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Techno-Economic Assessment and Sensitivity Analysis of Electricity Generation from Wind Energy in a Low-Wind-Speed Region of Egypt

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ABSTRACT

This study conducts a detailed techno-economic evaluation and sensitivity analysis of wind energy generation in Egypt's Fayoum Governorate, a region characterized by low wind speeds. It represents the first investigation of wind energy potential encompassing four key locations within the governorate: Qarun Lake, Rayan Valley, Kom Ushim, and Fayoum City. Statistical analysis of long-term wind data, based on the Weibull distribution, shows a consistent average wind speed of 6.02 m/s at a 50-meter hub height across all sites. Eight small- to medium-scale wind turbines were assessed for their annual energy output, capacity factor, and Levelized Cost of Electricity (LCOE) using the System Advisor Model (SAM). Among these, the Endurance E3120 50 kW turbine emerged as the most cost-effective, with the lowest LCOE of 4.85 ¢/kWh and the highest capacity factor. The sensitivity analysis identified capital cost as the dominant factor influencing LCOE, followed by the fixed charge rate. Overall, the findings confirm the technical and economic viability of small wind turbine deployment in low-wind-speed inland areas, encouraging broader adoption of decentralized renewable energy solutions in Egypt.

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1. Introduction

The ongoing global economic crisis has significantly affected countries worldwide, with developing nations being particularly vulnerable. One of the most evident repercussions of this crisis is its impact on the energy and electricity sectors. In Egypt, a large portion of the population experiences daily power outages lasting between one to two hours. This issue stems from Egypt's heavy reliance on fossil fuels, which currently account for approximately 90% of its total energy supply [1]. Moreover, the rapid population growth and rising energy demand have exacerbated the depletion of fossil fuel resources, posing a serious challenge to the sustainability of the national economy. As a result, there is an urgent need to transition toward renewable energy sources to meet future energy demands, conserve limited fuel reserves, and mitigate emissions of greenhouse gases [2]. Egypt possesses abundant wind energy resources, particularly in coastal regions such as the Gulf of Suez and the Nile Valley, where high and stable wind speeds are observed. At a hub height of 50 meters, average wind speeds in these regions can reach up to 10.5 m/s (Fig. **1**) [3-6]. As of 2022, Egypt's total installed renewable energy capacity is approximately 6.1 GW, comprising 2.8 GW from hydropower and about 3.3 GW from solar and wind power sources [1]. In line with its Vision 2030 goals, the Egyptian government has set an ambitious target to develop wind energy projects totaling 18.5 GW by the year 2030.

While considerable progress has been made in harnessing wind energy in high-wind-speed zones such as the Gulf of Suez [3, 4, 7], inland and low-wind-speed regions remain largely underexplored, despite their geographic, demographic, and logistical significance. Among these, Fayoum Governorate stands out as a promising yet underutilized region due to its uniform wind speed distribution and high residential energy consumption. However, existing literature offers limited insights into the wind energy potential of Fayoum, particularly in the context of techno-economic feasibility and sensitivity analysis. To address this gap, the present study offers the first comprehensive assessment of wind energy potential in Fayoum, focusing on small- and medium-scale wind turbines optimized for low-wind-speed conditions. The findings are intended to provide valuable guidance for energy planners, investors, and policymakers seeking to expand decentralized renewable energy infrastructure in inland Egypt.

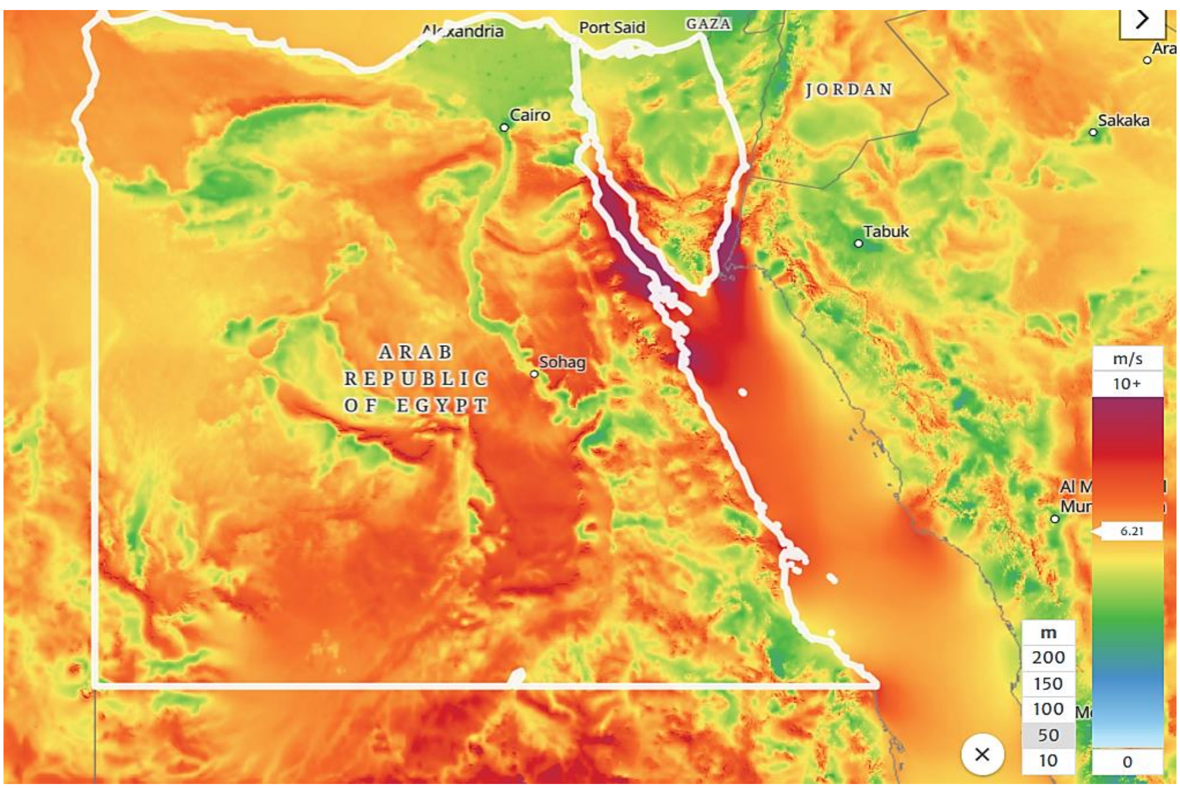


Figure1: Egyptian Wind Atlas : Mean wind speed at 50 m above ground level (https://globalwindatlas.info) [8].

