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RENEWABLE ENERGY

Assessment of Wind Energy Potential in Western Mountain: Nalut and Yefren as Case Study

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ABSTRACT

An estimation of wind potential is considered as the first essential step in transition toward renewable and environmental friendly energy. It is therefore necessary to have detailed knowledge of the wind to select the suitable wind turbine for a certain site and also estimate its performance accurately. It believes that wind energy can compensate the shortage in power supply, in additional to mitigate the carbon footprint. The present research seeks to achieve decentralization and decarburization as they are one of the sustainability substrates, by means of examine the capability of each location and highlighting the futures. The findings of the present research reveal that it is worth to investigating in wind energy in the Western Mountain cities such as Nalut and Yefren as the LCOE are 4.3 and 4.5 ¢/kWh, respectively, when using Suzlon (3.3 MW) wind turbine, which is much less than the price of purchasing electricity by the Libyan General Electrical Company and estimated at 10 ¢/kWh. In addition, preventing about 3.3 ton CO_2/kWp of wind energy of emission in the atmosphere.

تقدير امكانيات طاقة الرياح في منطقة الجبل الغربي بليبيا: دراسة حالة مدينتي نالوت ويفرن

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الكلمات المفتاحية

منطقة الجبل الغربي
طاقة الرياح
تكلفة الكربون الاجتماعية
معامل القدرة
تكلفة انتاج وحدة

الملخص

يُعد تقدير امكانيات طاقة الرياح الخطوة الاولى في طريق التحول نحو الطاقات المتجددة والصديقة للبيئة. وبالتالي فانه من الضروري توفر معلومات ومعرفة عن توفر طاقة الرياح واختيار نوع توربينات الرياح المناسبة لكل موقع معين. يمكن لطاقة الرياح ان تعوض العجز في امدادات الطاقة التي تعاني منه البلاد، بالاضافة الى تلطيف البصمة الكربونية. يسعى البحث الحالي لتحقيق اللامركزية وحياد الكربون في قطاع صناعة الطاقة الكهربائية حيث يمثلان مفتاح الاستدامة في مجال الطاقة، وذلك باختبار امكانية توليد الكهرباء عن طريق انشاء مزارع طاقة الرياح في عدة مو اقع في منطقة الجبل الغربي، وكذلك تحديد توربينة الرياح الانسب لكل منطقة من خلال محاكاة سبع انواع من توربينات الرياح التجارية. تكشف النتائج المتحصل عليها في هذا البحث الجدوى الاقتصادية للاستثمار في طاقة الرياح في منطقة الجبل العربي، حيث كانت تكلفة انتاج وحدة الطاقة LCOE أقل بكثير سعر شراء الطاقة الكهربائية التي حددته الشركة الليبية العامة للكهرباء وهو 10 سنت لكل كيلووات ساعة. حيث قدرت LCOE بحوالي 4.3 سنتا لكل كيلووات ساعة في مدينة نالوت، بينما بلغت 4.5 سنتا لكل كيلووات ساعة في مدينة يفرن، وذلك عند استخدام توربينة رياح نوع (SUZLON (3.3 MW. اضافة الى منع انبعاث ما يقدر 3.3 طن من CO2 لكل كيلووات قدرة من توربينات الرياح في الهواء الجوي سنويا.

Introduction

Driven by concerns about climate change and global warming, at the end of 2023 around 77.6 GW has wind energy been integrated into electrical grids, resulting in a cumulative installed capacity of 906 GW. In the next five years (2023-2027) Africa and the Middle East are anticipated to build 17 GW of new wind energy capacities, including 3.6 GW in Egypt, 2.4 GW in Saudi Arabia, 2.2 GW in Morocco and about 5.3 GW in South Africa [1]. Wind energy's relevance arises from its ability to work harmoniously with solar energy in hybrid renewable energy systems. Wind energy is distinguished by its capacity to create electricity constantly, driven by fluctuating wind speeds, as opposed to solar energy, which only runs during daylight hours [2-10].
Despite the enormous proven potential that Libya possesses of renewable energies [11], as the annual energy potential for solar PV reaches 1,750 kWh/kWp [12], and about 3,855 kWh/kWp for wind [13], however, the contribution of renewable energy in the produced energy mix does not exceed 1% [14]. In COP 27 (The UN Climate Change Conference) which taking place in Sharm El-Sheikh-Egypt, the Libyan government announced its strategic plan to generate electric power from some of the renewable energies

