Economic Valuation of Electrical Wind Energy in Egypt Based on Levelized Cost of Energy

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Abstract- Due to the increasing demand for electricity, Egypt as a nation of limited fossil fuels resources needs to diversify power generation portfolio by integrating renewable energy resources. In fact, wind energy has a great potential due to its economic efficiency as demonstrated by Egypt's wind atlas. This paper presents an overview of the feasibility of having wind power plants at several windy regions in Egypt, along the Gulf of Suez, both sides of the Nile, Mediterranean Sea and South Upper Egypt. This was investigated based on huge historical wind speed measurements taken at a height of 50 m over 20 and 30 years. Electricity cost values are computed based on the levelized cost of energy for the electrical power generation from different wind turbines at three scattered regions. The research results would offer objective guidelines for energy policymakers and utility operators to consider energy portfolios that are more economically feasible.

Keywords Renewable Energy, Wind Energy, Cost Analysis, Economic Levelized Cost of Energy (LCOE), Electricity Generation Costs.

1. Introduction

In this section, the economic valuation of electrical wind energy in Egypt based on levelized cost of energy that is available in the literature for technical and economic perspective, and contributions of the presented manuscript are explored in detail.

1.1. Motivation

Accelerated technological development leads to an increase in the rate of fuel consumption around the world. Simultaneously, rising negative impact of CO2 emission on the environment, increasing prices and restricted reserves of fossil fuel have intensified global attentions to renewable energy sources [1]. The wind power production is available domestically and has an increasing rate reaching 20% annually, with a global installed capacity of 651 GW across the globe in 2019 [2]. This rapidly increases rates reveal that many countries have become highly interested in this kind of power sources to enhance their overall generation and reducing reliance on traditional sources of energy [3]. At the end of 2019, the top countries for renewable energy capacity investment were China, the United States, Japan, India, United Kingdom, and Taiwan [4].

1.2. Literature review

Wind energy potential depends on the existence of a good wind resource, the proximity to the transmission system for economic connections, and on the fact that, there are no other problems that hinder wind development (such as, military communications and radar systems) [5]. The economic growth of wind capacity depends on the cost of wind relative to alternatives.

In the presence of high-impact, low-probability (HILP) such as natural disasters, the resilience of electrical power systems has become an inseparable part in analyzing the systems reliable performance but fails to model high-level and less likely contingencies. General application areas of resilience are presented as economic, social, engineering and organizational [6].

Renewable energy, electrical vehicle, smart buildings have recently emerged as part of the electricity infrastructure. Since they have generated particular interest in demand forecasting [7]. The main requirements of a future electrical power grid are summarized in [8].

The heating, ventilation and air conditioning (HVAC) system accounts for a large proportion of the overall energy usage of smart buildings. Researchers have recently explored the potential of commercial buildings with proactive demand-side participation due to the re-structuring of the wholesale electricity market and the development of retail electricity markets. In [9], the authors proposed model predictive controller (MPC) based optimization method to generate proactive demand-bid curves for the smart buildings to optimize their energy consumption in line with variable prices. In [10-11], the authors offered a nonlinear economic model predictive controller NL-EMPC to reduce the net cost of energy consumption by building's HVAC system while at the same time maintaining the comfort level of building occupants. The literature also presents a computing-efficient linear model predictive controller LMPC for building HVAC systems [12]. LMPC features a non-linear MPC (NLMPC) that offers a remarkable computational advantage.

Over the past few years, Egypt has witnessed remarkable development in the field of utilizing renewable energy to face the energy deficit crisis; it occupies a leading position in the Africa and Middle East [13]. Egypt owns natural resources and tremendous potentials of wind energy in almost all regions [14]. The New and Renewable Energy Authority (NREA) in collaboration with National Laboratory Risoe (Denmark) has worked extensively over the last years to create a comprehensive wind atlas for Egypt. Egyptian wind atlas, given in Fig. 1 [15], indicates that there are several promising areas in the Suez Gulf and on both sides of the Nile with high wind speeds, which could be ideal for setting up major wind power generation projects [16-19]. Other studies on the wind characteristics and its effectiveness [20-23] have suggested additional locations for wind power plants along the Mediterranean and Red Sea coasts in Egypt. Table 1 shows the wind farm projects that were implemented in Egypt (basically in the Red Sea region). It explores the installed capacity of each project, the number of turbines, and the power of each turbine [24].

1.3. Contributions of paper

This study focuses on the potential of wind energy to provide an economic analysis of wind energy in Egypt. In a number of studies, the cost of wind energy was calculated on the basis of present value cost (PVC) [25-27]. In this paper, a levelized cost of electricity (LCOE) method is utilized for wind energy economic analysis [28-29]. The effect of changing selected input values such as capacity factor, capital cost and operation and maintenance (O&M) cost on LOCE is thoroughly discussed.

1.4. Paper layout

The paper organization is presented as follows: Section 2 provides the levelized cost of energy (LCOE). Section 3 introduces the characteristics of wind energy at different regions in Egypt. Section 4 presents the environmental cost analysis and the results of analysis for three windy regions in Egypt. Finally, the conclusion of the paper is listed in section 5.

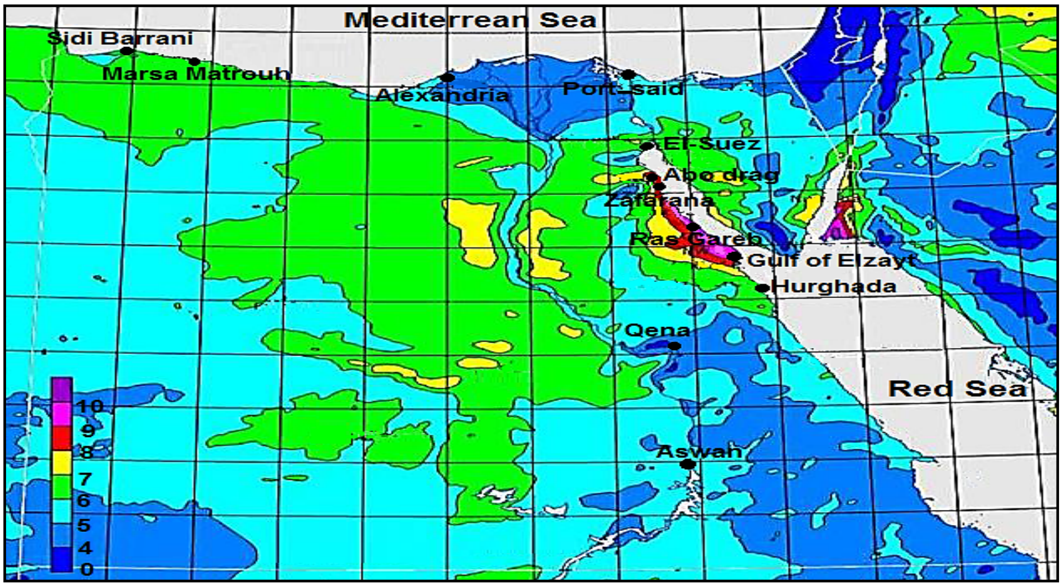

Fig.1. Egyptian wind speed atlas estimated at 50 m above ground level [15].

