

TECHNO-ECONOMIC ASSESSMENT OF OFFSHORE WIND ENERGY PROSPECTIVE ALONG THE LIBYAN COAST

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ABSTRACT

This study assesses the potential of offshore wind as an energy source in Libya and develops a comprehensive database of wind resources. Meteorological data from the RETScreen Clean Energy Management Software program was used to analyze wind energy characteristics and generate wind energy at selected locations with a height of 10 m and a depth of 50 m. The study found that Derna had the highest wind speed, while the Ajdabiya and Benghazi sites consistently had the lowest average wind speeds. The study found that the collective energy potential in shallow waters along the Libyan shore constitutes about 13% and 45% of the existing renewable and wind energy capacity, with an estimated technical capacity of 339 GW/h. The results indicate the shallow seas of Derna, Tobruk, and Misrata are ideal for offshore wind energy development due to their abundant wind resources and low energy costs, with average costs ranging from \$100 to 400 \$/MWh.



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1. INTRODUCTION

The utilization of conventional fossil fuels results in increased carbon emissions and elevated levels of global warming and, subsequently, contributing to climate change. The existence of these issues necessitates resolutions, hence fostering the inclination towards sustainable energy sources (Moria & Elmnifi, 2020; Serban, Paraschiv, & Paraschiv, 2020). Renewable energies encompass several sources such as wind, solar

energy, hydropower, and biomass. These sources are sustainable, clean, and cost-effective when compared to traditional sources. Wind energy, in particular, is regarded as a clean and practical solution for fulfilling energy requirements. Recently, numerous studies conducted by experts have specifically examined the utilization of wind energy for power generation across various regions globally. Libya currently lacks wind energy projects, has insufficient wind capacity, and possesses inadequate and unreliable data on wind

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resources in most regions of the nation (Elmnifi et al., 2024). Overwhelmed by the time required to prepare wind data for assessing power generation in Derna, a city located on the coast of the Mediterranean Sea in Libya. The study conducted comprehensive analysis of wind patterns, examining annual, seasonal, and daily fluctuations at the specified locations. The assessment employed information on wind patterns and speeds, collected every 3 hours, over duration of 10 years from 2000 to 2009. The utilization of Weibull bounds to analyze and describe the distribution and behavior of wind speed and their frequencies at unique heights has been studied and applied. The utilization of Weibull distribution (Weibull statistics methods) has been determined for wind turbine energy generation at high altitudes. The overall strength obtained from wind turbines of different sizes and at significant heights was compared and found to be predictable within a year. It has been determined that as the wind strength change system (WECS) of the same height has a lower rated rhythm, the power factor values get stronger, especially in extreme circumstances. They employed the latest scientific techniques, specifically Spena and Ahwide's method, to assess the available wind energy capacity. The results of each previously seen strategy were fascinating. Moreover, the calculated cost in dollars per kilowatt-hour for both wind turbines, which exhibit remarkable efficiencies regardless of the identical power output of 1650 KW, has been ascertained.

The data analysis was expected to aid in identifying the optimal sites in Libya for the installation of new wind turbines that could potentially harm the visual appeal of the landscape. This research has demonstrated its utility in strategizing the deployment of gargantuan wind turbines at designated sites along the Mediterranean coastline. Libyan power innovation relies heavily on petroleum supplies, including normal fuel, heavy oil, and light oil, which are considered essential resources (Ahwide & Ismail, 2016). Libya is experiencing rapid growth and development in all aspects of life, which will require the Libya to significantly increase its capacity in the coming years. This growth includes improvements in various sectors and the overall enhancement of people's lives, regardless of energy consumption considerations. The primary rationale is that Libya has a significantly high power allocation, namely the tariff imposed by the Libyan government for the cost per kilowatt-hour of electricity. The current tariff for residential electricity is 20 dirhams per kilowatt-hour, compared to the previous rate of 100 dirhams per kilowatt-hour. This reduction is due to the decrease in the cost of natural gas, which is the primary source of power generation.

To mitigate the scarcity and the ongoing fluctuations in electricity demand, it is crucial to assess all electrical systems for future viability. The most essential among these are wind power and solar power initiatives, which can significantly contribute to meeting a substantial portion of this demand and minimizing carbon dioxide

emissions. The features encompass convenient data preparation on the website, along with the city's endeavors to govern innovation. The assessment offers a comprehensive evaluation of wind conditions over a lengthy period of time, utilizing the average values of short-term wind speed increases to determine the yearly mean values over a one-year duration. From November 4, 2020 to December 30, 2023, the daily breeze directions that were most severe were NW, N, NNW, and WNW. The letters E, ESE, and SE are used to address approximately half of the population. Eastern and southeastern breezes are frequently encountered and tend to occur simultaneously. The most remarkable directions are NW, WNW, W, and NNW, which, comprising around 46% of the projected force, are accompanied by a northerly wind.

It is important to note that the excessive occurrence of northward winds originating from unproductive areas can result in an excessive frequency of soil erosion events. This reality should be perceived as an opportunity to implement appropriate changes in order to make wind turbine more cost-effective and generate easy power (Asghar et al., 2022). The low environmental impact and long-term sustainability of wind energy make it an attractive option. The objective of this project is to explore the capacity of internet sites in southern Pakistan for the production of wind energy. Wind velocity data is obtained from a reliable internet source located on the southeast coast of Pakistan, covering duration of one year. The document includes frequency distributions of wind speed and energy density at three different heights, as well as seasonal variations in wind speed. Additionally, it provides estimates of the intensity that may be expected from commercial enterprise turbines. The website being examined is classified as a class four-wind power site, with an annual average wind speed of 67 m/s and a power density of 414 W/m² at a height of 50 m. The website is suitable for both wind farms and standalone systems.

Ahmed et al., 2010. investigated the monthly and seasonal patterns of wind characteristics for wind energy applications using wind speed data collected between 2002 and 2008 from four meteorological stations in the Liguria region of Northwest Italy, specifically Capo Vado, Casoni, Fontana Fresca, and Monte Settepani. According to the findings, Capo Vado is an exceptional website with a monthly average wind speed ranging from 2.8 to 9.98 m/s at a height of 10 m. The monthly wind power density ranges from 90.71 to 1177.79 W/m². The highest power generation occurs in December, reaching a rate of 3800 MWh. They will provide data on establishing wind power websites and setting up cost-effective wind farms for energy production in the Liguria region. Additionally, they will expand their research on a monthly and seasonal basis to assess the progress of these websites, with a focus on optimizing power density. Mostafaeipour (Mohamadi et al., 2021) analyzed the wind velocity of several key cities in the Yazd region,

which is located in a central part of Iran. Furthermore, an examination is conducted to determine the practicality of implementing wind turbines to harness wind energy, and the issue of wind velocity and the potential for wind generation at certain locations is examined.