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available in the country for the next 30 years, which aims to achieve the participation of renewable energies in the mix of electric energy production by 25% by 2025, 30% by 2030, and 60% by 2050, and that will be mainly from concentrated solar energy, PV solar and wind energy [15]. The great challenge faced by engineers and scientists the lack of reliable measured data and the suitable sites to establish renewable energy industry in Libya [16]. Many local studies examined the potential of wind energy in Libya.

In Hun city, an analysis carried by [17] showed that at 60 m height above the ground, the annual average wind speed is about 5.7 m/s and the wind power density is about 190 W/m^2. It could be noticed that at 60 m height, the maximum wind speed is about 7.3 m/s in April, while the minimum wind speed is about 5.7 m/s in October. About 90% of the wind speeds are less than 11 m/s, about 84% of speeds are less than 10 m/s and about 50% of wind speeds are higher than 6 m/s. The highest wind speed is 21 m/s with 0.14% occurrence. The wind shear exponent was evaluated as 0.18 and the roughness length for the site as 0.17 m, which indicates that the roughness class for the location is 2.5. According to comparison of two wind turbines, the analysis indicated that Vestas V112-3000 gave the highest capacity factor of 42%, while Nordex N100- 2500 gave capacity factor of 41%.

In Zwara city, wind speeds are measured and recorded every 10 minutes at three elevations of 10 m, 30 m, and 50 m above ground level. The analysis showed that the annual average wind speed are 4.51, 5.86, 6.26 m/s for the considered elevations. And the corresponding average annual wind power densities were 113.7, 204.2, 243.5 W/m^2, respectively [18].

In order to determine the most suitable wind turbine for operating in AL-Magrun city, the annual energy yield and wind direction were evaluated for wind turbines with capacities ranging between 1.65 MW and 2 MW. The wind turbine (Gamesa 90/2000 - Germany) recorded the highest wind energy production about 6.05 GWh/year [19].

Belal in [20] collected and analysed wind data at Tajora. The results showed that the minimum and maximum daily average wind speed varies from 2.35 m/s to 4.69 m/s, and the annual average wind speed is 3.24 m/s. Among the Forward design, activity is estimating the wind resources available at the site for sizing the system to provide the site water requirements of 5 m³/day.

Abdalla, et al. in [21] conducted a research in three different locations Magron, Musrata and Dernah cities. The results confirm that the highest wind shear occurs during stable conditions at night and for longer in winter days, and the lowest during unstable and neutral atmospheric conditions near midday specially in summer days. Non-dimensional wind speed profiles were obtained and their behaviour was identified and compared. The available wind energy history was evaluated considering the effect of atmospheric stability conditions on the estimated extracted energy for each site.

As Dernah has the highest wind energy potential, Al-Behadili also condcted a stdy using CDM software [22]. The main findings of the research showed that, the CO_2 reductions is 362,201.82 tCO_2e/year and CERs for the first ten years of the lifespan of the Dernah Wind Farm-I is $320,838,372 for the first ten years, likewise the entire wind turbines lifespan (25 years) is $641,676,744. Based on the obtained results, it can be concluded that it is worth to investing in wind energy in Dernah city. Therefore, registering wind energy projects as CDM projects and earning CERs is the most practical way to promote wind energy. The obtained results could be benefit for policy makers and investors who are interested in CDM wind energy projects.