2. Literature Review

Assessing the wind energy potential of selected sites is essential and plays a pivotal role in determining the financial and operational viability of wind energy projects [9-14]. The Levelized Cost of Electricity (LCOE) remains the most widely used economic indicator for evaluating project feasibility. Several studies have utilized simulation tools such as HOMER Pro, SAM (System Advisor Model), and RETScreen to estimate LCOE, Net Present Value (NPV), and Payback Period (PBP) [15-20] . These tools enable detailed modeling of wind turbine performance based on local wind profiles and turbine-specific power curves, while also incorporating cost components such as installation, operation, and maintenance.

In Egypt, pervious researches have been conducted to investigate the potential of wind energy through the deployment of wind turbines and wind farms in various regions. For example, Ahmed *et al*. [21] evaluated the economic feasibility of a standalone wind energy system to supply electricity to an industrial facility in a remote area. Ahmed Shata [6] investigated wind energy potential along the South Sinai coastline. Similarly, Ghitas *et al*. [22] assessed the wind resource of Helwan City, Cairo, using two years of measured wind data. A broader review was presented by [4], covering wind energy capacity across Egypt's Mediterranean, Red Sea, and Western Desert regions. In addition, a technical and economic evaluation of electricity generation using eight different small wind turbines has been carried out at 17 sites to estimate annual energy output [4]. Other studies have focused on large-scale projects, such as the techno-economic assessment conducted at the Hurghada wind farm [23-25]. he environmental impact of wind farms in Gabal El Zeit and the Suez Gulf has also been thoroughly analyzed [26, 27]. Moreover, Abdelhady *et al*. [28] xamined Egypt's offshore wind energy potential in the Mediterranean Sea, conducting a techno-economic evaluation at seven sites using a 7.0 MW offshore turbine.

However, there are few studies that have carefully examined the potential of wind energy in areas with low wind speeds. Ahmed [29] conducted a comprehensive techno-economic assessment in the Shark El-Ouinat region in Egypt's southwestern desert, demonstrating average annual wind speeds of 6.5 m/s at 10 m height and an energy density of approximately 582 kW/m² at 100 m hub height. Tonbol *et al*. [7] assessed potential wind farm locations along the Mediterranean coast using a 16-year dataset (2007-2022) from stations for coastal weather monitoring. Wind speeds ranging from 4-6 m/s were common at Ras El-Tin, Abu Qir, and Port Said, while lower speeds of 2-4 m/s were recorded at Marsa Matruh and Arish. Ahmed [30] further confirmed the technical and economic feasibility of a proposed 200 MW wind farm at Sidi Barrani, where wind speeds average 6.1 m/s at 10 m height.

Sensitivity analysis is crucial for identifying parameters that significantly influence the economic feasibility of wind energy systems. A number of studies have applied tornado and spider diagrams to assess the impacts of variables such as discount rate, capital cost, and inflation rate on LCOE [31]. Other studies [32-34] have consistently shown that capital costs and interest rates are the most influential variables, especially in developing countries where access to affordable financing remains a major challenge. Nevertheless, few sensitivity analyses have been carried out for inland wind resources in Egypt [35], indicating a clear research gap that this investigation seeks to fill. Table **1** presents a concise summary of the literature reviewed.

2.1. Research Gap and Contribution

While many existing studies have focused on high- and medium-wind-speed regions, relatively little attention has been given to low-wind-speed areas, despite their potential for small-scale renewable energy development; particularly in energy-intensive residential sectors. This research investigates the wind energy potential in such a region, specifically focusing on Fayoum Governorate, located at a latitude of 29°30' and a longitude of 30°86', approximately 100 km southwest of Cairo. Furthermore, comprehensive sensitivity analyses addressing the economic conditions; such as capita cost, and operating cost; are sparse. This study addresses these gaps by evaluating wind energy generation potential using long-term wind data, selecting appropriate wind turbine models, and conducting an in-depth techno-economic and sensitivity analysis using the SAM software tool.

Table 1: Comparative review of related work on wind energy assessments in egypt and similar regions.

Author(s)	Location	Objective	Methodology/Tools	Key Findings	Relevance to Current Study
Ahmed *et al*. [21]	Isolated area, Egypt	Economic feasibility of standalone wind system	Techno-economic analysis	Wind energy system is viable for customer in remote area	Highlights wind potential beyond coastal zones
Ahmed Shata [5]	South Sinai, Egypt	Wind potential evaluation for electricity generation	Wind data analysis	South Sinai has sufficient wind potential for generation	Supports exploration in coastal zones
Ghitas *et al*. [22]	Helwan, Cairo	Wind resource assessment	2-year wind data, station measurements	Moderate wind potential; viable for small systems	Urban inland site study
Abdelhady *et al*. [28]	Mediterranean Sea, Egypt	Offshore wind energy techno-economic evaluation	SAM, 7 MW turbine simulation	Offshore wind at seven sites feasible with 7 MW turbine	Offshore benchmark study
Ahmed [29]	Shark El-Ouinat (SW Egypt)	Techno-economic assessment in low-wind-speed region	Wind speed + energy density estimation	Average 6.5 m/s wind; viable for 100 m hub turbines	Validates viability in desert low-speed zones
Ahmed [30]	Sidi Barrani, Egypt	Feasibility of a 200 MW wind farm	Cost and energy modeling	Average wind speed of 6.1 m/s at 10 m; economically viable	Encourages large-scale projects in moderate-speed zones
Tonbol *et al*. [7]	Mediterranean coast, Egypt	Site selection for wind farms	16-year dataset (2007–2022)	Wind speeds 4–6 m/s at most stations	Informs coastal low-wind-speed viability
Various [15-20]	General/Global	Use of software tools for LCOE, NPV, PBP calculations	SAM, HOMER Pro, RETScreen	Tools accurately simulate technical and economic feasibility	Supports your use of SAM for multi-scenario analysis
Abdelhady *et al*. [4]	17 Locations, Egypt	Evaluation of 8 small wind turbines	AEP, CF, and economic indicators	Identifies turbine suitability by location	Supports small wind turbine deployment strategy
Ahmed Shata [6]	North Sinai, Egypt	Wind hybrid system modeling for rural electrification	Weibull, Hybrid simulations	Viability in low-density residential areas with hybrid setups	Shows small-scale wind applications in rural settings
Various [31-34]	Algeria , Global	Sensitivity of economic parameters on LCOE	Tornado/spider diagrams	Capital cost, inflation, and discount rate are most influential	Justifies inclusion of detailed sensitivity analysis
Hamouda [35]	Egypt	Economic feasibility and sensitivity analysis of wind energy at Cairo	Weibull mathematical model	The present value becomes positive when the electricity price increases by 5% and the discount rate is equal to or less than 8%	sensitivity analysis
Current Study	Fayoum Governorate, Egypt	Techno-economic and sensitivity analysis in low-wind region	Weibull, SAM, cost analysis, sensitivity	First detailed assessment across four inland sites in Fayoum	Fills research gap on wind in low-wind-speed inland Egypt