This study used information from eleven stations collected between 1992 and 2005, or almost thirteen years, to determine the wind power potential at various network locations. The hourly average wind speed data that was gathered at heights of 10 m, 20 m, and 40 m was statically analyzed in order to estimate the wind intensity period capacity for the Yazd region. The wind conditions at 20 and 40 meters have been ascertained by using the force rule and extrapolating the data from the 10 meters. The majority of the stations are not appropriate for the installation of wind turbines since, based on the data, their annual average wind speed is less than 4.5 m/s. There are greater winds in Herat. This website offers exceptional wind energy bundles specifically designed for distant places. However, additional data is required, as the existing information for Herat is only applicable to the year 2004. The towns of Aghda, Gariz, and Maybod experience a consistent yearly wind speed of 3.96 m/s, 3.95 m/s, and 3.83 m/s respectively, at a height of 10 m above ground level. These towns may effectively harness wind energy by installing small-scale wind turbines.

The wind speed records from the Tabas and Bafgh locations indicate a yearly drop in average wind speeds, ranging from 1.56 m/s to 2.22 m/s at a height of 10 meters. The wind speeds at different elevations were analyzed on a monthly and yearly basis to determine the most suitable wind turbine installation for top-rated stations in Yazd. The analysis of wind data collected within the Southern Appalachian Mountain region of the Southeastern US was presented (Şener, Añtil, & Sharp, 2023). Observations were collected at an elevation of 50 meters above ground level at 9 specific locations between the years 2002 and 2005. Monthly average wind speeds, energy densities, wind shear, and turbulence forces, as well as monthly maximum gusts, are supplied. Yearly average wind speeds differ from the predictions provided by AWS True Wind. There are also reported diurnal variations in wind speed. Annual wind roses are provided for each individual website on the net. The annual range of wind speeds varies from 5.5 to 7.4 m/s, with the highest average wind speeds occurring around the margins near the northern TN-NC line. A 20% increase in snowfall and an evening enhancement of wind speed have been observed.

The prevailing wind typically originates from the westward directions. The anticipated annual power output from a small wind farm with fifteen 1.5 MWGE turbines varies between 50 and 75 million kilowatt-hours (MkWh), with predicted capacity factors ranging from 25% to 3% (Mahdi & Bellel, 2023; Ould Bilal et al., 2011; Arslan et al., 2020; Wais, 2017). This assessment demonstrates that the boundaries within the region are

suitable for implementing large-scale wind development. Recent studies on wind power use suggest that the most favorable regions for harnessing wind energy are primarily located in coastal areas. (Mahdi & Bellel, 2023) assessed the wind data on the Nouakchott website. The data for the cover examination was collected at the Nouakchott climate station throughout a span of five years (ASECNA). The wind's time trial records are meticulously documented, including details about pace and route. The impacts were authorized to assess the wind capacity and specifically focus on the most beneficial intervals for harnessing wind power. April and May are the windiest months, with average wind speeds of 5.28 m/s and 5.2 m/s, respectively. Significant diurnal variations in wind speeds are seen, with higher speeds during the day compared to the night.

An assessment was carried out in Libya to assess the viability of harnessing wind energy in seven coastal areas. Annual measurements were taken to determine the wind speed and wind energy density at these locations. The wind speed distribution was analyzed using Weibull distribution functions. The study revealed that the winds in Derna, Tubark, and Misrata exhibit greater intensity, with average velocities ranging from 4.6 to 6 meters per second. An investigation was conducted to examine and evaluate the performance of six distinct wind power generation devices. Among them, the Repower wind farm with a capacity of 2000 kW demonstrated the highest capability for generating electricity in the specified regions (Jary et al., 2021).

An empirical study carried out in Libya has substantiated wind energy's significant potential to function as a sustainable and environmentally responsible energy source. Life cycle assessment methods were applied to assess the energy, economic, and environmental aspects of possible wind farms. The system boundaries were established to encompass environmental and economic factors throughout several stages in the life cycle of the wind farm. The energy productivity at 12 sites in Libya was estimated using System Advisor Model software, based on climatic data. A novel metric called isoelectric life cycle cost has been created, and the findings indicate that the Gamesa turbine is deemed the most economically and environmentally viable option. The greenhouse gas (GHG) emissions ranged from 32 to 70 grams of GHG per kilowatt-hour (GGH/kWh), while the carbon payback times varied from 4.5 to 12.3 months. The projected time it takes for the energy generated to offset the energy used in production ranged from 13 to 22 months. The levelized cost of electricity, taking into account all costs over the lifetime of the system, ranged from 4.8 to 8.4 cents per kwh (Nassar et al., 2024).

Another study evaluated solar and wind energy based on one year of collected data for the year 2022 using daily record data from Zawiya in Libya. The data were compared with five satellite products: MERRA-2, CFSR, ERA5, ERA5-Land, and Terra Climate. Measured in

order to determine its accuracy, appropriateness, and dependability. According to the results, all satellite products can be utilized for preliminary solar source evaluation, however CFSR and ERA5-Land perform well when evaluating wind sources. Using the finest satellite product available, the potential of wind and solar energy was assessed for five coastal agricultural districts between 2000 and 2022. In order to determine the required electricity demand based on traditional farm practices, the efficacy of solar and wind energy systems was examined.

According to a different assessment, wind energy has been found to be a practical and environmentally benign solution to meet Libya's present rise in electricity consumption. According to the report, Libya has a lot of potential for wind energy, especially near Derna. Following an evaluation of 22 locations for wind potential, it was concluded that small-scale wind devices are a feasible means of producing electricity in the nation. The technological and economic elements of wind farms with capacities of 100 and 10 MW were thoroughly examined. The performance of these plants was specifically studied in relation to wind losses and interference. Decision-makers can benefit from the analysis's conclusions.