One of the largest local study carried by El-Osta, et al. [23], analysis conducted the wind energy potential of 12 Cities (Tripoli, Zawiya, Msallata, Brack, Gharyan, Sirte, Hun, Qatrun, Ghat, Benghazi, Kufra and Dernah). The results showed that the wind turbine type "Gamesa-2000" exhibited the most favourable economic with a 100 MW wind turbines farm capacity. The capital cost is estimated of $146,916,400, the GHG emission factors across all examined cities ranged from 32 to 70 g GHG/kWh, the carbon payback durations spanning from 4.5 to 12.3 months. The estimated energy payback period varied from 13 to 22 months, while the Livelezed Cost of Energy with considering the GHG emissions during the lifespan of the wind turbine (LCLCOE) ranged from 4.8 to 8.4 ¢/kWh.

17 wind turbines have examined by using the System Advisor Model (SAM) at twelve locations in Libya (Ajdabiya, Al-Jufra, Al-Kufra, Benghazi, Sebha, Sirte, Tubroq, Tripoli, Ghat, Ghadamis, Gharyan and Murzuq). The LCOE ranging from 1.5 to 5.9 ¢/kWh [11].

The capacity factors of 850 kW wind turbine capacity are estimated for four cities: Gharyan, Nalut, Asabah, and Alraiyna.The reslts showed that, the capacity factors are for Gharyan is 14.632%, Nalut is 13.55%. Asabah is 16.5 and Alraiyna is 17.14%. These values imply that Alraiyna has the potential to generate 1.275861 MWh annually [24].

Issah et al. estimated the annal yielda and the capacity factor of wind energy for several sites in Libya (Asabah, Tarhunah, Alheira, Ghutalriah, and Msalath). Tarhunah has the maximum annual energy and capacity factor while Ghut-alriah has the minimum annual energy and capacity factor. Existing data resources indicates that the mean annual wind speed of over 7.67 m/s in Tarhunah with theoretical capacity factor exceeding 44.13522 %. These values indicate that Tarhunah could generate an annual energy 1275861 kWh [25].

The above literature review showed that some cities have been studied more than once, but the cities included in this study have not been studied before, even though they are located in a mountainous area and are likely to have a high potential of wind energy.

Sites Information

Yefern (32.049122°N, 12.511159°E) and Nalot (31.891008°N, 10.998284°E) are located at Western Mountain. A geographical map for the study sites are shown in Fig. 1.

Hourly time series climatic data has been obtained from SODA platform (https//www.soda-pro.com/web-services/radiation/helioclim-3-archives-for-free). The wind speed, ambient temperature, and global horizontal solar irradiance of Yefren and Nalut are illustrated in Figs. 2 and 3 respectively.

The hottest days expand for 3.9 months, from 27th of May to 24th of September, with an average daily high temperature above 31°C. The hottest month of the year in Yefren is July month, with an average high of 36°C and low of 18°C. The cool season lasts for 3.3 months, from 27th of November to 6th of March, with an average daily high temperature below 18°C. The coldest month of the year in Yefren is January month, with an average low of 2°C and high of 14°C [26].

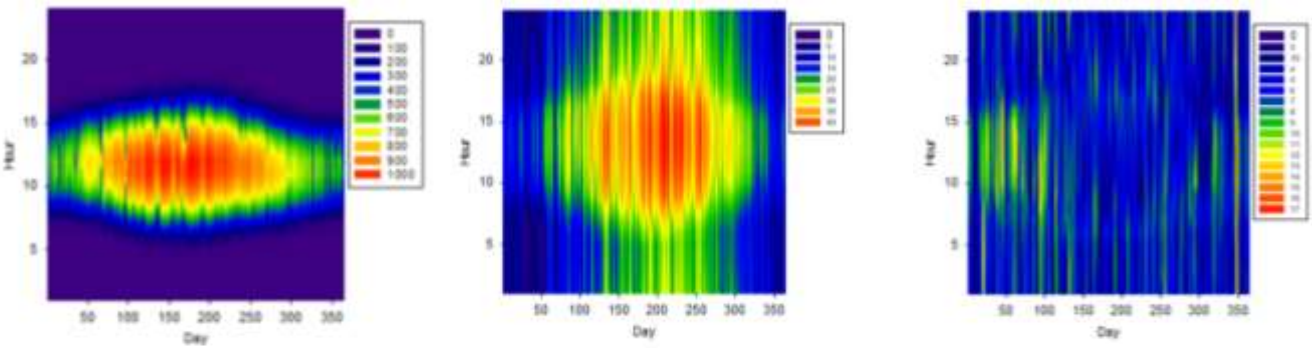
The average hourly wind speed in Yefren experiences mild seasonal variation over the course of the year. The windier part of the year lasts for 7.0 months, from 18th of November to 19th of June month, with average wind speeds of more than