Fayoum spans an area of 6068.70 km² and had a population of 4.1 million as of 2024 [36]. Residential activities accounted for approximately 65% of the region's total energy consumption in 2021 [37] highlighting the importance of identifying localized energy solutions. According to the Fayoum wind atlas, wind speeds in the region range from 6 to 7 m/s at a 50 m hub height (Fig. **2**). This study presents the first comprehensive evaluation of wind resources across four strategically selected sites, representing diverse land uses: coastal (Qarun Lake and Rayan Valley), industrial (Kom Ushim), and urban (Fayoum City). Site selection was based on factors including grid accessibility, land availability, and geographic representation. Their coordinates and elevations are provided in Table **2**.

To assess the feasibility of wind energy deployment in these low-wind-speed areas, this study considers small wind turbines ranging from 3 to 300 kW. These turbines are designed to operate at lower cut-in wind speeds (as low as 2.5-3 m/s), making them suitable for regions with moderate wind conditions. Their lightweight blades, optimized aerodynamics, and low land-use footprint enhance energy capture and allow installation on rooftops, small plots, or rural farms. Small wind turbines offer practical benefits for off-grid, rural, and urban environments where centralized grid expansion may not be viable. By reducing reliance on fossil fuels and supporting distributed renewable generation, these systems contribute to improved energy security and sustainability in Egypt's low-wind-speed regions.

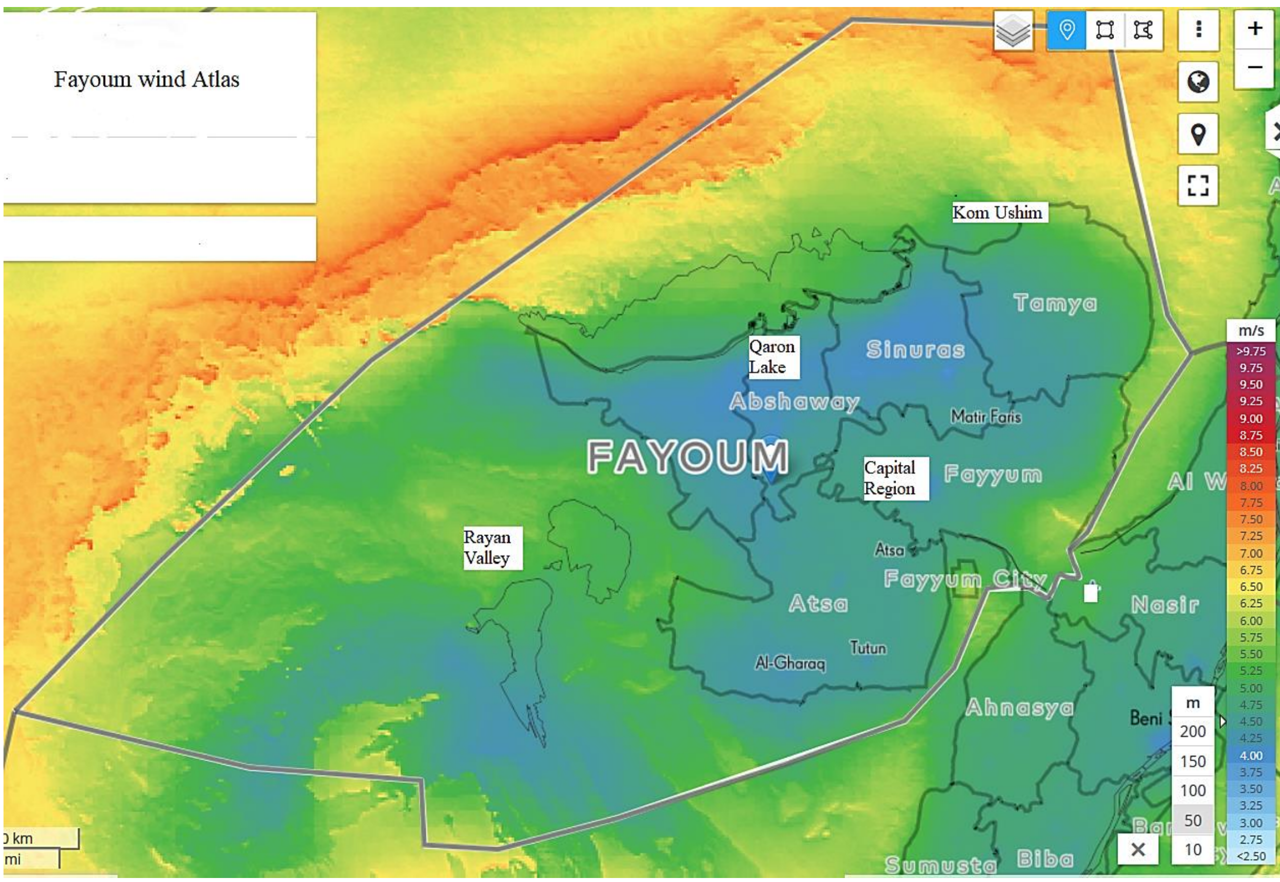


Figure 2: Fayoum Wind Atlas at 50 m indicating the geographical locations for the four selecting sites: Qarun Lake, Rayan Valley, Kom Ushim, and the capital region (https://globalwindatlas.info) [8].

Table 2: Geographical coordinates of the selected sites.