Based on the aforementioned studies, it is evident that Libya lacks substantial research and development in the field of offshore wind energy. Offshore wind energy is a significant renewable and clean energy source, particularly in Libya, a coastal country with significant potential. However, the country's reliance on fossil fuels poses environmental and economic challenges. This study aims to fill this gap by providing accurate and reliable information on the technical and economic feasibility of developing offshore wind energy projects in Libya. The study will analyze technical factors, such as wind and wave nature, offshore depth, and environmental impacts, and conduct a comprehensive economic assessment to determine the cost of establishing, operating, and maintaining projects. The findings will contribute to decision-making and sustainable development strategies for the Libyan energy sector.

Hence, the primary objective of this study was to examine the potential of harnessing offshore wind energy in coastal cities of Libya. This paper presents an evaluation of the wind energy capabilities of seven locations (Tobruk, Derna, Benghazi, Ajdabiya, Sirte, Misurata, and Tripoli) situated along the Libyan coast of the Mediterranean Sea. The assessment focuses on the potential for generating electricity from wind by utilizing high-capacity wind turbines with power outputs ranging from 1250 kW to 2000 kW. The data on several small wind turbines (ranging from 0.3 kW to 0.6 kW) and all relevant information on wind energy were obtained from the RETScreen Clean Energy Management Software.

2. METHODOLOGY

2.1 Study site description and wind data

The research included the selection of cities situated along the Mediterranean coast. The study utilizes monthly data over a duration of 4 years, namely from 2020 to 2023. Basic statistical technique was used to compute the mean monthly wind velocity at a 10 m elevation, and to validate the results using the RETScreen program for conditions of the chosen sites. Figure 1 displays a map of Libya, indicating the locations of cities and providing their corresponding geographical coordinates in Table 1.

Table 1. The precise latitude and longitude coordinates of the points where weather data is collected

Location	Latitude and longitude	Average speed, (m/s)	Height, (m)
Tobruk	32.14° N 23.96° E	6	10
Derna	32.64° N 22.6° E	6	10
Benghazi	31.94° N 20.11° E	5	10
Ajdabiya	30.68° N 20.2° E	3.9	10
Sirt	31.13° N 16.64° E	5	10
Misrata	32.24° N 15.13° E	6	10
Tripoli	32.75° N 13.21° E	4.6	10

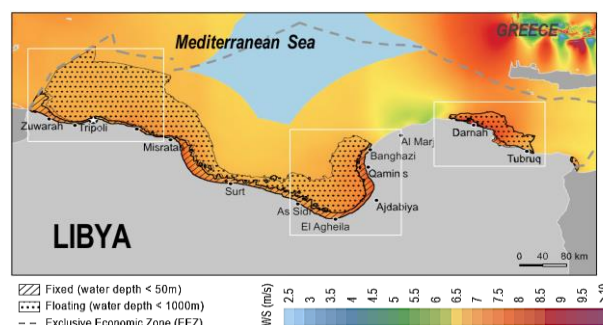


Figure 1. Offshore Wind Technical Potential in, Libya
Fixed: 52 GW, Floating 287 GW, And Total: 339 GW

The wind resource evaluation conducted at each site identifies the optimal sites for harnessing wind energy. To compare these resources, wind measurements need to be converted to the relative values of a location located in an open region at a height of 10 meters above ground level. The features of the surrounding location significantly affect the wind data produced by the RETScreen software for simulation. Therefore, we must make the necessary adjustments for these wind readings. These modifications specifically affect key patterns to align Weibull's rule with sites that are influenced by varying degrees of weight. Mean wind speed readings for the whole duration of the data period table 1 shows the whole set of seven places at a distance of 10 meters. The cities of Derna, Misrata, and Tobruk saw the greatest yearly average wind speed of 6 m/s, while Ajdabiya had the lowest average wind speed of 3.9 m/s. To evaluate the seasonal fluctuations in wind speed at all sites, the data is organized every month, and the highest, average, and lowest wind speeds for each

month are recorded. Figure 2 shows the extraction of weather results for selected locations by software the RETScreen. The charts are shown in Figure 3. The figure shows the greatest average monthly wind speed in January or August across all locations. This period aligns with the increased energy consumption across the seven locations due to the air conditioning load. In September, October, and November had the most minimal average wind velocities across all locales.



Figure 2. The extraction of weather results for selected locations by software the RETScreen

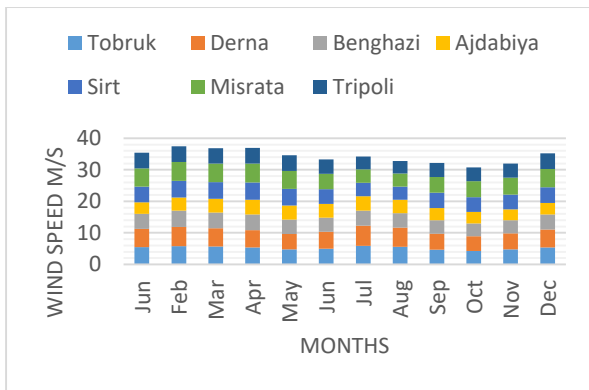


Figure 3. Wind speed for the study site

2.2 Wind speed distribution

The wind measurements acquired by the simulation exhibit significant variability. Hence, while analyzing wind energy, it is crucial to focus on a limited number of critical factors that may effectively elucidate the characteristics of wind velocity data (Mohammed et al., 2019, Baseer et al., 2015, Jenkins et al., 2019). Utilizing a probability distribution function is the most straightforward and efficient approach to the study. Various probability density functions may be used to characterize the frequency curve of wind speed. The Weibull, Rayleigh, and Lognormal functions are often used for fitting the probability distribution of the observed wind speed. We use the Weibull probability distribution in this context. The above expression represents the probability density function, as stated in reference (Ayed et al., 2022, Nassar et al., 2023, Ould Bilal et al., 2013, Fazelpour et al., 2015).