Table 1. The projects of wind farms in Egypt.

No. of project	No. of turbines	Wind turbine power(kW)	Total nominal power (MW)	Financing country
Zafarana-1	50	600	30.00	Netherlands
Zafarana-2	55	600	33.00	Germany
Zafarana-3	46	660	30.36	Netherlands
Zafarana-4	71	660	46.86	Germany
Zafarana-5	100	850	85.00	Spain
Zafarana-6	94	850	79.90	Germany
Zafarana-7	142	850	119.85	Japan
Zafarana-8	142	850	119.85	Netherlands
Gulf of El-Zayt-1	20	2000	40.00	Spain
Gulf of El-Zayt-2	100	2000	200	Spain
Ras Gharib	125	2100	262.5	United States

2. Levelized Cost of Energy (LCOE)

The levelized cost of energy (LCOE) metric replicates the unit energy cost, considering capital, operation and funding costs, over the project lifetime. The metric usually determines the expense of the lifetime of the energy system under consideration (such as wind, solar and nuclear power sources), divided by the assumed lifetime production of energy to deliver as an output [30]. In other words, it is the cost per unit energy. The following are the main inputs of this method [31]:

- Initial cost of investment expenditures (I)
- Maintenance and operation expenditures (M&O)
- Fuel expenditures (if applicable) (F)
- The project discount rate (r)
- The life of the system (n)
- The electrical generation in the year (E)

$$\text{LCOE} = \sum \frac{\text{Net present value(NPV) of total costs over life time}}{\text{Net present value (NPV)of energy generation over life time}} \quad (1)$$

$$\text{LCOE} = \sum_{t=1}^{n} \left[\frac{I_t + M_t + F_t}{(1+r)^t}\right] / \sum_{t=1}^{n} \left[\frac{E_t}{(1+r)^t}\right] \quad (2)$$

The capital cost of wind energy includes the following major categories as illustrated in Fig. 2:

- Turbine cost: comprising tower, blades and transformer.
- Civil works: comprising foundations for the towers and construction costs for preparation of site.
- Grid connection costs: comprise substations and transformers, and also the connection to the regional distribution system or transmission lines.
- Other capital costs: include the control systems, buildings construction, project consultancy, engineering and management costs, etc.

The cost of operation and maintenance (O&M) is considered the most critical component of the overall investment cost of wind energy projects. This cost includes insurance, replacement parts, management, renting of the site, consumables, and utility side expenses. Given the rapid development of the wind turbine technology, O&M specifications are considerably, relying on the turbine sophistications and age.

The cost of wind power is closely associated with the respective capacity factor (CF) at the production sites [32], while the CF depends on the characteristics of the wind resource at each production site and the turbine technical characteristics.

Hence, the merits of LCOE include the following points:

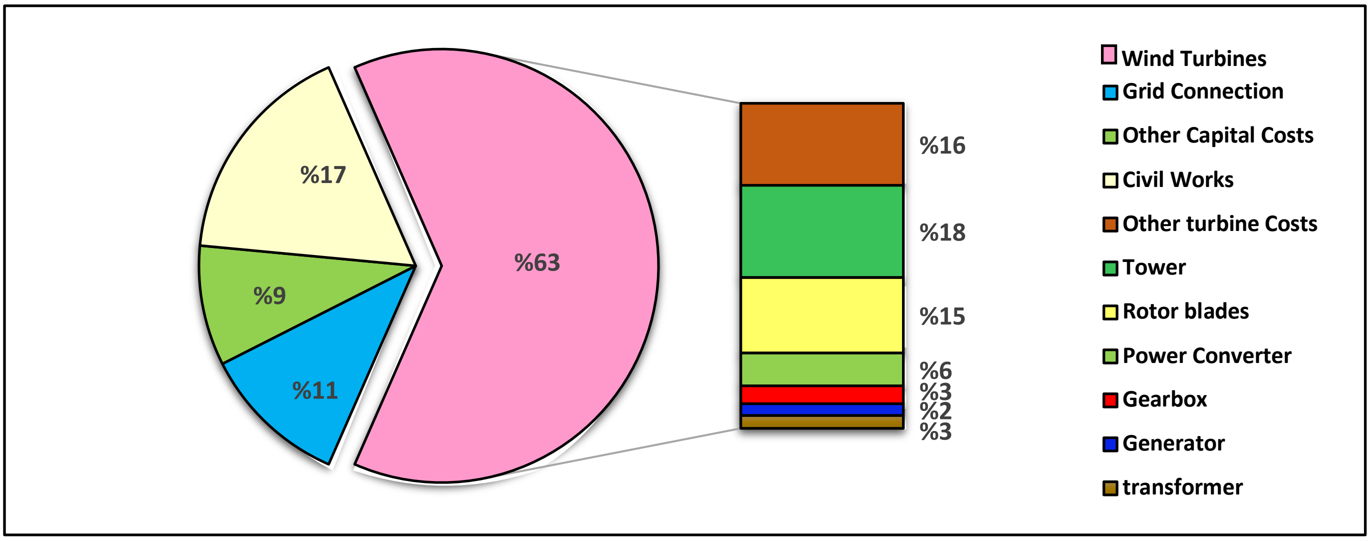

Fig. 2. Capital expenditures for the wind reference project [33].

- Measure value across the longer term, showing estimated life-cycle costs.
- Highlight opportunities for individuals and community to create various project scales (community, facility or commercial).
- Assess viability of having wind power projects on an economic basis, compared to utility energy rates and prices.

3. Wind Energy Characteristics at Different Regions in Egypt

This paper divides Egypt's overall land into three different regions according to their range of wind speeds. Based on wind speed data, an assessment of the wind energy capacity and cost estimate of each region is carried out. The first region (Region I) with high wind speed range (8 -11 m/s) occurs at Abo drag, Zafarana, Ras Gareb and Gulf of El-Zayt is shown in Fig. 3. As per the annual average wind speed (AAWS) shown in Fig. 4, the windiest region among these locations is Gulf of Elzayt (AAWS is 10.06 m/s) and the least blowing wind is at Ras Ghareb (AAWS is 8.25 m/s). The second region (Region II) comprising medium wind speed range (6-8 m/s) locations, covers the Eastern and Western parts of the Nile, Marsa Matrouh, Sidi Barrani, El-Suez and Hurghada, as shown in Fig. 5. AAWS of these sites is shown in Fig. 6 where the windiest region among these locations is at El-Suez (AAWS of 6.16 m/s) and the least wind occurs at Sidi Barrani (AAWS is 6.02 m/s).