Site	Latitude (N)	Longitude (E)	Elevation (m)
Qarun Lake	29° 46'	30° 76'	- 40
Rayan Valley	29° 25'	30° 47'	- 14
Kom Ushim	29° 54'	30° 92'	3
Capital region	29° 32'	30° 85'	23

3. Methodology

In this research, a techno-economic investigation of wind energy potential is conducted using the System Advisor Model (SAM); a robust simulation tool developed by the National Renewable Energy Laboratory (NREL) for modeling renewable energy systems [38, 39]. The assessment follows a systematic approach that integrates technical performance evaluation with economic feasibility analysis. The process begins with a wind resource assessment, wherein wind speed and direction data are collected from sources such as NREL, NASA POWER, or local meteorological stations. The Weibull distribution is applied to model wind speed variability at the selected site.

In the technical analysis phase, a suitable wind turbine is selected either from SAM's built-in database or by inputting custom turbine specifications, including power curves and hub height. Key performance indicators such as Annual Energy Production (AEP) and Capacity Factor (CF) are then computed to estimate energy output. The economic assessment incorporates capital expenditures (CAPEX); including turbine costs, installation, and grid connection; as well as operational expenditures (OPEX), such as maintenance, insurance, and land leasing. To determine overall project feasibility, the Levelized Cost of Electricity (LCOE) is calculated as a principal financial metric.

Finally, a sensitivity analysis is performed by varying critical parameters such capital cost, fixed charge rate, and fixed- variable operating expenses, to evaluate their influence on economic outcomes. This comprehensive approach provides a realistic framework for assessing the viability of wind energy projects in low-wind-speed regions.

3.1. Mathematical Modeling

For the statistical analysis of wind speed distributions, the most common model used to describe wind speed probability distribution is the Weibull distribution due to its flexibility, simplicity, and strong empirical fit to real-world data. Defined by two parameters; shape (k) and scale (c); the Weibull distribution can accurately represent a wide range of wind conditions, from uniform to highly variable wind profiles [40-43]. Its analytical tractability allows for straightforward calculation of key parameters such as mean wind speed, wind power density, and turbine energy output, making it highly suitable for wind energy assessments. Compared to other models like the Rayleigh or log-normal distributions, the Weibull model consistently demonstrates superior accuracy in fitting measured wind data across diverse geographic regions [44, 45]. As a result, it has become a standard approach in both academic research and industry practice, and is integrated into widely used simulation tools such as HOMER, SAM, and RETScreen [46]. Therefore, the probability distribution function of the Weibull model is a key statistical parameter extracted from wind speed data for estimating wind energy resources. The probability density function (PDF) of the Weibull distribution is expressed by the following equation:

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

Where:

$f(v)$ is the Weibull distribution probability density function, v is the wind speed in m/s, k is the Weibull shape parameter and *c* is the Weibull scale parameter (m/s) and can be calculated by equation (2) and (3) respectively.

$$k = 0.83 \times \bar{v}^{0.5} \tag{2}$$

$$c = \frac{\bar{v}}{\Gamma(1 + 1/k)} \tag{3}$$

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{4}$$

where $\bar{v}$is the mean of wind speed over any specified periods of time. One of the most major features of the Weibull function which makes this distribution more useful for wind power projects is that once these parameters are measured at a specific height, they can be adjusted to different heights. In particularly, if the values c_{10} and k_{10} are defined as Weibull parameters at 10 m above ground level; the Weibull parameters distribution c_h and k_h at any height *(h)* can be estimated as following [47]:

$$c_h = c_{10}\left(\frac{h}{10}\right)^n \tag{5}$$

$$k_h = k_{10}\left[1 - 0.0881\, ln\left(\frac{h}{10}\right)\right]^{-1} \tag{6}$$

$$n = [0.37 - 0.0881\, ln\, c_{10}] \tag{7}$$

Where n is the power law coefficient. In this study, the power law expression is used as in equation (7) [48]. Then the wind speed (V_h) at any height (*h)* can be calculated by equation (8).

$$V_h = V_{10}\left(\frac{h}{10}\right)^\alpha \tag{8}$$

Where

V_{10}: wind speed at 10 m height; and (α) the wind shear coefficient values and can be calculated by equation (9) [49]:

$$\alpha = 0.37 - 0.0881 \ln V_{10} \tag{9}$$

Then the wind power potential at any specified site can be determined by calculating the wind power density. The wind power density *(P)* indicates the amount of power available at specified area perpendicular to the wind stream moving with mean speed $\bar{v}$ (m/s) and can be expressed per unit area as following [50]:

$$P = \frac{1}{2}\rho\bar{v}^3 \tag{10}$$

Since, ρ =1.225 kg/m^3 at 1 atm pressure and 15 ^{o}c temperature. The air density can be corrected in equation (11) [51]:

$$\rho_c(kg/m^3) = 3.845\frac{P_p}{T} \tag{11}$$

Taking $P_p = 1 * 10^5$N/m^2, and $T = 298$K for Egypt. Hence the modified wind power density can be expressed using the following formula [52]:

$$P_c = 0.585\bar{v}^3 \tag{12}$$

Then the wind power density at height (h) illustrated by equations (13):

$$P_h(W/m^2) = P_{10}(h/10)^{3\alpha} \tag{13}$$

Then the power output of the wind turbine (P_T) can be calculated as follow:

$$P_T = \frac{1}{2}\rho A c_p v^3 \eta \tag{14}$$

Where c_p is Betz coefficient equal to 16/27 (59.3%) [53]. $A$is the area swept by the rotor, and $\eta$is the wind turbine's efficiency. Then the output energy of the wind turbine, could be calculated by multiplying the number of hours in each wind speed interval with the corresponding output power from wind turbine power curve as follow:

$$Eout = 8760 \sum_{v_{cut-in}}^{v_{cut-out}} (P_T(v) \times f(v)) \tag{15}$$

The capacity factor of the wind turbine (equation (16)) is defined as the ratio of its yearly actual energy output $Eout$, to the rated yearly energy produced per year $Erated$, when the turbine operating at rated wind speed for all the year.

$$Cf = Eout/Erated \tag{16}$$

3.2. Wind Speed Data Description

Long-term wind speed data spanning 11 years were obtained from NASA [6] for all selected sites at hub heights of 10 m and 50 m. Tables **3** and **4** present the average monthly and annual wind speeds for the four selected locations at these respective heights. As shown in Table **3**, Rayan Valley records the highest annual average wind speed of 4.32 m/s at 10 m, followed by Qarun Lake. According to Table **4**, the maximum annual average wind speed at 50 m hub height is 6.15 m/s. Despite these variations, the current study confirms that the average wind speed across Fayoum Governorate remains relatively uniform.