4.5 m/s. The windiest month of the year in Yefren is May, with an average hourly wind speed of 4.9 m/s. The calmer time of year lasts for 5.0 months, from the 19th of June to the 18th of November month. The calmest month of the year in Yefren is August month, with an average hourly wind speed of 4.1 m/s [26].

While in Nalut, the hot season lasts for 3.7 months, from the 29th May to the 21st September, with an average daily high temperature above 32°C. The hottest month of the year in Nalut is August month, with an average high of 36°C and low of 21°C. The cool season lasts for 3.3 months, from the 26th of November to the 3ed of March month, with an average daily high temperature below 19°C. The coldest month of the year in Nalut is January, with an average low of 3°C and high of 14°C [26].

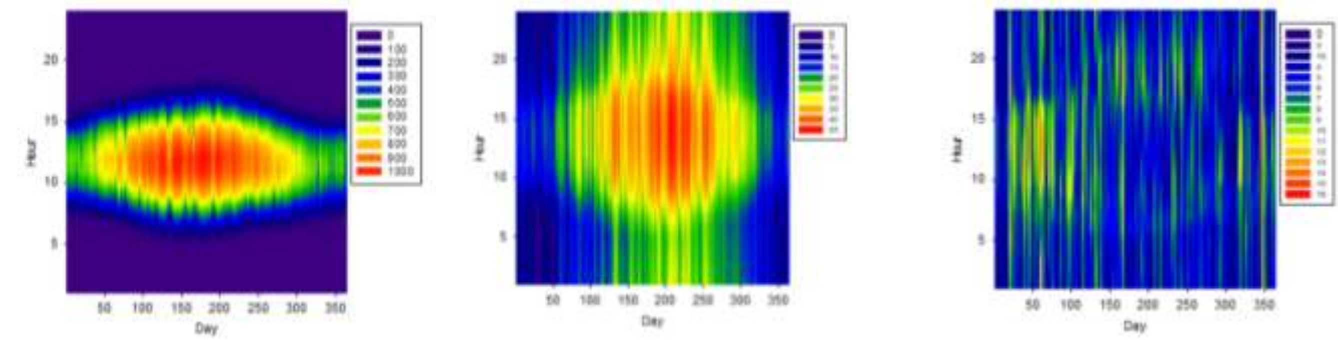
The average hourly wind speed in Nalut experiences mild seasonal variation over the course of the year. The windier part of the year lasts for 6.5 months, from January 26 to August 10, with average wind speeds of more than 4.5 meters per second. The windiest month of the year in Nalut is May, with an average hourly wind speed of 5.0 m/s. The calmer time of year lasts for 5.5 months, from August 10 to January 26. The calmest month of the year in Nalut is October, with an average hourly wind speed of 4.0 m/s [26].

Fig. 1: Study sites locations



(a) (b) (c)

Fig. 2: Key climatic parameters for Yefren city: (a) Global solar irradiation; Wh/m^2, (b) Ambient Temperature; °C and (c) Wind speed; m/s at 10 above the ground.



(a) (b) (c)

Fig. 3: Key climatic parameters for Nalut city: (a) Global solar irradiation; Wh/m^2, (b) Ambient Temperature; °C and (c) Wind speed; m/s at 10 m above the ground.

Methodology

The approach that followed in the present research is presented in Fig.4.