Finally, the low wind speed region (Region III) (≤ 6 m/s) refers to Mediterranean Sea and South Upper Egypt locations; this region includes: Alexandria, Port- said, Qena, Aswan [34] as highlighted in Fig. 7. AAWS of these sites are detailed in Fig. 8; the windiest site among these locations is Alexandria (AAWS is 5.34 m/s) and the least windy site is at Aswan (AAWS is 4.92 m/s).

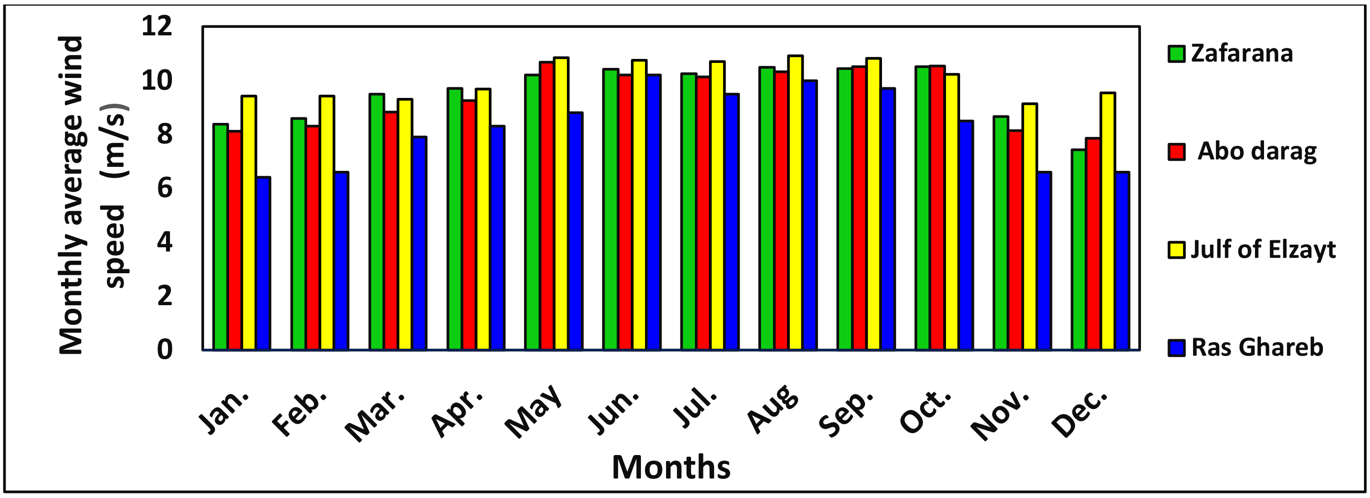

Fig. 3. Monthly average wind speed of Zafarana, Abo Darag, Julf of Elzayt and Ras Ghareb.

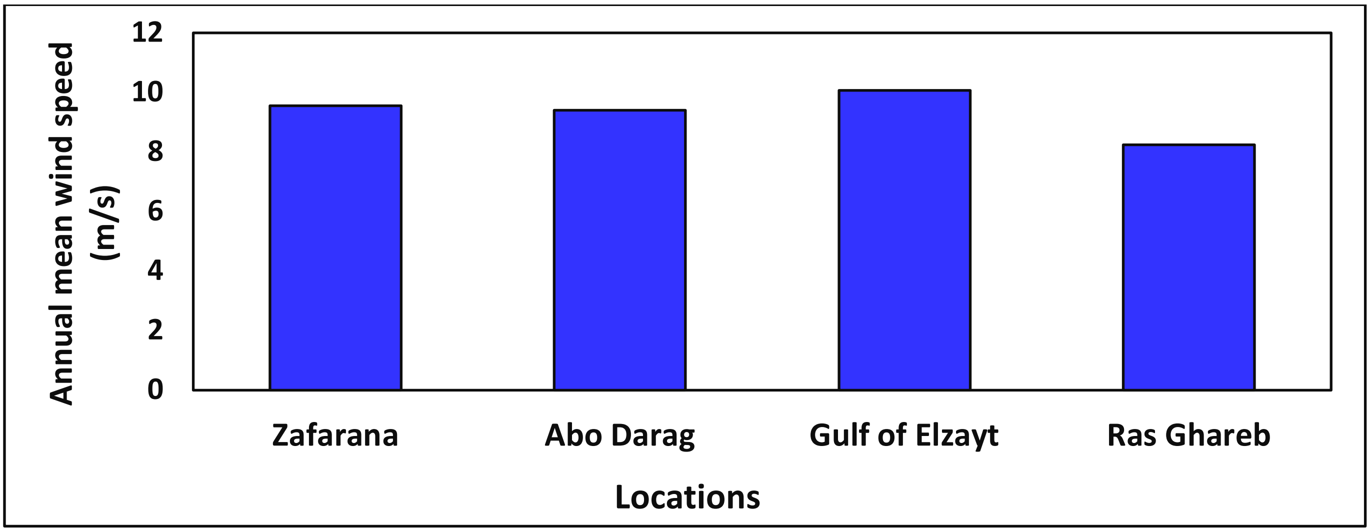

Fig. 4. Annual average wind speed of Zafarana, Abo Darag, Julf of Elzayt and Ras Ghareb.

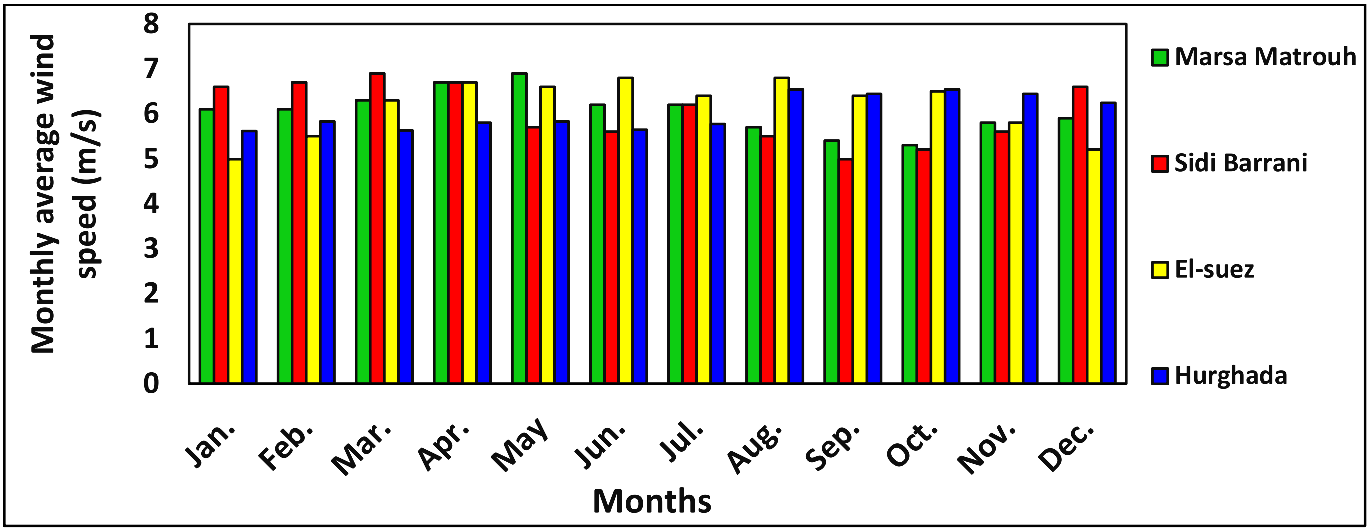

Fig. 5. Monthly average wind speed of Marsa Matrouh, Sidi Barrani, El-suze and Hurghada.