Table 3: Monthly and annual average wind speeds (m/s) at 10 m height (2008-2018).

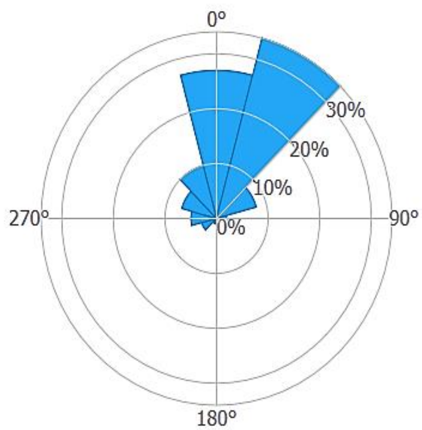
Month	Rayan Valley	Qarun Lake	Kom Ushim	Capital Region
Jan	3.7	3.5	3.6	3.5
Feb	3.8	3.6	3.7	3.6
Mar	4.2	4.1	4.2	4.1
Apr	4.4	4.4	4.4	4.4
May	4.6	4.6	4.5	4.6
Jun	4.9	4.9	4.7	4.9
Jul	4.9	4.8	4.6	4.8
Aug	4.5	4.5	4.3	4.5
Sep	4.6	4.5	4.3	4.5
Oct	4.4	4.3	4.1	4.3
Nov	3.9	3.7	3.7	3.7
Dec	3.8	3.6	3.7	3.6
Annual Average	4.32	4.21	4.16	4.21

3.3. Wind Direction

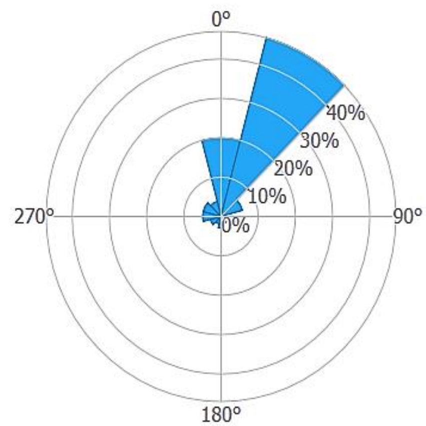
The wind rose diagrams presented in Fig. (**3**) illustrate the wind direction and frequency distribution for the four selected sites: Rayan Valley, Qarun Lake, Kom Ushim, and the Capital Region. Each diagram indicates that the prevailing wind direction is predominantly from the north, with varying degrees of frequency concentration across the sites. Qarun Lake exhibits the highest wind frequency, with a peak exceeding 40%, while the remaining sites display more moderate distributions, reaching up to 30%. Rayan Valley and Kom Ushim demonstrate similar wind patterns, with wind speeds predominantly oriented in the north-northwest direction. The Capital Region follows a comparable trend, albeit with slightly lower frequency levels. These findings suggest that wind patterns across Fayoum Governorate are relatively consistent, indicating favorable conditions for wind energy utilization; particularly in Qarun Lake, where wind intensity and frequency are most pronounced.

Table 4: Mean monthly wind speeds (m/s) at 50 m height (2008-2018).

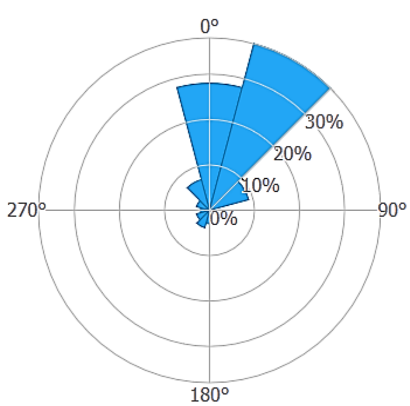
Month	Rayan Valley	Qarun Lake	Kom Ushim	Capital Region
Jan	5.7	5.3	5.6	5.3
Feb	5.7	5.5	5.6	5.5
Mar	6.2	6.1	6.1	6.1
Apr	6.3	6.2	6.2	6.2
May	6.3	6.3	6.1	6.3
Jun	6.6	6.6	6.3	6.6
Jul	6.5	6.4	6.1	6.4
Aug	6.2	6.2	5.8	6.2
Sep	6.3	6.3	6	6.3
Oct	6.2	6.1	5.9	6.1
Nov	5.9	5.6	5.6	5.6
Dec	5.9	5.5	5.7	5.5
Annual Average	6.15	6	5.91	6



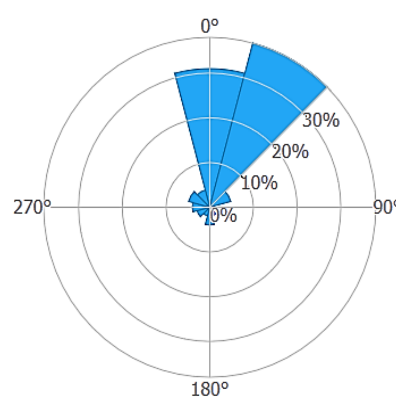
(**a**) Rayan Valley



(**b**) Qaroun Lake



(**c**) Kom Ushim



(**d**) Capital Region

Figure 3: Wind rose diagram of the four selected sites during the year.

4. Results and Discussion

4.1. Weibull Parameters Analysis

Tables **5** and **6** present the Weibull distribution parameters for wind speed at 10 m and 50 m above ground level (AGL). The results show that the highest Weibull parameter values at both heights are recorded at Rayan Valley, while the Kom Ushim site exhibits the lowest values. Fig. (**4**) and (**5**) illustrate the wind speed probability distributions for the four selected sites at 10 m and 50 m, respectively. These figures indicate that wind speed across Fayoum Governorate generally follows a similar probability distribution, suggesting a relatively uniform wind regime throughout the region.

Table 5: Weibull distribution parameters of the four selected sites at 10 m hub height.

	Rayan Valley	Qarun Lake	Kom Ushim	Capital Region
Annual average wind speed (m/s)	4.32	4.21	4.16	4.21
k	1.73	1.70	1.69	1.70
c (m/s)	4.85	4.72	4.66	4.72

Table 6: Weibull distribution parameters of the four selected sites at 50 m hub height.