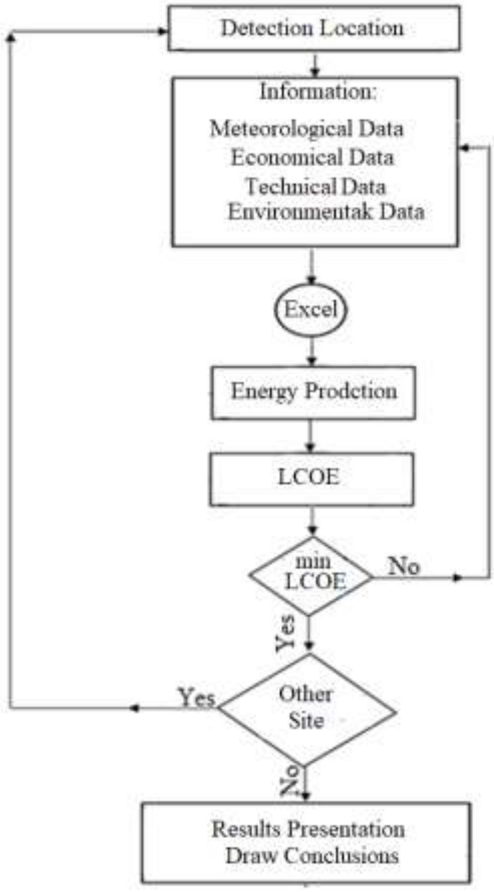


Fig. 4: Study Methodology Flowchart

Wind turbines are known as a technique of electricity generation and are widely used throughout the world as an alternative source to conventional energy that relies on fossil fuels. There are several varieties of wind turbines, which range in sizes and technologies. Large turbines are installed in large wind farms that are connected to the electrical grid, whilst smaller turbines can be used to generate limited electrical power in residential or commercial settings. A wind turbine installation requires a suitable site where the wind speeds are continuously high enough to operate efficiently. Precautions must be taken to guarantee the turbine's safe installation and operation, including regular maintenance to maintain its peak performance. The average cost of wind turbine maintenance and operation is roughly 1.5 cents per kWh, or around $45 per MW capacity per year [27].

Table 1 outlines the most crucial technical and economic characteristics that influence the performance of wind turbines. In general, eqn. (1) [28] may be used to determine the viability of wind energy generation at a certain site:

$$P_{max}(\mathrm{Z}) = 0.2693\ \rho_Z\ A\ V_Z^3 \qquad (1)$$

Whereas, $P_{max}(\mathrm{Z})$ represents the maximum output of a wind turbine at height Z above the ground surface W, where ρ_Z denotes the air density at the same height kg/m^3. A states for the rotor swept area m^2, V_Z indicates the wind speed at height Z above the ground surface m/s.

Furthermore, the productivity of wind farms may be evaluated using the power curve of wind turbines, as shown in Fig. 5, using equation (4) [29]:

$$E_W = \begin{cases} 0 & V_{Z,t} \leq V_{cutin}\ OR\ V_{Z,t} \geq V_{cutout} \\ P_{rat}\left(\dfrac{V_{Z,t} - V_{cutin}}{V_{rat} - V_{cutin}}\right) & V_{cutin} < V_{Z,t} < V_{rat} \\ P_{rat} & V_{rat} \leq V_{Z,t} < V_{cutout} \end{cases} \qquad (2)$$

Where: $P_{rat}$is the rated power of the wind turbine at rated wind speed V_{rat}, V_{cut-in} and $V_{cut-off}$ are the cut-in and cut-off wind speeds, and $V_{Z,t}$ is the wind speed at the wind turbine hub height (h_Z) and it is calculated from [30]

$$V_{Z,t} = V_{0,t}\left(\frac{h_Z}{h_0}\right)^{\propto} \qquad (3)$$

Where, $V_{0,t}$ is the wind speed at a certain elevation (h_0) and α is the wind shear coefficient (α=1/7)

The Levelized cost of generated energy (LCOE) including the cost of environmental damage by carbon dioxide (C_{CO2}) may be estimated by following equation [31]:

$$LCOE = \frac{\left(\frac{r(1+r)^n}{(1+r)^n - 1}\right) \times C_{Wind} + C_{\mathrm{O\&M}}}{E_{\mathrm{Wind}}} \qquad (4)$$

where: C_{Wind} the capital cost of the wind turbine system in $, $C_{O\&M}$ denotes the annual cost of operation and maintenance (0.015 $/kWh, or 45 $/kW/year), E_{Wind} is annual energy produced by the wind turbine system (kWh/year), n is the wind turbine lifetime (30 years), *r* the annual inflation rate (8%).