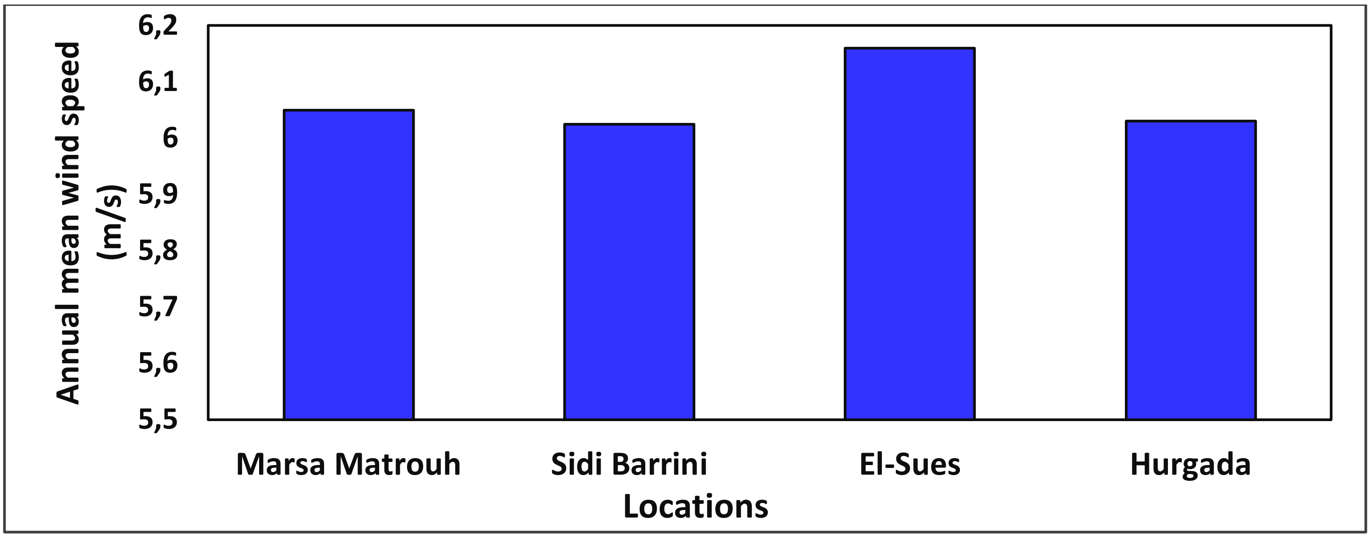

Fig. 6. Annual average wind speed of Marsa Matrouh, Sidi Barrani, El-suze and Hurghada.

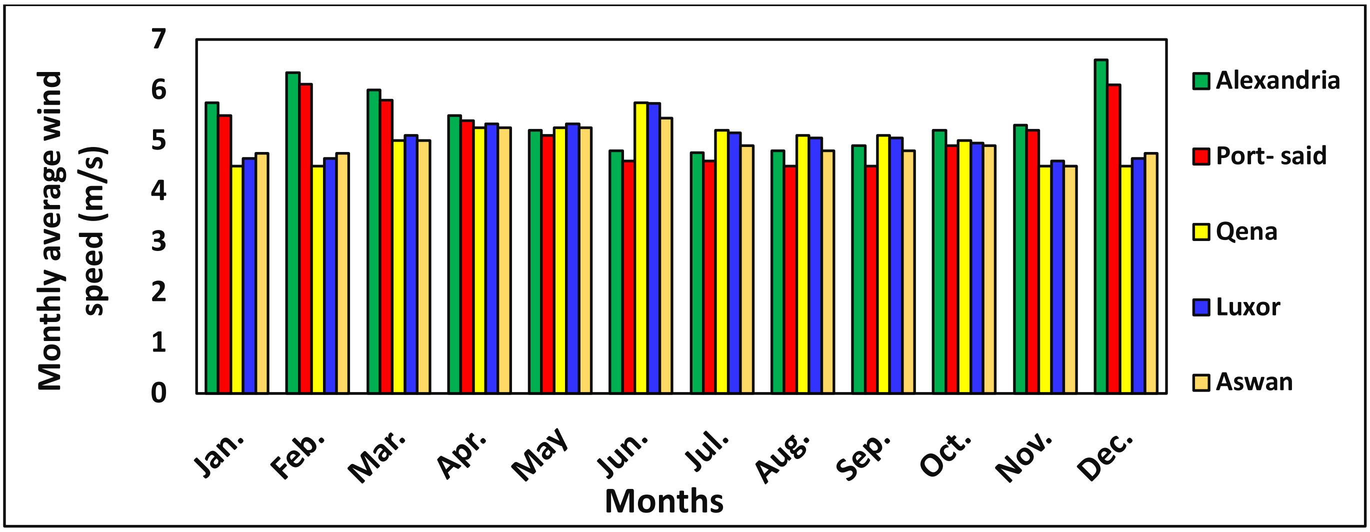

Fig. 7. Monthly average wind speed of Alexandria, Port-said, Qena, Luxor, Aswan.