	Rayan Valley	Qarun Lake	Kom Ushim	Capital Region
Annual average wind speed (m/s)	6.15	6.00	5.91	6.00
k	2.06	2.03	2.02	2.03
c (m/s)	6.94	6.77	6.67	6.77

4.2. Wind Turbine Performance Assessment

The above analysis indicates that wind speed across Fayoum Governorate follows a similar probability distribution with approximately uniform values. Consequently, the wind energy potential will be assessed at a single site, using Rayan Valley as a representative case study. To evaluate the performance of a wind turbine at a specific site, it is essential to calculate both the total energy output and the capacity factor. In this study, SAM (System Advisor Model) software is employed to estimate these parameters. The calculation methodology is outlined in Equations (13) to (16) in Section 2.3. The wind energy potential at the selected site is evaluated using eight different wind turbines (Table **7**) at a hub height of 50 meters.

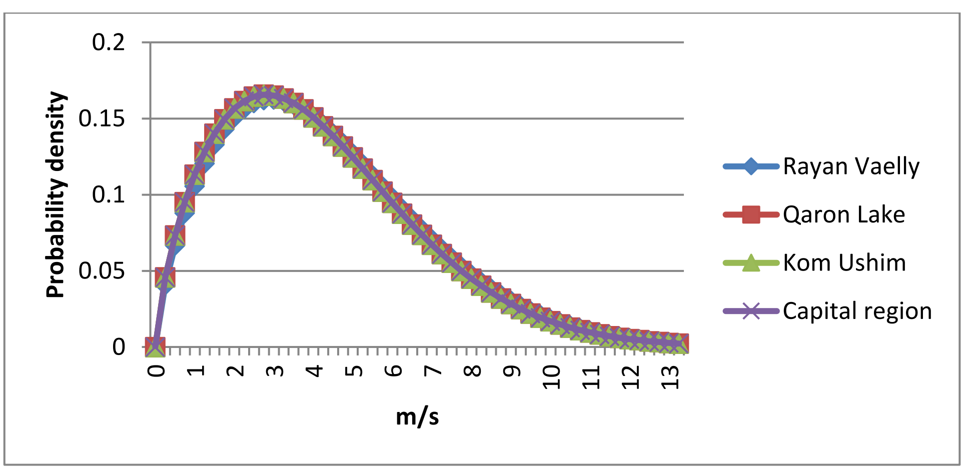


Figure 4: Weibull distribution of the wind speed at height 10 m for the four selected sites.

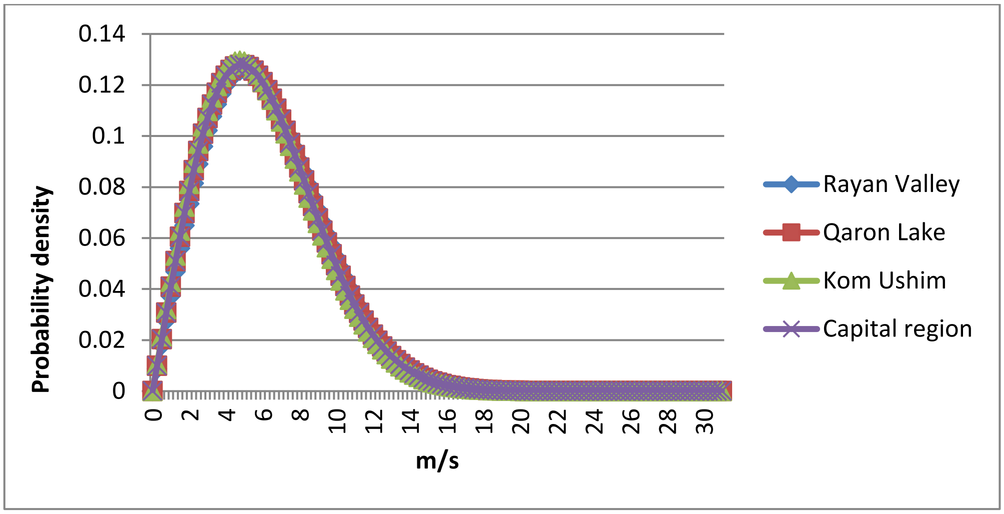


Figure 5: Weibull distribution of the wind speed at height 50 m for the four selected sites.

Table 7: Technical and economic data of the selected wind turbines.

Wind Turbine	Total Capital Cost ($)	Operating Cost ($/year)	Rated Power (kW)	Turbine Rotor Diameter (m)	Turbine Hub Height (m)	Cut in Wind Speed (m/s)	Rated Wind Speed (m/s)	Cut off Wind Speed (m/s)
Kestrele 400i	3,480	60	3	4	10 and 50	2	11	25
Evance R9000	5,800	100	5	5.5	10 and 50	2	11	20
Bergey exel s60	11,600	200	10	6	50	3	13	21
Jacob 21-30	23,200	400	20	9.5	50	4	14	22
Edurance - E3120	58,000	1000	50	19.20	50	2	13	17
NREL 100 kW	116,000	2000	100	13.8	50	2.7	11	25
Electria wind 200kW	232,000	4000	200	28	50	2	11	21
Enercon 500 kW	580,000	10,000	500	40	50	3	13	25

4.3. Annual Energy Output at 50 m Hub Height

Fig. (**7**) and (**8**) present the annual energy produced and capacity factor of each selected wind turbine at the study site, respectively. As shown in Fig. (**7**), the Enercon 500 kW turbine achieves the highest energy production, indicating that it is the most suitable option for the selected location. However, Fig. (**8**) reveals that the capacity factor of this turbine is relatively low, suggesting that energy output could be enhanced by increasing the hub height of the wind turbine.

Fig. (**8**) illustrates the capacity factor (%) of eight different wind turbines at a 50 m hub height for the selected site, reflecting their efficiency in converting available wind energy into electrical power. The Endurance E3120 demonstrates the highest capacity factor, exceeding 35%, followed closely by the NREL 100 kW turbine, making them the most efficient options. The Kestrel e400i and Evance R9000 exhibit moderate performance, each with capacity factors around 25%, while the Electriawind 200 kW shows a slightly lower value of approximately 20%. The Bergey Excel S60 and Enercon 500 kW turbines display lower efficiency, with capacity factors ranging between 15% and 20%, whereas the Jacob 21-30 turbine has the lowest capacity factor, at approximately 12%, indicating limited suitability for this location. This analysis highlights that the Endurance E3120 and NREL 100 kW turbines are the most efficient choices for maximizing energy output in this low-wind-speed region, while the remaining models may be less effective under the prevailing conditions.

