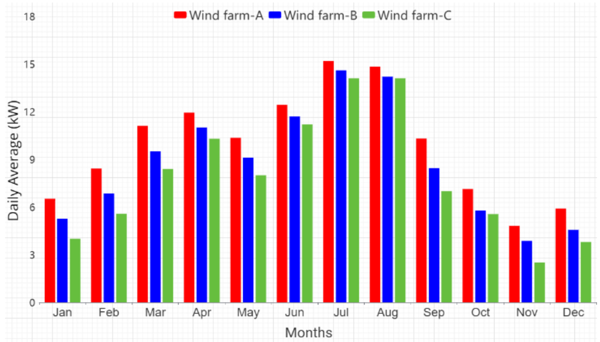

Fig. 7. The electric power generation for each wind farm; showing the daily average production in each month across one annual cycle

These findings confirm the research hypothesis that variations in individual turbine ratings directly impact the overall efficiency of the wind farm. Moreover, upon examining Fig. 7 and Fig. 5, it becomes evident that as wind speed decreases, the generation gap between the wind farms widens, reaching 51.9%. Specifically, in November, which is the month with the lowest wind speed, wind farm A, comprising small 1.5 kW turbines, exhibits superior performance.

These readings provide a thorough understanding of wind farms behavior, particularly regarding turbine sizes and the potential for regions experiencing low wind speeds to embrace wind energy. This emphasizes the importance of seriously considering the establishment of wind farms and seeking to invest in available wind energy for electrical generation, which will lead to a decrease in the consumption of fossil fuels in those areas. By mitigating the detrimental environmental and economic impacts associated with fossil fuels, this initiative aids these countries in fulfilling their international sustainability commitments.

4. Conclusion

Numerous global regions characterized by low wind speeds facing challenges wind farms utilization; However, the effectiveness of these installations greatly depends on the careful choice of turbine types within the wind farms. This academic paper focuses on the influence of varying turbine rated capacities on overall wind farm efficiency. The study proposed a simulation model consist of three distinct wind farms, each with a capacity of 51 kW but different in individual turbine capacities to investigate the research question using HOMER Pro control strategy. The simulation results showed superiority in the generating efficiency of a wind farm-A, which consisted of the smallest turbines over both farms B and C by 19% and 22% respectively, boasting a generating capacity reaching 86,775 kWh/year. Furthermore, this efficiency superiority grows more as the wind speed decreases further. These discoveries offer a comprehensive insight into the behavior of wind farms in this regard, prompting regions and nations facing low wind speeds to give serious thought to establishing wind farms. This move would result in reduced fossil fuel consumption, alleviating the adverse environmental and economic effects while meeting international sustainability goals.

While the study provides valuable insights, it also highlights certain limitations, including the necessity for a greater variety of turbine models with diverse sizes to attain a more precise and comprehensive perspective. Additionally, the absence of certain data regarding electrical losses in wind turbine generators is notable. Consequently, we suggest conducting future research that delves deeper into these aspects. This should involve considering all factors that could impact operational efficiency, such as the type and quantity of turbine blades, the electrical generator types employed, and investigating the effects of turbine spacing within the same wind farm.

The research makes significant contributions to various areas of knowledge. It sheds light on the impact of turbine ratings by establishing a direct correlation between turbine ratings and wind farm efficiency. The empirical evidence presented suggests that smaller turbines may outperform larger ones in conditions of low wind speed. Additionally, it explores the influence of wind speed variations on the efficiency gap among different wind farms, providing valuable insights for optimizing turbine performance. Moreover, the research supports the argument for targeted investments in wind energy infrastructure, especially in regions with low wind speeds, to promote renewable energy adoption and sustainability in policy and planning efforts.

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