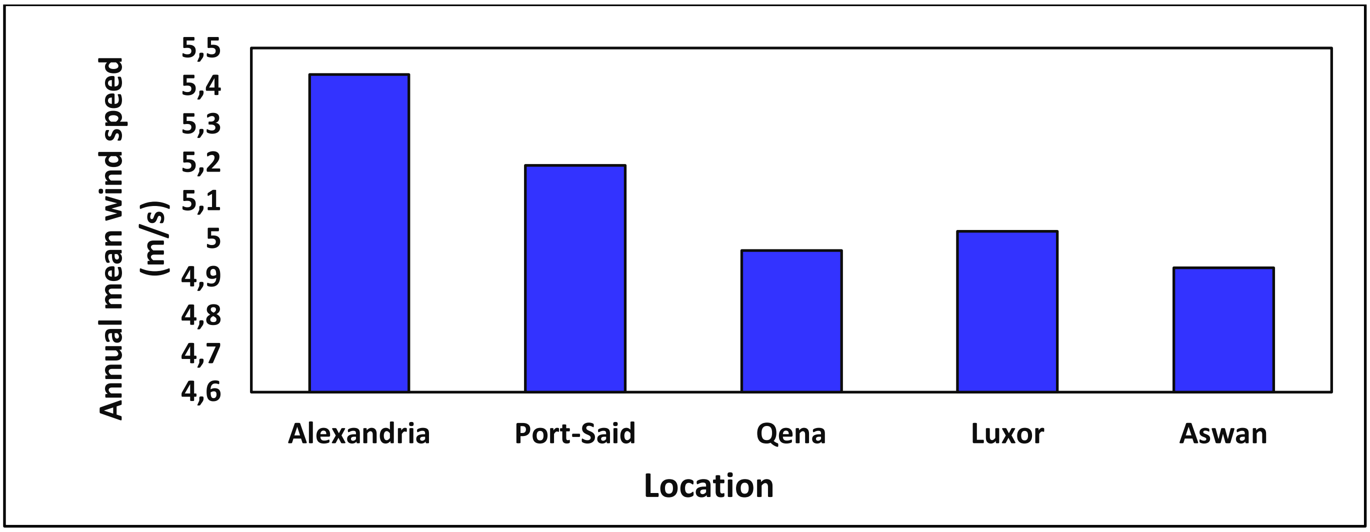

Fig. 8. Annual average wind speed of Alexandria, Port-said, Qena, Luxor, Aswan.

To calculate the cost per kWh of wind energy, three different kinds of wind energy conversion technology WECT, namely: Nordex N80 (2500kW), EnerconeE33 (330 kW) and Gaia (11kW) are chosen for these three regions, respectively. Table 2 summarizes the technical details of the selected wind turbines.

Table 2. Technical specifications of the selected wind turbines.

Wind turbine	Rated power (kW)	Diameter (m)	Swept area (m^2)	Cut in speed (m/s)	Rated speed (m/s)	Cut out speed (m/s)
Nordex N80	2500	80	5027	4	15	25
Enercon E33	330	34	876	3	12	28
Gaia	11	13	133	3.5	9.5	>25

Equation (3) presents the output mechanical power of a wind turbine [35]

$$P_m = 0.5\,\rho\,A\,V_\omega^3 C_p(\beta,\lambda) \quad (3)$$

The relationship between tip speed ratio (λ) and blade pitch angle (β) is defined as [36]:

$$C_p(\beta,\lambda) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)^{-21/\lambda_i} + 0.0068\lambda \quad (4)$$

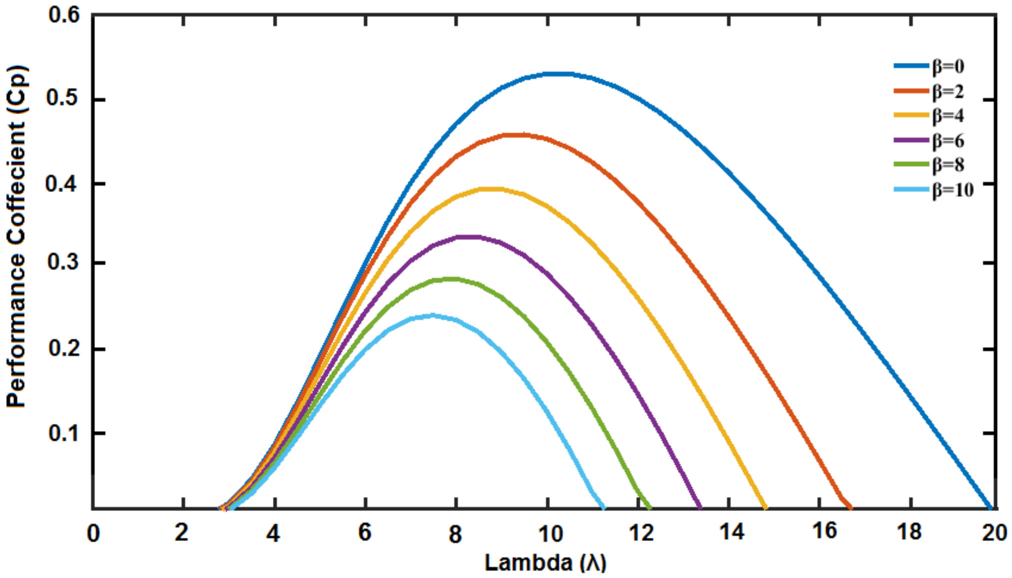

Fig.9. Power coefficient with tip speed ratio.

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \quad (5)$$

The tip speed ratio can be defined as:

$$\lambda = \frac{R\,\omega_t}{V_\omega} \quad (6)$$

Where: R is the rotor blade radius, ω_t is turbine angular speed. Fig. 9 demonstrates the graphical representation of the performance coefficient (C_p) with respect to continuously varying of tip speed ratio (λ) over different discrete values of blade pitch angle (β) [37].

4. Environmental Cost Analysis

To assess the environmental costs, the needed financial and technical information are capital costs, fixed operation and maintenance costs, capacity factor data, assumed lifetime and discount rate. A sample of recently examined projects in the United States suggested the limits for capital, operation and maintenance costs shown in Figs. 10-11. The cost of capital and energy generated by small wind turbines is still higher than large-scale wind turbines as shown in Fig. 11. The capacity factor curves for different wind speed of the selected wind turbines are shown in Fig. 12.

The discount rate is used to calculate the present value of the net cash flows that exist over the wind turbine's lifetime (typically 20 years) and assumed to be 8% in the base study of the LOCE calculations.