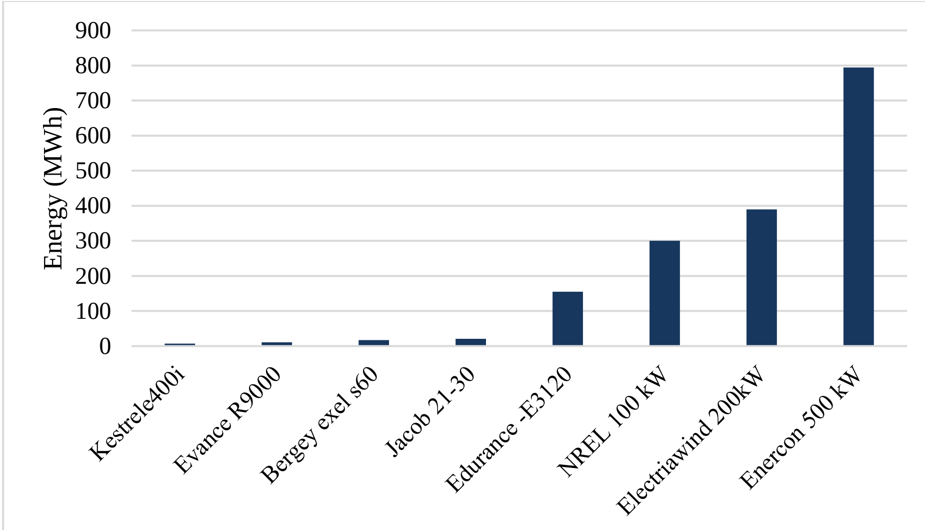


Figure 6: Annual energy output in (MWh) of the selected wind turbine at 50 m hub height.

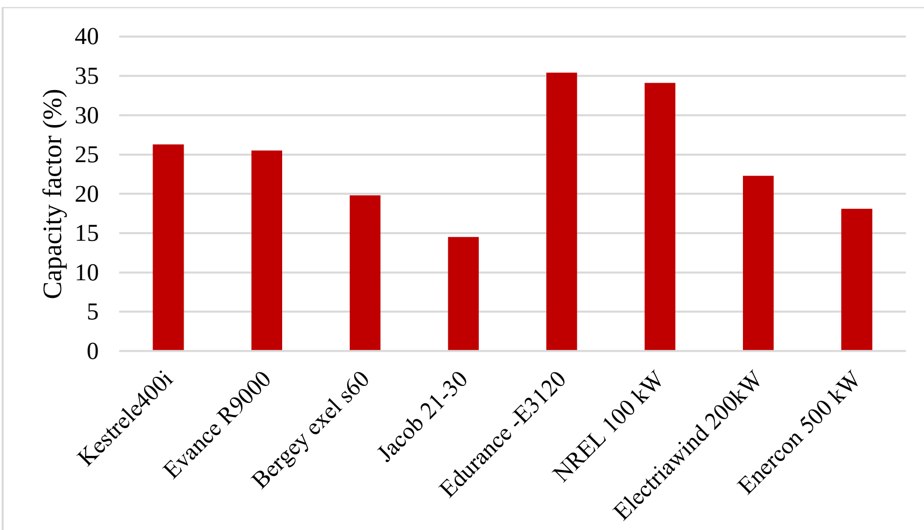


Figure 7: Capacity factor (%) of eight wind turbines for the selected site at 50 m hub height.

4.4. Levelized Cost of Electricity (LCOE)

The levelized cost of electricity, or LCOE, is calculated by dividing lifetime costs by energy production. Equation (17) could be used to calculate the levelized cost of electricity, which is the cost per kWh [54].

$$LCOE = \frac{FCR \times TCC + FOC}{E} + VOC \tag{17}$$

Where:

- FCR: Fixed Charge Rate (FCR) represents the project revenue required per unit of investment to cover the capital cost. It typically ranges between 0.07 and 0.12; in this study, an average value of 0.095 is adopted;

- TCC: Total capital cost of the wind turbine which includes the wind turbine purchase cost, land cost, power block system, labour cost, connection transmission line, and substation, and the transportation cost ($) (Table **7**);
- FOC: fixed operating cost ($) (Table **7**);
- VOC: Variable Operating Cost (VOC), expressed in $/kWh, typically ranges between 0.001 and 0.01 $/kWh. In this study, an average value of 0.0055 $/kWh is used;
- E: Annual electricity production (kWh).

Fig. (**9**) illustrates the Levelized Cost of Electricity (LCOE) in cents per kilowatt-hour (¢/kWh) for eight wind turbines at a 50 m hub height at the selected site, providing insight into their relative cost-effectiveness. The Jacob 21-30 turbine exhibits the highest LCOE, exceeding 12 ¢/kWh, indicating a relatively high cost per unit of energy produced. The Enercon 500 kW and Bergey Excel S60 turbines also show relatively high LCOE values, suggesting that they may not be the most economical options. In contrast, the Endurance E3120 and NREL 100 kW turbines demonstrate the lowest LCOE, approximately 4.85 ¢/kWh, making them the most cost-effective solutions for energy generation at the selected location. The Kestrel e400i, Evance R9000, and Electriawind 200 kW turbines fall within a moderate range, with LCOE values between 6.5 and 7.7 ¢/kWh. These results suggest that turbines with higher capacity factors, such as the Endurance E3120 and NREL 100 kW, tend to achieve lower LCOE, making them more economically viable choices for wind energy generation in low-wind-speed regions.