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

$f(v)$ represents the probability density of the speed v (m/s). The cumulative distribution function is expressed as follows (Bilir et al., 2015):

$$F = 1 - \exp \left[- \left(\frac{v}{c} \right)^k \right] \quad (2)$$

The distribution of the mean speed, denoted as v_m , is described by the F function and may be specified by Equation (3) (Ayodele et al., 2016).

$$v_m = C * F \left[\frac{1}{k} + 1 \right] \quad (3)$$

To approximate the formula, the following functions may be used for the values of c (m/s) and K within the specified range on the sites.

$$k = 0.9 + 0.2v_m \quad (4)$$

$$C = \frac{v_m}{F \left[1 + \frac{1}{k} \right]} \quad (5)$$

Wind energy density is the most reliable indicator of wind sources since it takes into account the frequency distribution of wind speed, air density, and the cube of wind speed. As a result, the computation can be ascertained by applying the subsequent equation (Manwell, McGowan, & Rogers, 2010):

$$P = \frac{1}{2} \rho C^3 F \left[1 + \frac{3}{k} \right] \quad (6)$$

Where c is the Weibull scale parameter, a measurement of the average wind speed during the time step expressed in m/s, and ρ is the air density during the time step expressed in kg/m³ (BWE, 2006).

$$E = \frac{1}{2} \rho c^3 T \left[1 + \frac{3}{k} \right] \quad (7)$$

2.3 Economic Factors Affecting the Cost of Wind Energy

The cost of financing, continuous operation and maintenance, and initial investment all have a major influence on the cost of wind power. The next paragraph provides a definition of those standards.

2.3.1. Cost of investment

The investment cost, sometimes referred to as the initial capital cost (I_c), includes all costs incurred from project inception to the start of operations. The variation depends on the particular region and the technology being used. According to Johnson (2006) and Manwell et al. (2009), I_c include the procurement of the turbine and its components, as well as their transportation and installation. This includes activities such as constructing the foundation,

installing the turbine, connecting it to the power grid, conducting tests, and commissioning.

2.3.2. Cost of financing

Financing costs, as described by Manwell et al. (2009), refer to the expenses incurred at the outset to fund the acquisition and installation of wind energy equipment. These costs also affect the overall cost of wind power. The source of capital might be a financial institution such as a bank or investors. The creditors will anticipate a repayment on the loan. For a bank, the term used to describe the profit gained is referred to as interest. Throughout the duration of the project, the accumulated interest might significantly contribute to the overall cost.

2.3.3. Cost of operation and maintenance

As soon as the wind farm begins to produce electricity, the O&M cost (O&M) comes into play. This includes the expenses incurred in repairing the turbine when it is damaged and making sure that it operates safely throughout the project life, which is referred to as the cost. In its simplest form, O&M means the expenses incurred in monitoring and upholding the wind turbines with the objective of getting the maximum possible output from them. This includes a variety of expenses, such as insurance, lease payments, taxes, payroll and other operating costs, in addition to preventive and corrective maintenance. The following equation has been used by Fazelpour et al. (2017), Mohammadi et al. (2016), and Minaeian et al. (2017) to define O&M as a proportion m of I_c : The following equation has been used by Fazelpour et al. (2017), Mohammadi et al. (2016), and Minaeian et al. (2017) to define O&M as a proportion m of I_c :

$$O\&M = m I_c \quad (8)$$

The relationship between turbine's investment cost (I_c) and operating and maintenance (O&M) costs is presented. The variable m is typically rising with the age of the turbine and its value is usually more than one. 5% and 3%. The older wind turbines were of 3% efficiency; however, the new and updated turbines are of 1% efficiency. 5% to 2%. The cost of the wind project was determined to be 2% in the economic evaluation in Libya.

The total cost that is required to be used for the development and operation of a system over its life span is referred to as its NPC. The following formula has been used by the authors to compute the NPC: The following formula has been used by the authors to compute the NPC:

$$NPC = I_c + O\&M \quad (9)$$

NPC means the entire cost incurred over the entire life cycle span of a wind energy plant. Siyal et al. (2016). The NPC (Net Present Cost) of a wind energy system will be determined by the sum of capital expenditures (including initial investment, ongoing maintenance, and salvage).

The NPC value has been calculated by means of the equation.

$$NPC = I_c + O\&M + SC \quad (10)$$

Illustrates that the initial cost (I_c), operating and maintenance cost (O&M), and salvage cost (SC) are added to get the net present cost (NPC). The dismantling costs (i. e. the costs of moving the parts of the system to a new power source and selling them) are known as the salvage cost (SC) of the system.

The capital recovery factor (CRF)

The Capital Recovery Factor (CRF) is a mathematical ratio that is used to transform the entire Net Present Cost (NPC) into the total cost spread out over a certain number of years (the system's lifespan) and at a particular interest rate (i). According to Hemami (2012), the calculation of CRF may be done in the following manner.

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (11)$$

An economic evaluation commonly assumes a period of 20 years, denoted as n . The US economic studies used a 30-year lifespan by enhancing the architecture of the wind turbine. However, this requires a significant yearly maintenance of wind turbines to repair essential components. The equation used by Haghighat Mamaghani et al. (2016) to estimate AC is as follows:

$$AC = NPC * CRF \quad (12)$$

In order to calculate the annualized cost (AC), Drew et al. (2015) only considered the initial investment cost (I_c). They assessed the operation and maintenance (O&M) expenditures for a single year and used the following equation (Drew et al., 2015):

$$AC = I_c * CRF + O\&M \quad (13)$$

Electrical system losses

$$= \left(\frac{\text{energy lost}}{\text{power input}} \right) \times 100 \quad (14)$$

Where:

Electrical system losses are the percentage of energy lost in the electrical system as a percentage of the input energy. The lost energy is the difference between the energy input to the system and the extracted energy from it or the energy used within the system. Input Power is the total amount of power that enters into the electrical system.

Levelized production cost of energy (LCOE)

The levelized cost of energy (LCOE) is the average cost per kilowatt-hour (kWh) generated by wind power. Hosseinalizadeh et al. (2017) defined the LCOE. By dividing the Annualized Cost (AC) by the Annualized Electricity Generation (ET) and expressing it in kilowatt

hours (kWh/year), the Levelized Cost of Electricity (LCOE) is obtained. The equation is expressed as follows:

$$LCOE = \frac{AC}{E_T} \quad (15)$$

Once the LCOE is lower than the local electricity rates, the project is said to be economically viable. The recent reduction in LCOE, which has been attributed to substantial technological innovation, increased competition in the market, and the achievement of economies of scale is a factor. The primary reason is the increase in the size of the wind turbines, as a result of which rotor diameter, height and blade length all grow. The reason is that the wind speed increases with height and it is directly proportional to the area covered by the rotating blades, therefore the bigger turbines are able to create more energy.