The cost of environmental damage (C_{CO2}) caused by CO_2 gas can be calculated by the following equation [32].

$$C_{CO2} = EF_{CO2} \times E_t \times \emptyset_{CO2} \qquad (5)$$

Table 1: Key Technical Characteristics of Wind Turbines

Wind Turbine Type	Tower Height (m)	Rotor Diameter (m)	V_{cut-in} (m/s)	V_{rat} (m/s)	V_{cut-ot} (m/s)	Rated Power (kW)	Country of Origin	Capital Cost ($)
Gamesa (2.0MW)	140	114	2.5	10	25	2000	Germany	2,945,000
Acciona (1.8MW)	80	77	3.5	11.1	25	1800	Spain	2,662,000
Enercon (2.5MW)	149	115	3.0	12.0	34	2500	Germany	3,381,000
Vestas (1.65MW)	108	82	2.5	13.0	32	1650	Denmark	2,414,000
Gold wind (1.5MW)	100	82.3	3.0	10.3	30	1500	China	2,210,000
Nordex (1.0MW)	70	54	3.5	14.0	25	1000	Germany	1,361,000
Suzlon (3.3MW)	140	120	4.0	9.5	20	3300	India	3,204,000

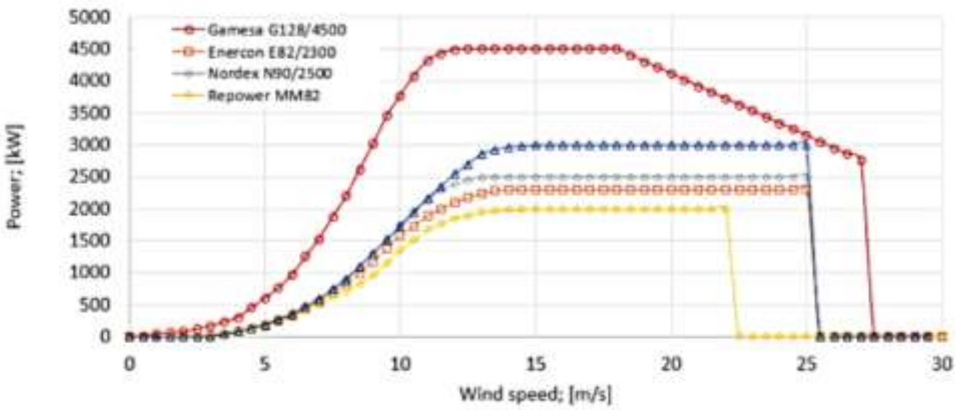


Fig. 5: The power curves of some wind turbines [28]

where: EF_{CO2} represents the CO_2 emission factor of the electric power generation system (kg CO_2/kWh) [33], $\emptyset_{CO2}$ represents the carbon social cost (\$/ton CO_2), which may be considered as \$ 70/ton CO_2 [34].

Results and Discussion

The energy production from seven commercially famous wind turbines for the two considered cities are estimated with the wind speed frequency that representing the domain of operation of these turbines. Fig. 5 illustrates the energy production for Yefern City. The results showed the importance of choosing the type of wind turbine so that largest energy can be generated in a specific location. The frequency of the wind speed that depicted in Fid. 5 shoes that the dominant wind speeds lie in the interval between V_{cutin} and V_{rat} , which was the most frequent with Vestas (1.65 MW) wind turbine. However, the best wind speed domain of wind turbine operation is at wind speed belongs to interval $[V_{rat}, V_{cutout}]$. In this range of operation Gamesa (2.0 MW) shows best operation behaviour as it has the largest wind speed frequency of 14.3%.

Table 2 tabulated the total annual energy produced by the five wind turbines under the climatic conditions of both Nalut and Yefren.