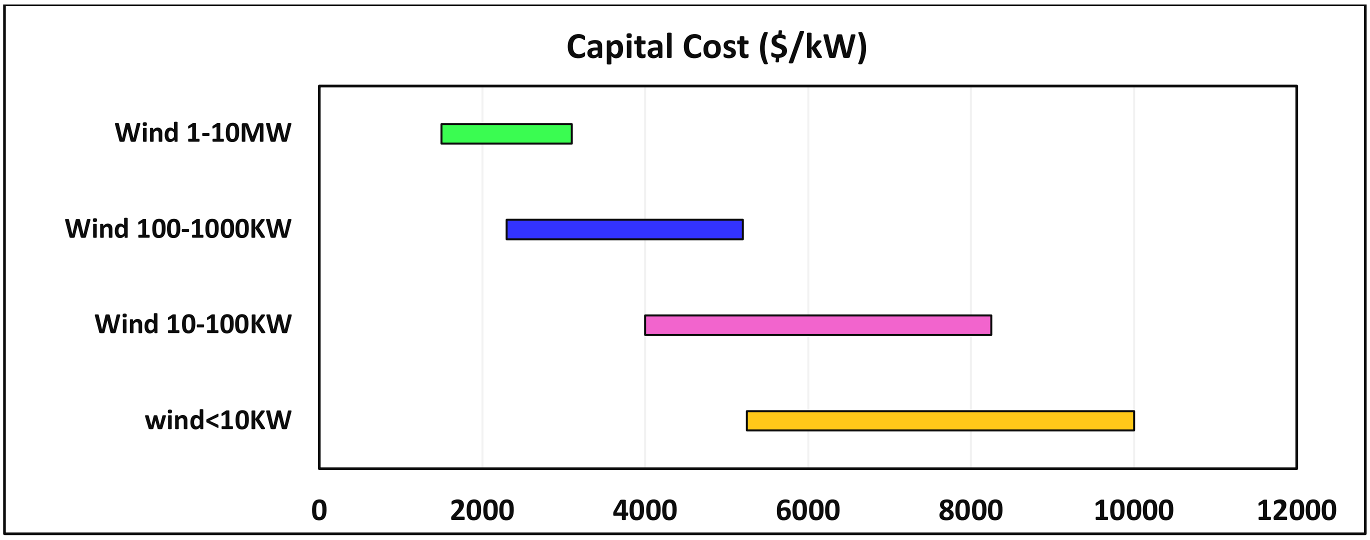

Fig.10. Recent capital cost estimates for wind energy technology [40].

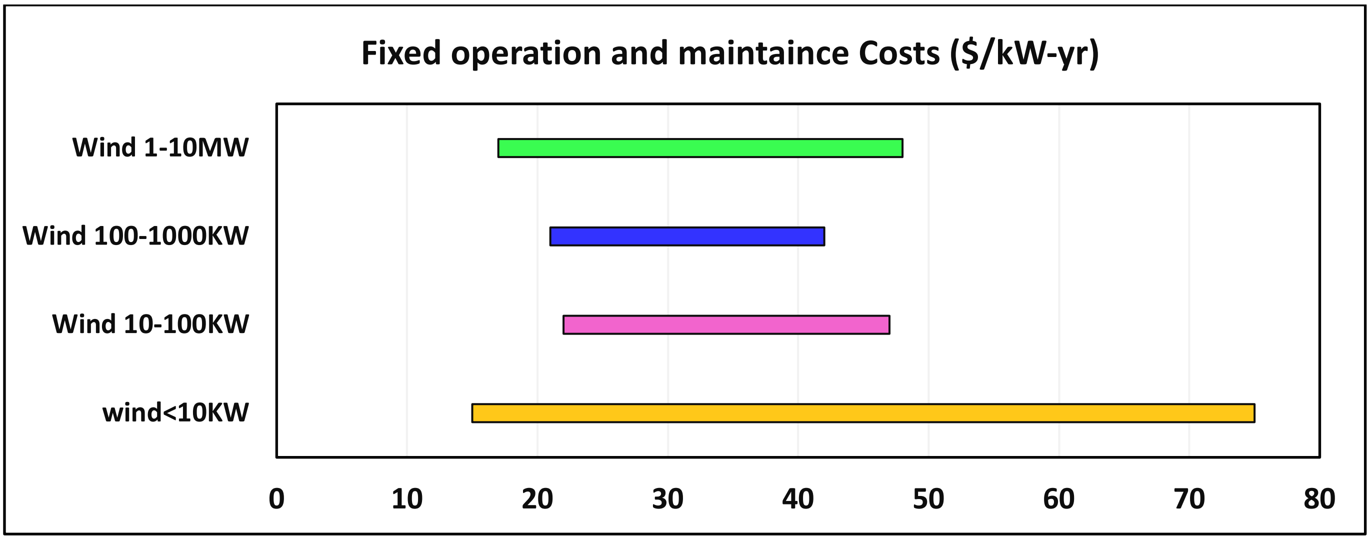

Fig. 11. Operation and maintenance (O&M) cost for wind energy technology.

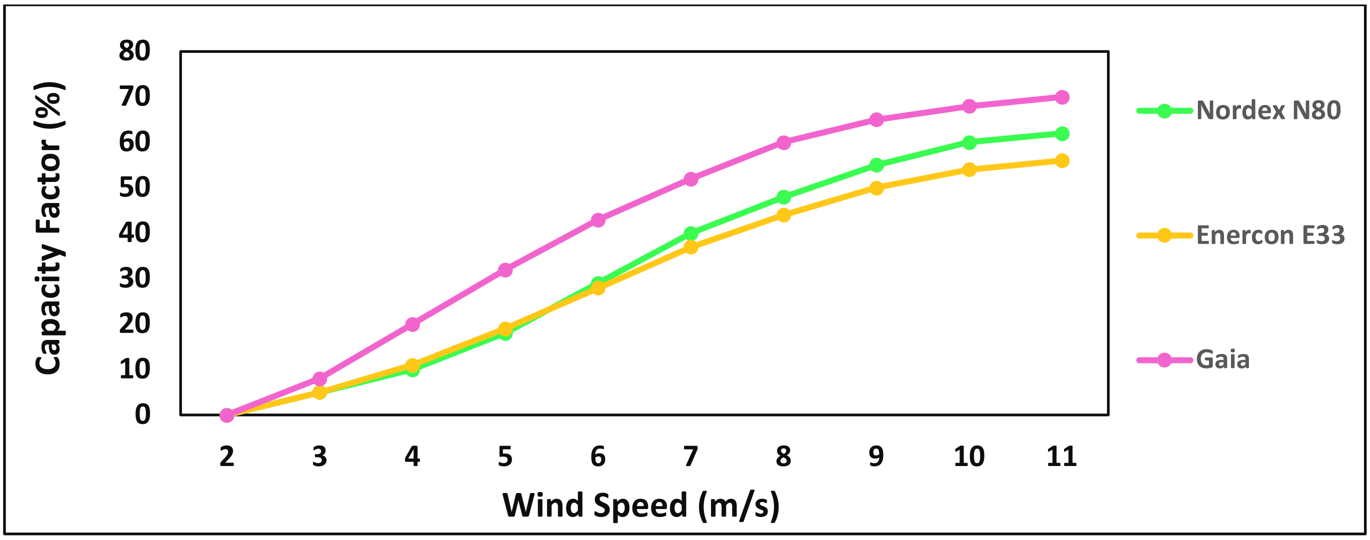

Fig 12. Capacity factor curves for different wind speed of the selected wind turbines.

The variation in the LCOE $/kWh with the capacity factors for the selected WECT (Nordex, Enercon and Gaia) is presented in Table 3. The cost per unit energy decreases from 0.052 $/kWh to 0.035 $/kWh for Nordex WECT and from 0.121$/kWh to 0.077 $/kWh for Enercon WECT. Similarly for GaiaWECT, the charge decreases from 0.941$/kWh to 0.198 $/kWh.