3. RESULTS AND DISCUSSIONS

In this section of the study, the main conclusions drawn from the statistical examination of the average wind speed from 2020 to 2023 are explained.

3.1 Characteristics of wind speed and Weibull distribution parameters

The range of average wind speeds recorded at the study sites is shown in Figure 3. The location of Derna has a maximum wind speed of 6.4 m/s, whilst the site of

Ajdabiya records a low wind speed of 3.5 m/s. Therefore, it can be determined that at a height of 10 meters, the wind speed ranges from 3.5 to 6.4 meters per second.

3.2 Wind systems at research locations

The data gathered at a height of 10 meters was used to estimate the variance in average monthly wind speed and energy intensity for all seven cities. The data obtained are shown in Tables 2 and 3. Figure 4 shows that the greatest monthly average wind speed recorded for the year was 4.6 m/s in Derna and Misrata, and 4.2 m/s in Tobruk and Sirte.

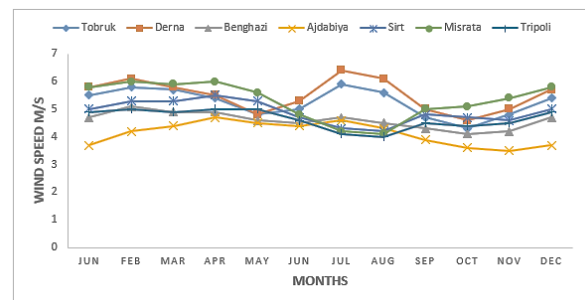


Figure 4. Monthly average wind speed

In April, the wind speed reached 5.9 m/s at the Tobruk and Sirte locations. The Benghazi locations of Ajdabiya have recorded the lowest monthly average wind speeds of 3.7 m/s and 4.5 m/s.

Table 2. The average monthly capacity (W/m²) at the research locations

Location	Tobruk	Derna	Benghazi	Ajdabiya	Sirt	Misrata	Tripoli
January	137.23	139.76	118.53	46.87	120.65	139.97	115.66
February	139.45	142.34	120.84	77.75	125.32	140.98	120.87
March	138.94	138.96	115.53	90.76	124.76	139.96	118.86
April	134.34	137.65	114.96	117.67	137.76	140.75	119.87
May	115.56	114.45	118.86	95.23	124.76	140.65	120.87
Jun	120.12	125.34	117.97	90.53	118.73	114.64	117.76
July	142.34	148.65	118.87	118.50	89.96	72.76	70.98
August	136.34	142.34	95.96	89.75	77.92	70.83	69.81
September	118.36	120.65	89.74	64.92	92.78	120.76	92.75
October	90.32	118.76	70.86	41.62	91.87	122.87	90.97
November	114.43	120.87	77.94	36.78	89.98	135.65	92.87
December	132.57	138.63	91.96	47.83	120.42	139.85	94.32

Table 3. The monthly Weibull coefficients (k, c) for all sites situated at a height of 10 m

Location		Tobruk	Derna	Benghazi	Ajdabiya	Sirt	Misrata	Tripoli
January	k	2.75	2.9	2.35	1.85	2.5	2.9	2.45
	c	5.6	5.2	3.67	2.75	3.8	4.35	3.75
February	k	2.9	3.05	2.55	2.1	2.65	3	2.5
	c	5.3	4.61	4.05	3.1	4.35	4.5	3.8
March	k	2.85	2.9	2.45	2.2	2.7	2.95	2.45
	c	4.85	5.2	4.1	3.3	4.32	4.45	3.65
April	k	2.7	2.75	2.45	2.35	2.75	3	2.5
	c	4	4.1	4.2	3.55	4.07	4.03	3.8
May	k	2.4	2.5	2.3	2.25	2.65	2.8	2.5
	c	3.5	3.7	3.6	3.45	3.75	3.9	3.85

Location		Tobruk	Derna	Benghazi	Ajdabiya	Sirt	Misrata	Tripoli
June	k	2.5	3.2	2.25	2.2	2.35	2.4	2.3
	c	3.75	4.7	3.45	3.3	3.45	3.7	3.5
July	k	2.95	3.05	2.35	2.3	2.15	2.1	2.05
	c	4.4	4.55	3.85	3.5	3.35	3.3	3.07
August	k	2.8	2.5	2.25	2.15	2.1	2.05	2
	c	4.2	3.75	3.55	3.36	3.4	3.25	3
September	k	2.35	2.3	2.15	1.95	2.4	2.5	2.2
	c	3.55	3.7	3.49	2.9	3.7	3.75	3.45
October	k	2.15	2.5	2.05	1.8	2.35	2.55	2.2
	c	3.25	3.6	3.25	2.8	3.55	3.85	3.4
November	k	2.4	2.85	2.1	1.75	2.3	2.7	2.25
	c	3.6	3.7	3.6	2.6	3.7	4	3.45
December	k	2.7	2.7	2.35	1.85	2.5	2.9	2.45
	c	5.4	5.3	3.95	2.85	3.9	4.35	3.75

The average monthly energy density at the study sites is displayed in Table 2. The highest energy densities were recorded in May in Derna and Tobruk at 148.65 W/m² and 142.34 W/m², respectively. In March, Misurata recorded 139.96 W/ m², Sirte recorded 137.76 W/m², and Tripoli recorded 120.87 W/m². In November, Ajdabiya, Misurata, and Benghazi had the lowest energy density at 36.78 W/ m², 70.98 W/ m², and 77.94 W/ m², while Tripoli had the lowest energy density in August at 69.81 W/ m². The majority of the monthly average power density across all sites in Table 2 is more than 30 W/ m². Some wind turbines may be used to generate electricity.

The monthly Weibull parameters for each of the seven sites are identified in this study as well. The scale and form characteristics that were computed for the research sites are shown in Table 3. We see that for Derna, Tobruk, and Misurata, the monthly scale coefficient varies from 3.9 to 5.6 m/s. The ranges for Benghazi, Tripoli, Sirte, and Ajdabiya are 3.2-2.25 m/s and 3.0-4.2 m/s, respectively. The gauge parameter values at each site show that wind turbines can generate power based on wind potential.