Environmentally, as this amount of energy will be generated by a cleaner source of energy (such as wind energy), a quantity of CO_2 debate will be prevented from emission to the environment. As the CO_2 emission factor of the Libyan electricity generation system is about 857 kgCO_2/MWh [32]. Accordingly, the annual prevented CO_2 from emission to the environment (Q_{CO2}) in tonnes, the associated social cost (C_{CO2}) and the LCOE have been calculated and tabulated in Table 3.

It is clear from Table 3 that the minimum LCOE value is \$0.043165 per kWh for the Suzlon (3.3 MW) type turbine in Nalut city. Furthermore, reducing the annual carbon footprint by 3,321 kgCO_2/kWp.

The present study reveals that it is worth to investing in wind energy as the LCOE is less than the price of electricity that the Libyan General Company of Electricity and Renewable Energy will buy the electricity from renewable energy sources at 10 ¢/kWh [13].

Table 4 includes crucial details for decentralization electricity in Libya such as city names, specific wind turbine type, and their respective LCOE values.

Table 4: Wind Turbine Types for Each Region and LCOE (¢/kWh)

City	Wind Turbine Type	LCOE (¢/kWh)
Ajdabiya	NEG Micon 44-750	5.11
Al-Jufra	Enercon E40 1600W	5.89
Al-Kufra	Suzlon S64-950	3.00
Benghazi	Siemens SWT-3.6MW	2.09
Sabha	Vestas V27-225kW	3.88
Sirte	Pitchwind 30kW	4.37
Tobruk	GE 1.5sl	1.53
Tripoli	Gamesa G114/2000	2.5
Ghat	Bonus 1300	2.97
Ghadames	Aeolos 50kW	3.75
Gharyan	Xzeres 442SR	1.74
Murzuq	GE2.5XL	4.1
Nalut	Suzlon 3.3 MW	4.32
Yefren	Suzlon 3.3 MW	4.45

Table 2: Total annual energy produced by each turbine in MWh

City	Gamesa (2.0MW)	Acciona (1.8 MW)	Enercon (2.5 MW)	Vestas (1.65 MW)	Gold wind (1.5 MW)	Nordex (1.0 MW)	Suzlon (3.3 MW)
Nalut	9013	5573	8887	5369	5776	2235	12786
Yefren	8717	5390	8582	5191	5575	2161	12398

Table 3: Prevented CO_2 from emission, the associated social cost and the LCOE

City		Gamesa (2.0MW)	Acciona (1.8 MW)	Enercon (2.5 MW)	Vestas (1.65 MW)	Gold wind (1.5 MW)	Nordex (1.0 MW)	Suzlon (3.3 MW)
Nalut	Capacity Factor	51.4%	35.3%	40.6%	37.1%	44.0%	25.5%	44.2%
	Q_{CO2}; ton/year	7,724	4,776	7,616	4,601	4,950	1,915	10,958
	C_{CO2}; \$/year	540,690	334,324	533,131	322,086	346,502	134,078	767,032
	LCOE; \$/MWh	46.99842	68.59118	56.5799	64.83133	55.02227	90.33295	43.164641
Yefren	Capacity Factor	49.8%	34.2%	39.2%	35.9%	44.9%	24.7%	42.9%
	Q_{CO2}; ton/year	7,470	4,619	7,355	4,449	4,778	1,852	10,625
	C_{CO2}; \$/year	522,933	323,346	514,834	311,408	334,444	129,638	743,756
	LCOE; \$/MWh	48.59433	70.91997	58.59072	67.05441	57.00603	93.42625	44.515494