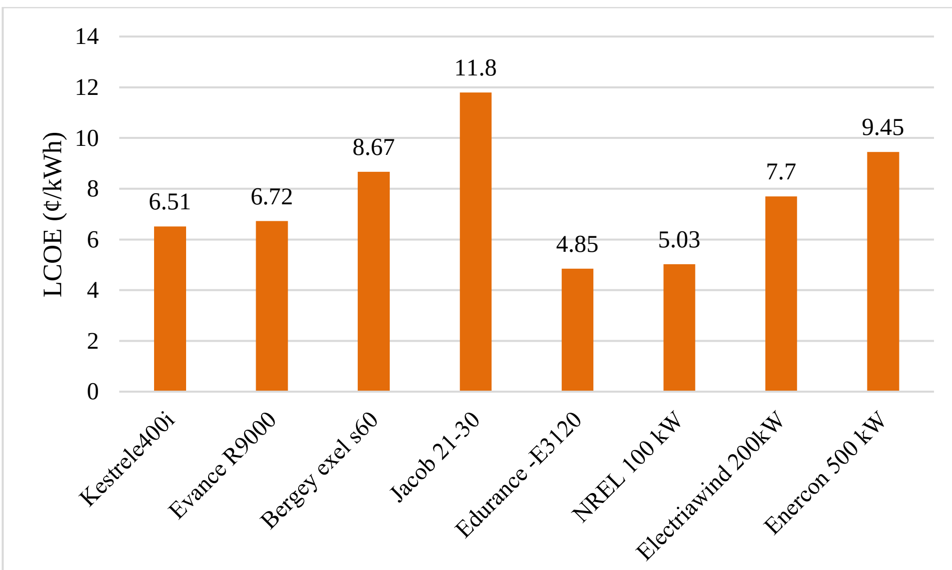


Figure 8: The LCOE in (¢/kWh) of the eight wind turbines at 50 m of the selected site.

4.5. Sensitivity Analysis

Fig. (**9**) presents a tornado chart that illustrates the sensitivity of the Levelized Cost of Electricity (LCOE) to variations in key economic parameters, including capital cost, fixed charge rate, operating cost, and variable operating cost. The chart reveals that the capital cost ($58,000 ±10%) exerts the most significant influence on LCOE, as demonstrated by the longest bars, indicating that changes in capital investment lead to substantial shifts in the cost of electricity. Similarly, the fixed charge rate (0.098 ±10%) also has a considerable effect, reflecting its role in determining the annualized capital recovery. In contrast, the operating cost ($1,000 ±10%) and variable operating cost (0.0055 $/kWh ±10%) exhibit relatively minor impacts on LCOE, suggesting their limited influence on overall cost outcomes. The analysis underscores the critical importance of managing capital cost and financing conditions to minimize LCOE and enhance project viability.

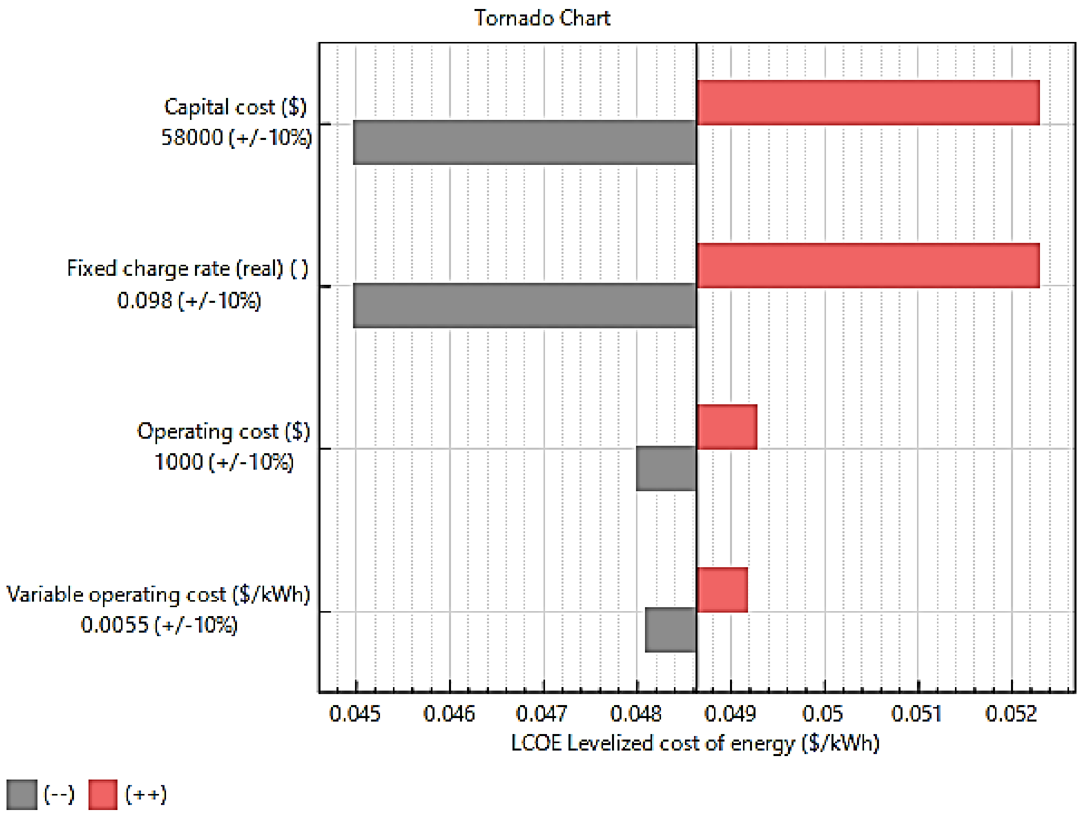


Figure 9: Sensitivity of the LCOE against key economic parameter.

5. Summary and Conclusion

This study assessed the feasibility of wind energy projects in Fayoum Governorate, a low-wind-speed inland region of Egypt, through the analysis of long-term wind data, evaluation of turbine performance, and a comprehensive techno-economic and sensitivity analysis. The results reveal that wind speeds in the region are relatively consistent, averaging around 6.0 m/s at 50 m hub height across all selected sites. Among the evaluated turbines, the Endurance E3120 and NREL 100 kW models emerged as the most suitable in terms of energy output and cost-effectiveness, achieving LCOE values below the global average. The sensitivity analysis further emphasized the dominant role of capital cost in determining project viability, underscoring the need for cost-competitive turbine solutions and supportive financial policies. These results affirm the feasibility of installing small- and medium-scale wind turbines in low-wind-speed regions like Fayoum, offering a practical pathway for enhancing local energy security, promoting sustainability, and supporting Egypt's national renewable energy targets. Future work should explore the integration of hybrid systems and the optimization of hub height to maximize energy yield in similar inland regions.

Conflict of Interest

The authors hereby declare that they have no significant financial or nonfinancial interests to disclose. Additionally, there are no competing interests that could be perceived as influencing the content of this article.

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