In another prospective, a key consideration for utility scale generation technologies is the impact of the availability and capital cost on LCOE values. The LCOE is altered by different values capital costs from 0.0365 to 0.039 $/kWh, 0.082 to 0.101 $/kWh and 0.215to 0.426 $/kWh for regions I, II and III respectively, as shown in Table 4. The economic analysis carried out in this paper does not take into account the increase in operations and maintenance costs. Generally, the O&M costs for newer WECT are low, but these expenses increase with the decrease in the useful lifetime of the WECT. The rate of increase depends on the wind condition of the location, the configuration of the turbine and the efficiency of the components. The LCOE is affected by different values of capital costs; it spans from 0.035 to 0.041 $/kWh, 0.088 to 0.095 $/kWh and 0.314 to 0.326 $/kWh for regions I, II and III respectively, as shown in Table 5.

The results of this analysis for three windy regions in Egypt are presented in Figs. 13-15. From these figures, it can be observed that, all selected input parameters are sensitive for LCOE. The capacity factor has a very positive effect on the LCOE, i.e. the LCOE decreases as CB values increase. This explains why a site with a high wind turbine capacity factor is desirable (economically). Typically, the increase of the capital and O&M costs have adverse impacts on the economic viability of wind energy system development as the LCOE increases. In fact, it can be observed from Figs. 13-15 that, the capital and O&M costs have insignificant impacts on the LCOE.

Table 3. The impact of capacity factor on the LCOE for windy regions in Egypt.

Wind turbine	Wind Speed (m/s)	Capacity factor (%)	Average Capital Cost ($/kWh)	Average O&M cost ($/kWh-yr)	LCOE ($/kWh)
Gaia 11kW (Region III)	3	8	6125	35	0.941
	3.5	15			0.502
	4	20			0.377
	4.5	26			0.29
	5	32			0.235
	5.5	38			0.198
Enercon E33 330kW (Region II)	6	28	2600	31.5	0.121
	6.5	33			0.103
	7	38			0.089
	7.5	41			0.083
	8	44			0.077
Nordex N80 2500kW (Region I)	8.5	52	1550	32.5	0.052
	9	55			0.04
	9.5	58			0.038
	10	60			0.036
	10.5	61			0.036
	11	62			0.035

Table 4. The impact of capital cost on the LCOE for windy regions in Egypt.

Wind turbine	Average Capacity factor (%)	Capital Cost ($/kWh)	Average O&M cost ($/kWh)	LCOE ($/kWh)
Gaia 11kW (Region III)	23.5	4000	35	0.215
		4850		0.257
		5700		0.299
		6550		0.341
		7400		0.384
		8250		0.426
Enercon E33 330KW (Region II)	37	2300	31.5	0.082
		2450		0.087
		2600		0.092
		2750		0.096
		2900		0.101
Nordex N80 2500KW (Region I)	58	1500	32.5	0.0365
		1520		0.037
		1540		0.0375
		1560		0.038
		1580		0.0385
		1600		0.039

Table 5. The impact of O&M cost on the LCOE for windy regions in Egypt.

Wind turbine	**Average Capacity factor**	**Average Capital Cost ($/kWh)**	**O&M cost ($/kWh-yr)**	**LCOE ($/kWh)**
Gaia 11KW (Region III)	23.5	6125	22	0.314
			27	0. 317
			32	0.319
			37	0.321
			42	0.324
			47	0.326
Enercon E33 330KW (Region II)	37	2600	21	0.088
			26.2	0.09
			31.5	0.092
			36.7	0.093
			42	0.095
Nordex N80 2500KW (Region I)	58	1550	17	0.035
			23.2	0.0365
			29.4	0.037
			35.6	0.038
			41.8	0.039
			48	0.041

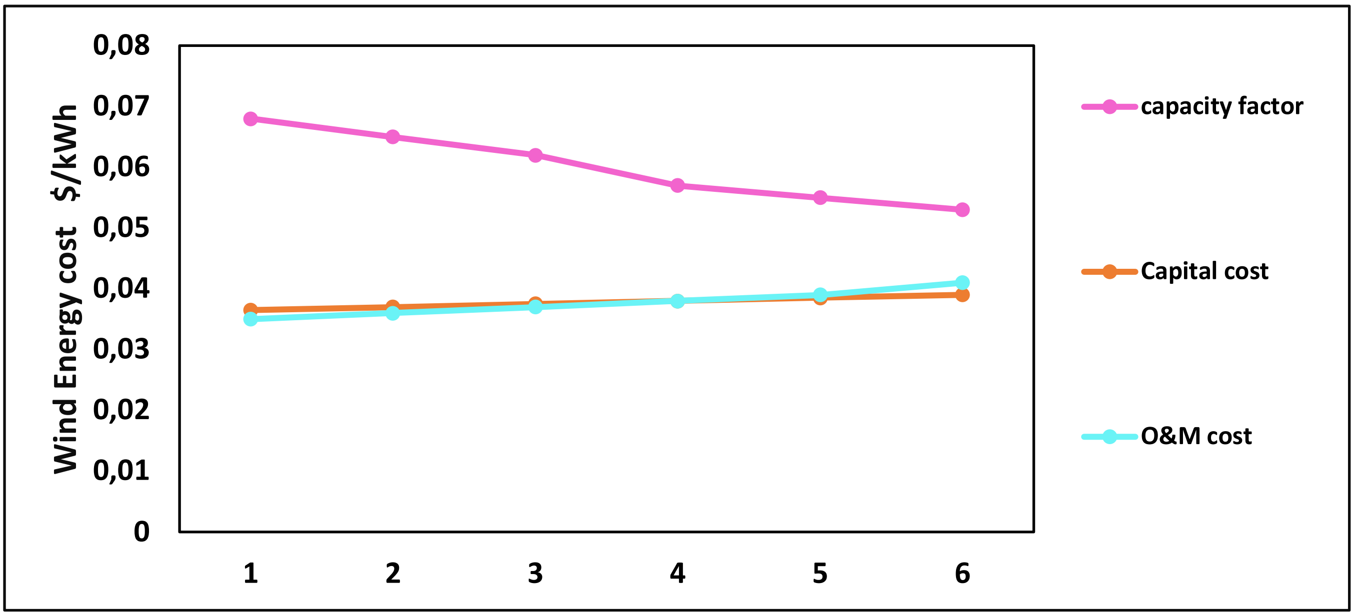

Fig 13. Impact of selected input parameters on the wind energy cost for region I.