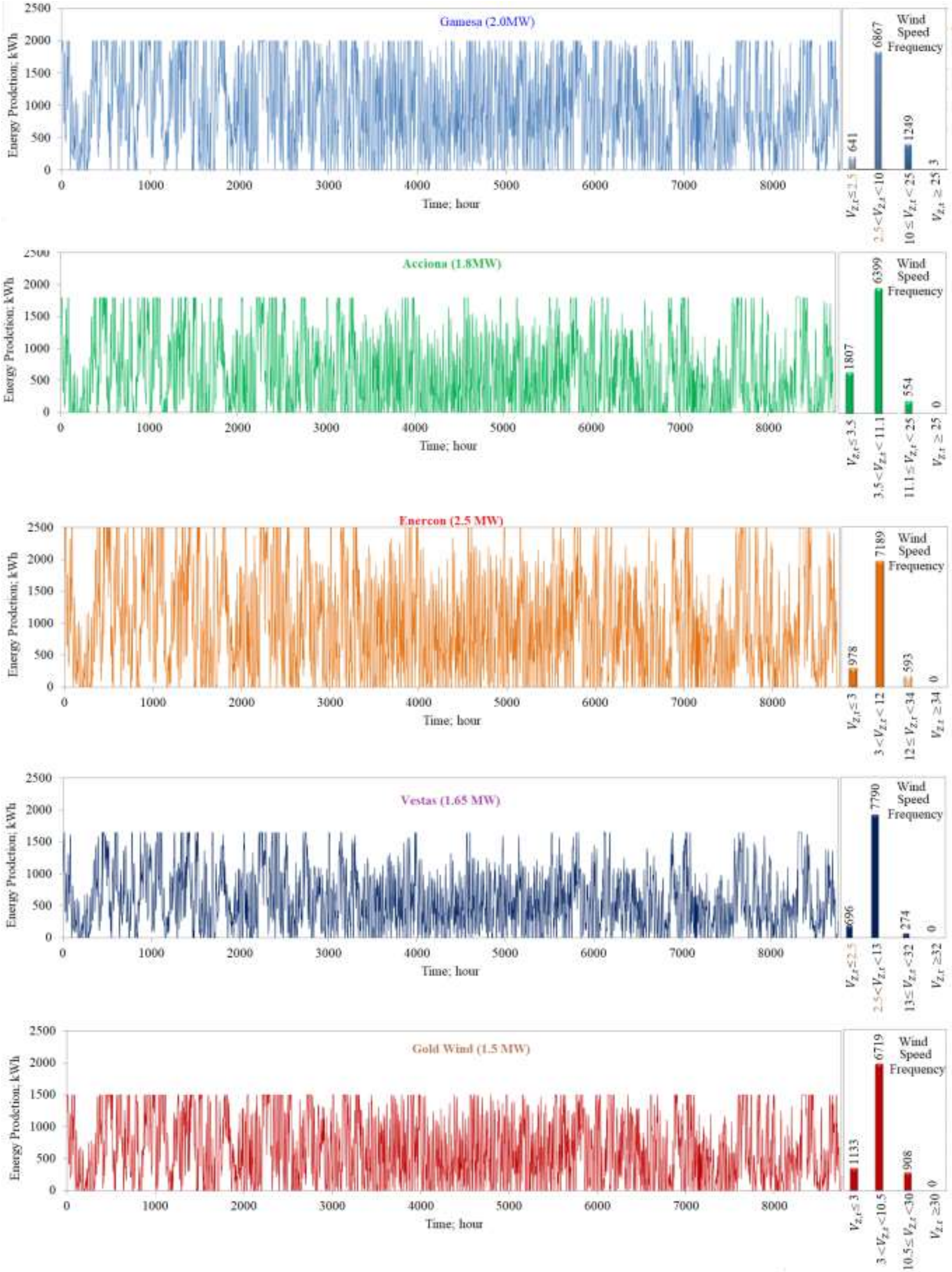


Fig. 6: Continue

Fig. 6: Energy production and wind speed frequency for several types of wind turbines for Yefren City.

Conclusion

Using real climatic data of Yefren and Nalut cities in the Western mountain, seven famous commercial wind turbines were simulated for the purpose of generating electricity. The most appropriate technology for each site was chosen according to minimum LCOE. According to the study's findings, investing in wind energy is the best option available for renewable energy in all of the cities that were examined. Among all the technologies tested, the Suzlon 3.3 MW had the lowest cost per unit of electricity produced. As the Libyan electrical energy sector emission factor accounts 0.967 kg CO_2/kWh, therefore, construct a wind turbines farm of 1000 MW capacity with an average capacity factor of 40% will be prevented about 3.82 million tonnes of CO_2 from being released into the atmosphere, saving an estimated $286.329 million in carbon tax each year.

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