3.3 Offshore wind turbine design

Offshore wind turbines are used as renewable energy sources to harness offshore wind energy for the purpose of power generation. These turbines are regarded a form of wind turbine, and are differentiated by their placement in oceans and seas, where they get strong and consistent winds, which allow them to produce significant quantities of power. Offshore wind turbines provide several benefits. One of the most notable of these traits is that offshore winds are generally stronger and more constant compared to onshore winds. Marine turbines have the capability to consistently produce significant quantities of power, making them a dependable and trustworthy energy source. Furthermore, the vast expanses of the oceans and seas provide enough untapped territory, enabling the construction of many offshore turbines without the need to depend on restricted land resources. Consequently, the oceans may be efficiently used to produce electrical power and fulfil the increasing demands for energy. Various methods exist for the installation of offshore wind turbines. Fixed turbines are

often installed on stationary towers at the seabed of oceans or seas, and are secured to the deep-sea using concrete or steel piles. These turbines function in a manner similar to wind turbines on land, using the wind's motion to spin the blades and produce electrical power. As seen in Figure 5. Floating offshore wind turbines are installed on floating constructions that rest on the water's surface. These structures provide them with the ability to manoeuvre, navigate, and effectively harness offshore wind. These turbines are intriguing because of their ability to be put in offshore locations with greater sea depth, farther away from the coast. This allows them to take advantage of stronger wind speeds and produce more energy.

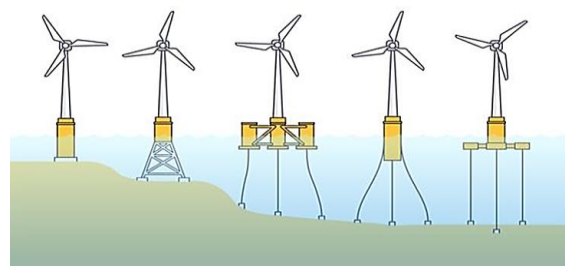


Figure 5. Types of offshore turbines

3.4 Energy generated and power factor

3.4.1. Characteristics of wind turbines

The investigation included the selection of wind turbines from many manufacturers, as shown in Table 4 and Figure 6. These sources provide detailed technical characteristics of the turbines and illustrate the variations in power curves with respect to wind speed (Ayed et al., 2022). The power output of these wind turbines varies from 1250 to 2000 kW for large-scale turbines, and from 300 to 600 kW for small-scale turbines. The wind turbines were used for testing purposes, wherein the output power and capacitance factor were calculated at each location. This assessment was conducted to determine the suitable wind conditions for the turbines, which would enable them to produce energy for grid connection or isolated applications.

Table 4. The specifications of both big and small commercial wind turbines sourced from many factories

Wind turbine type	Capacity (kW)	Area (m ²)	Height (m)	Cut-off wind (m/s)	Evaluated wind (m/s)
large size					
Eco 62	1250	3020	60	25	13.5
Eco 80	1670	5030	70	25	14
Repower	2000	5280	100	25	3
Small size					
Eolsengal / 500	0.5	7	18	12	9
Inclin / 600	0.6	3	7	13	11
Yellow- sand	0.3	5	12	15	8

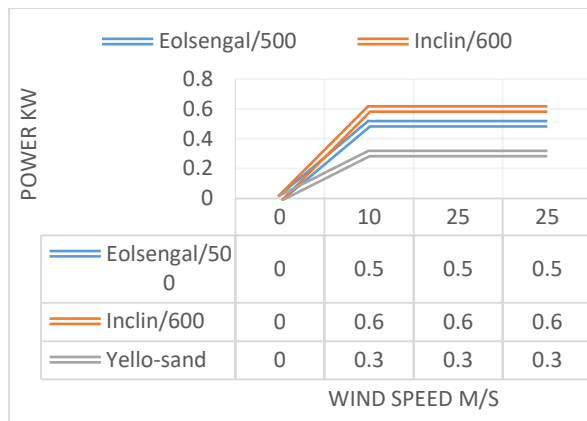


Figure 6. The power curves of the chosen turbine

3.4.2. Generation of energy from wind turbines

The yearly power generation was computed for various big and small wind turbines throughout the seven locations. The findings for the energy produced from all the wind turbines employed in this investigation are shown in Table 5. The findings suggest that the Derna, Misurata, and Tobruk sites exhibit higher output energy compared to the other locations. Large wind turbines consistently provide more output power than tiny wind turbines at all sites, owing to their larger size. When it comes to using energy, it is advisable to use wind turbines with higher power output.

Table 5. The yearly output power (MWh/ year) from six commercial wind turbines across all locations

Wind turbine type	Tobruk	Derna	Benghazi	Ajdabiya	Sirt	Misrata	Tripoli
large size							
Eco 62	1387.43	1449.77	1160.06	870.38	1194.45	1339.82	1113.127
Eco 80	1587.53	1895.47	1260.56	1037.49	1294.65	1540.27	1123.13
Repower	2191.13	2575.97	1612.56	1337.99	1750.85	1990.87	1143.187
Small size							
Eolsengal / 500	0.924	1.114	0.773	0.725	0.852	1.030	0.695
Inclin/ 600	0.660	0.856	0.644	0.659	0.774	0.936	0.631
Yellow- sand	0.706	0.955	0.704	0.743	0.799	1.010	0.732

The factory capacity factor, PCF, is the proportion of the factory's actual yearly production to its rated output. The wind turbines' technical parameters mentioned in this study may be found in Table 5. Within the shown illustrations, specifically figures 7 and 8. The yearly power production is shown in megawatt-hours per year (MWh/year) together with the plant capacity factor (PCF) expressed as a percentage (%). The most viable locations for wind stations are Derna, Tobruk, and Misurata. The locations yielded a maximum power output of 2575, 2191, and 1990 MW per year from a repower wind turbine with a capacity of 2000 kW. Additionally, a commercially available wind instrument of type Eco 62 with a rated capacity of 1250 kW produced 1445, 1387, and 1339 MWh per year at power conversion factors of 15%, 13%, and 12% respectively.

The PCF analysis of these six wind turbines across all sites indicates that the Derna, Tobruk, and Misurata locations had the highest efficiency wind turbine.

A low-power wind turbine is more effective in areas with low or moderate wind capacity (Nassar et al., 2023).