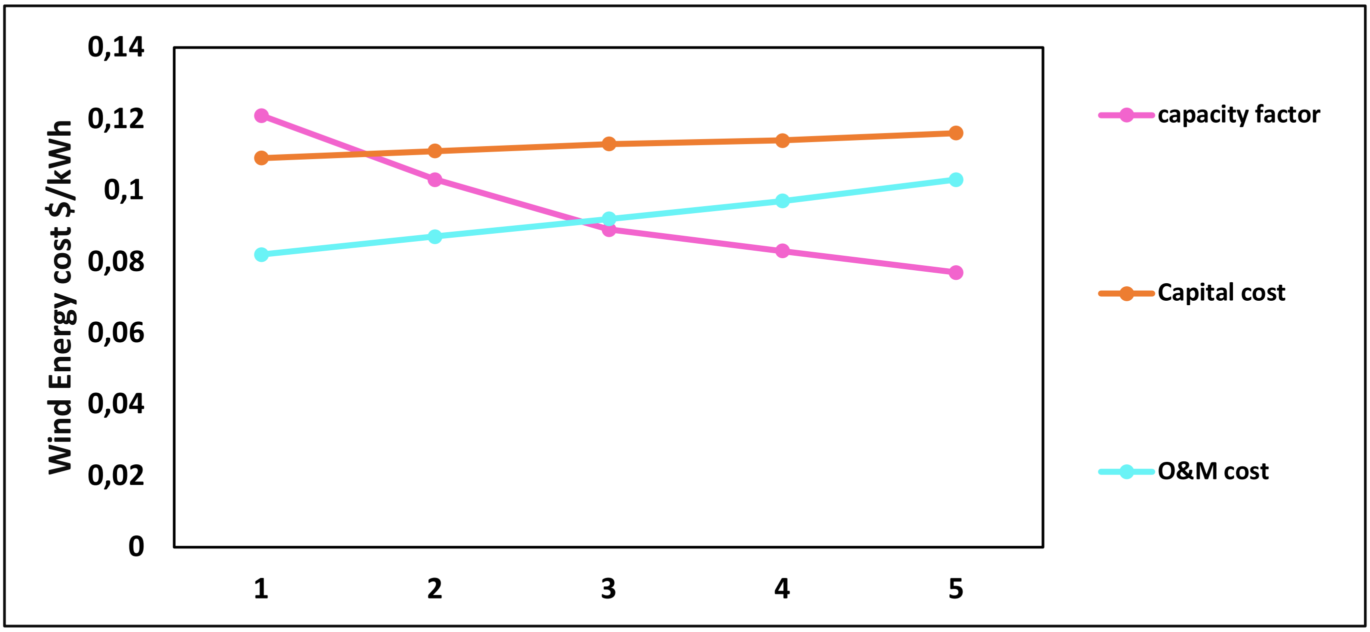

Fig 14. Impact of selected input parameters on the wind energy cost for region II.

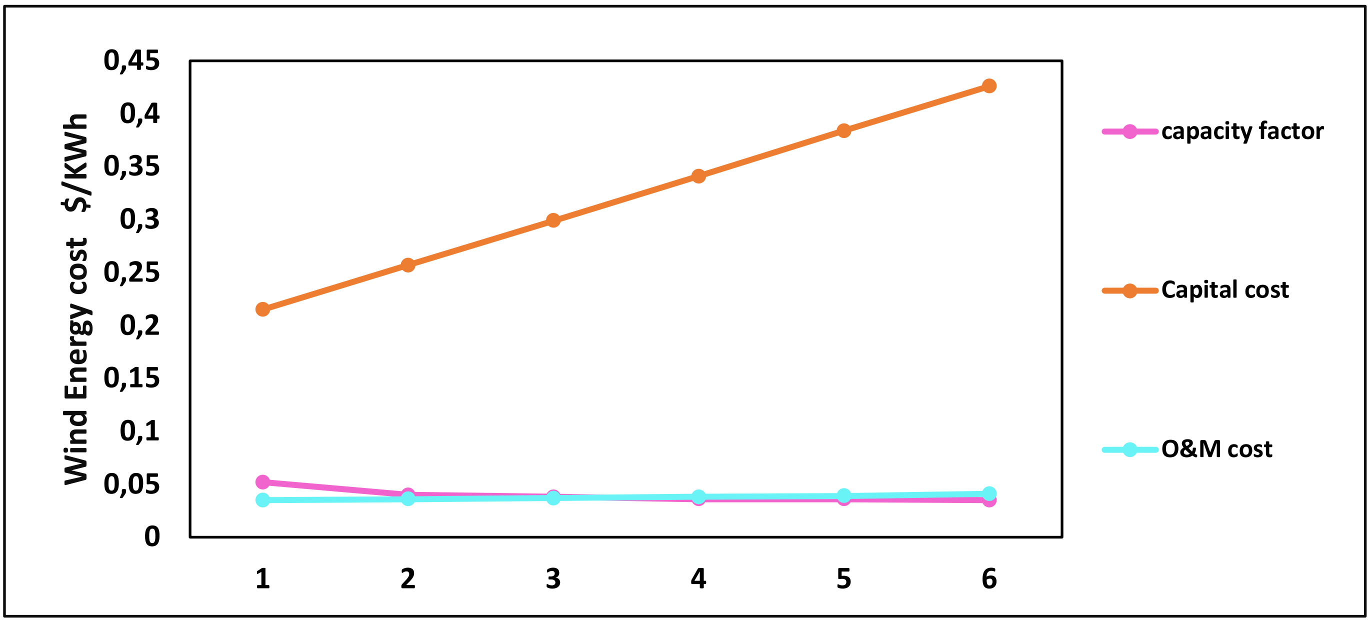

Fig 15. Impact of selected input parameters on the wind energy cost for region III.

5. Conclusion

In this paper, wind energy characteristics and LCOE calculation for different regions in Egypt are investigated. Monthly and annual historical average wind speed data have been analyzed and three different types of wind turbines have been chosen to investigate wind power economic viability as shown in Tables 13–15 based on this analysis. After analyzing, the key findings can be summarized as follows:

1- In the first region, wind energy is economically more feasible compared to the second region, and in the second region it is economically more feasible compared to the third.
2- The Gulf of Elzayt, Zafarana, Abu Darag and Ras Ghareb have the best potential of wind energy, suitable for large-scale production of electricity.
3- Alexandria, Port-said, Qena, Luxor, Aswan have less wind energy feasibility, ideal for small-scale wind power plants.
4- In the LCOE method, the cost per kWh wind energy charge ranges from 0.052 to

0.041$/kWh, 0.121 to 0.095 $/kWh and 0.941 to 0.326 $/kWh respectively for regions I, II and III.

5- The sensitivity analysis shows that, increasing the wind turbine capacity factor can have a positive effect on the LOCE of the electricity produced by the WECS.

Increasing capital and O&M costs has a negative impact on the LOCE of the electricity produced by the WECS.

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