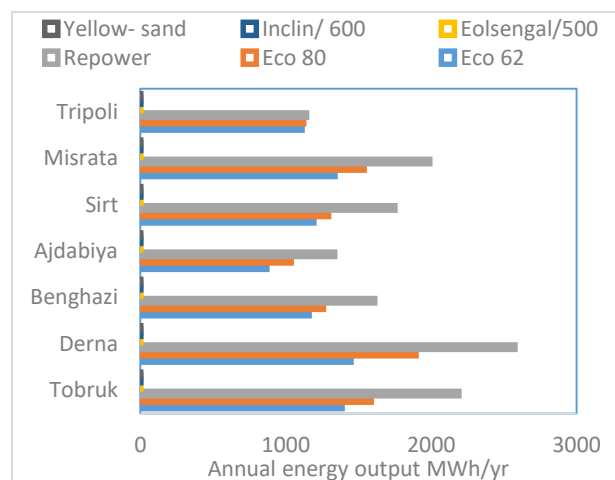


Figure 7. The yearly power generation of various wind turbines across all locations

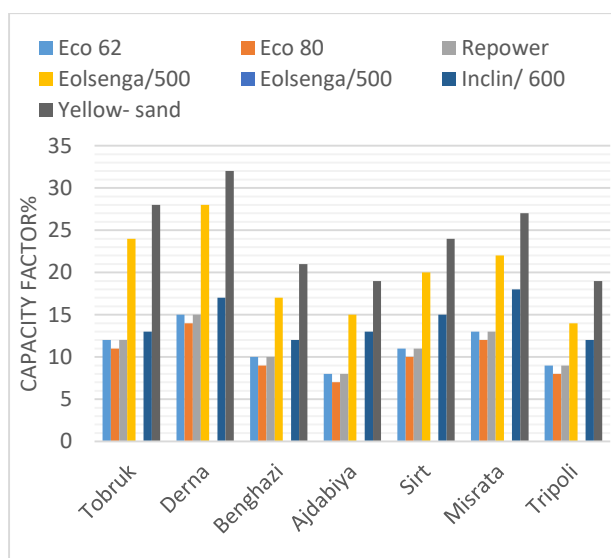


Figure 8. The capacity factor of various wind turbines across all locations

A thorough analysis was conducted to ascertain the geographical distribution of resources across the 7 cities under examination via a meticulous examination of city-by-city comparisons. Figure 9 illustrates a detailed comparison of individual cases for two distinct types of water depths: those less than 60 m and those that are deeper than 60 m. Depth setting at 60 m was used to distinguish a potential floating technology resource from a potential fixed-bottom resource.

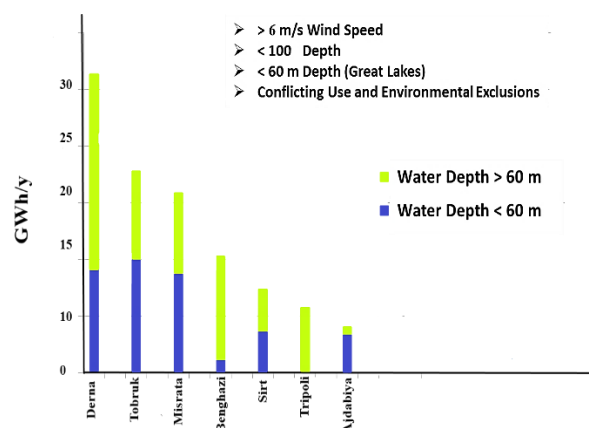


Figure 9. The net technical energy potential of offshore wind, which is 52 GWh/year. This capability is categorized by city and is specifically intended for depths greater than or less than 60 meters

Figure 9 shows that after deducting all technology, conflict-use and environmental resource exceptions, the city of Derna has the largest share of the total resources, followed by Tobruk, Misrata, and Benghazi. The large energy source in these cities is due to the presence of a large amount of ocean area that includes relatively long coastlines and wide continental shelves. However, the quantity of resources is not a good indicator of the quality of resources. These coastal cities tend to have a large

number of resources at low wind speeds between 6 m/s and 8 m/s, and a net capacity factor of less than 35%.

The resource assessment utilized NREL offshore wind cost studies to analyze electrical system loss, considering project distance from cable landfall and increased cable lengths as sites became deeper and more remote, primarily influenced by distance and water depth. Electrical system losses had been calculated to account for the improved cable lengths as web sites become deeper and more faraway. Electrical losses are assumed to be normally a characteristic of distance from the point of interconnection (DStoL) and water intensity (WD), and are represented by way of Eq. (14).

Figure 10 depicts a visual depiction of the equation, illustrating the minimal losses that occur near the shore and shallow water, as projected based on the given assumptions and equation. The system losses are predicated on the premise that the most economical technology will be used for power transmission. The statistics shown in Figure 10 demonstrate that the electrical losses of these systems vary from 1% to 5%.

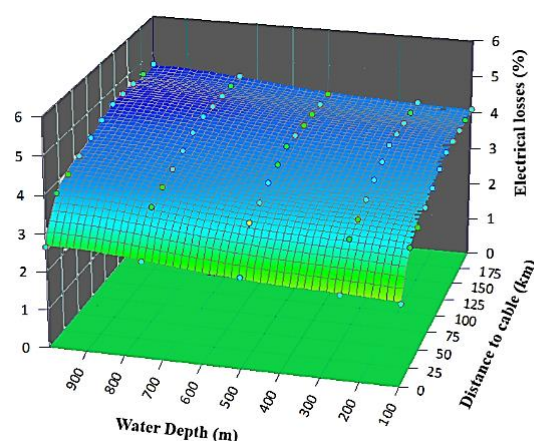


Figure 10. The amount of energy lost in the electrical system as it travels from the offshore location to the substation on land

In order to conduct a sensitivity analysis of the predicted levelized cost of electricity (LCOE) for the examined sites, we systematically alter the interest rate, operation and maintenance (O&M) expenses, energy production, and project duration.

The Figure 11 shows an evaluation of the levelized fee of power (LCOE) inside the seven cities. LCOE values are proven for every city. According to the figure, it is able to be visible that there are apparent variations in LCOE values among cities. It can be concluded that the top city faces a better price of strength as compared to different lower towns, at the same time as the lowest fee of strength characterizes the lower towns.

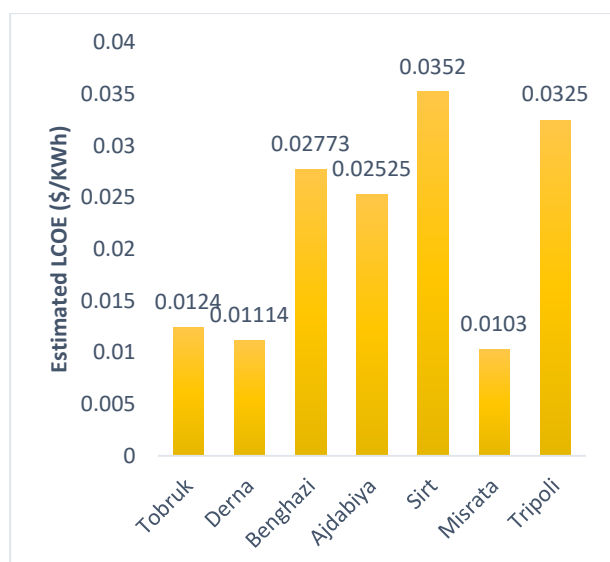


Figure 11. Estimated leveled cost of electricity (LCOE)

These variations may have several motives, which includes the value of extracting and generating the power sources utilized in every metropolis, the value of infrastructure and distribution, and protection and control prices. It is vital to take those differences into account while studying and developing power guidelines in different countries. Countries can look for strategies to enhance the efficiency of strength technology and reduce its costs, along with promoting the usage of renewable power resources and making use of new generation to enhance efficiency. Countries can also advantage from training discovered from countries with low strength expenses to reinforce their us of a's strength quarter. Figure 11 depicts the sensitivity analysis of the leveled cost of electricity (LCOE) by altering the interest rate within the range of 1% to 10% (Drew, Phimister, & Ross, 2015). Based on this statistic, it can be concluded that the leveled cost of electricity (LCOE) is significantly influenced by changes in the interest rate. It is observed that as the interest rate increases, the leveled cost of energy (LCOE) also increases (Ang et al., 2022). Conversely, when the interest rate decreases, the LCOE decreases as well.

3.4.3. Uncertainty

Wind projects' uncertainty is expressed using probabilities of exceeding values (P50, P75, and P90). Banks typically use P75 or P90 values. P50 indicates 50% energy yield exceeding P50, while P75 indicates 25% chance of not reaching P75 level of AEP. Uncertainty (σ) is standard deviation from the mean and doubt in calculated AEP. It must be combined with individual assessment processes to define total uncertainty for a project. Classical approach assumes normal distribution, with P50 value representing the mean. The total uncertainty can be calculated using the

relationship provided if the individual uncertainty components are independent.

The equation $\sigma^2 = \sum_{i=1}^N c_i^2 \sigma_i^2$ represents the combined uncertainty, c_i is the sensitivity, σ_i is the individual uncertainty component, and N is the number of uncertainty components. Total uncertainty is more sensitive to larger values, while individual uncertainty components have specific estimation or calculation methods based on their nature. The highest uncertainty in numerical models is due to the importance of accurate site modelling in terms of financial risk.

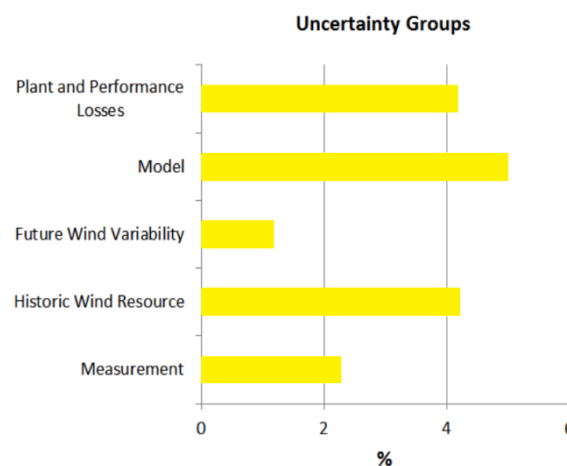


Figure 12. Uncertainty groups

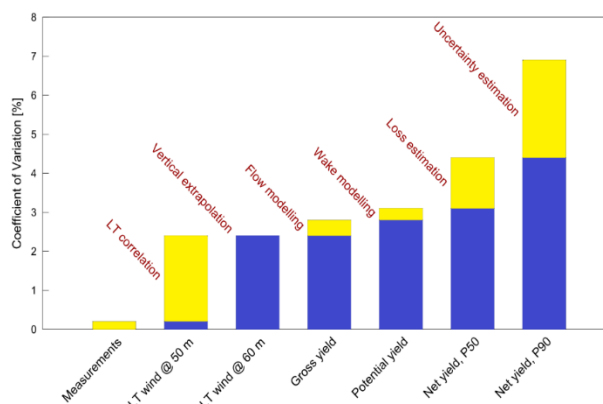


Figure 13. Estimated uncertainty wind turbines varies from 1250 to 2000 kW

The figure 13 shows that the "wind speed at 50 m" measurement has the greatest uncertainty or variance, while the "net yield, P90" measurement has the least uncertainty or variance. The chart generally shows that wind turbine measurements have varying degrees of certainty. Uncertainty in wind turbine measurements can be caused by a number of factors that affect system performance.

4. CONCLUSIONS

An offshore wind resource assessment and cost analysis are conducted using a model built upon the RETScreen

Clean Energy Management Software application. Estimating the energy potential, levelized production cost, and availability of a specific location may be facilitated by using wind data, technological characteristics, and costs in a spatially continuous grid cell way. In addition, maps depicting the geographical arrangement of wind speed and energy production have been created at sea depths of up to 50 m throughout the western and eastern coast of Libya. Utilizing current data and maps may serve as a catalyst for policy improvement.

The findings provide the following deductions:

The estimated yearly wind energy capacity along the Libyan coast varies from 500 to 2500 MW/km². The anticipated technical capacity for offshore wind on Libya's eastern and western coastlines is 339 GW/h. The

entire potential represents around 45% of the current capacity for renewable energy and wind energy in Libya. Approximately 40% of the total capacity for offshore wind power is located at sea depths of up to 50 meters. This includes 52 GW of fixed turbines and 287 GW of floating turbines. These offshore wind installations have the potential to be economically competitive with existing renewable energy sources. The current research finds that the shallow seas of Derna, Tobruk, and Misrata are the most ideal areas for offshore wind energy development in terms of wind resources and economic costs. In the sea depths ranging from 0 to 50 meters and 50 to 60 meters, the average energy cost on the eastern coast of Libya is 100\$ and 300\$ / MWh, whereas on the western coast of Libya it is 200 \$ and 400\$ / MWh, respectively.

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