Feasibility Analysis of the Wind Energy Potential in Libya using the RETScreen Expert

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ABSTRACT

This study focuses on the evaluation of the economic viability of various scale wind farms and the assessment for the first time of the wind power potential of 22 locations distributed over Libya. The study utilizes monthly mean wind data collected from the NASA power dataset. The analysis includes determining and analyzing the mean wind speed, frequency distribution, and Weibull distribution scale and shape factors. The results showed that Darnah is the most promising location for insulation wind farms due to the high value of wind speed. Moreover, RETScreen software is used to estimate the energy output and conduct an economic feasibility analysis of the wind farm. Additionally, this paper establishes a relationship between the wake effect, airfoil losses, and the potential for greenhouse gas (GHG) mitigation and the performance of wind farms. The results indicate that wind projects are economically viable when the EWT-DW 52 with a capacity of 500 kW is used. The study findings show that the wake effect is a crucial consideration in wind farm design, and it can be minimized through strategic spacing and turbine design. Furthermore, the accumulation of dirt and debris on wind turbine blades can significantly reduce a wind farm's energy output, causing turbine inefficiency and decreasing the overall energy production. Additionally, the energy production cost from a wind farm is less than that of the electricity tariff and can result in a profitable wind energy project.

Keywords-Libya; wind energy potential; grid-connected; wind farm; farmRETScreen; feasibility analysis; wake effect; airfoil losses

I. INTRODUCTION

Renewable energy sources have significant potential to provide clean and affordable energy to developing countries like Libya. According to the International Energy Agency (IEA), over 1.2 billion people worldwide lack access to electricity. Renewable energy can provide clean and reliable electricity to these populations, especially in rural and remote areas where grid access is limited [1]. Moreover, many developing countries rely heavily on imported fossil fuels for their energy needs, which can make their energy systems vulnerable to price fluctuations and supply disruptions. Investing in renewable energy can help these countries reduce their dependence on imported fuels, and increase their energy security [2]. Furthermore, these countries are often the most vulnerable to the impacts of climate change. By transitioning to renewable energy, these countries can reduce their GHG emissions and contribute to the global effort to mitigate climate change [3, 4]. Besides, burning fossil fuels for energy production can have significant negative impacts on human health, especially in developing countries where air pollution is often a major problem [5].

Wind and solar energy have gained increasing attention in recent years as a way to reduce emissions and fossil fuel consumption. Recently, the use of wind and solar energy has been increasing rapidly in many countries such as Germany, China, USA, Denmark, Brazil, and Costa Rica [6-8]. Renewable energy sources generate electricity without emitting harmful GHGs, which contribute to climate change. According to the Intergovernmental Panel on Climate Change (IPCC), the world must reduce its carbon emissions by at least 50% by

2030 to avoid the worst impacts of climate change [9]. This means transitioning to renewable energy is no longer an option, but a necessity. Renewable energy is becoming more cost-effective and competitive with traditional energy sources, making it more accessible to consumers [10].

A. Literature Review related to the Current Electricity Situation in Libya

Libya's electricity sector is dominated by fossil fuels. According to the IEA, in 2018 natural gas accounted for approximately 98% of Libya's electricity generation, with the remaining 2% coming from oil-fired power plants. The country has significant natural gas reserves, which have historically been used to fuel power plants and provide domestic heating and cooking fuel. However, the ongoing conflict and instability in Libya have disrupted natural gas production and distribution, leading to shortages and disruptions in electricity supply. In addition, the damage to the oil infrastructure and the resulting decline in oil production has limited the fuel availability. As a result, many of Libya's power plants have been operating well below their capacity, leading to frequent power outages and load shedding.

The electricity sector in Libya is also characterized by an aging and poorly maintained infrastructure, which has contributed to the unreliability of the electricity supply. Many of the country's power plants and transmission lines require repair and modernization, and there have been limited investments in new infrastructure due to the political and economic instability. The Libyan government has attempted to address some of these challenges through a series of electricity sector reforms, including the establishment of the General Electricity Company of Libya (GECOL) in 1979, which is responsible for electricity generation, transmission, and distribution. The government has also pursued partnerships with foreign companies to develop new power plants and improve the efficiency of the existing ones. However, the ongoing conflict and instability have hindered the implementation of these reforms and investments. In addition, corruption and mismanagement have been significant challenges in the electricity sector, with allegations of embezzlement and fraud involving government officials and foreign companies. Despite these challenges, there have been some efforts to develop renewable energy sources in Libya, particularly solar power. The country has abundant solar resources, with high levels of solar radiation throughout most of the year. The government has expressed interest in developing solar power projects, and there have been some private sector investments in solar energy during the recent years. Nevertheless, the development of renewable energy sources in Libya has been limited by the challenges posed by the ongoing conflict and instability, as well as the lack of regulatory frameworks and incentives for renewable energy development. In addition, the high cost of renewable energy technologies and the limited access to financing have been significant barriers to the development of renewable energy in Libya. Moreover, the generation capacity and power plant infrastructure in Libya have historically been dominated by oil and gas-fired power plants. According to the Libyan Electricity Company (LEC), the country's installed generation capacity as of 2020 was approximately 7.5 GW, with a peak demand of around 7 GW. The majority of this capacity is made up of thermal power plants, which account for approximately 97% of the country's total installed capacity. The remaining 3% of the capacity is provided by hydroelectric power plants. Additionally, there are currently eight main thermal power plants in Libya, located in different regions of the country. The largest of these is the Al-Khums power plant, located on the Mediterranean coast east of the capital city of Tripoli, with a capacity of 2,500 MW. Other major thermal power plants include the Zawiya power plant near the city of Zawiya, with a capacity of 1,200 MW, and the Tripoli West power plant, with a capacity of 1,000 MW. In addition, there are also several smaller power plants located in different regions of the country, including diesel-fired and gas-turbine power plants. Furthermore, the hydroelectric power plants in Libya are all located in the western region of the country and have a total capacity of approximately 240 MW. The largest of these is the Wadi Al-Khijir power plant, with a capacity of 130 MW.

The electricity consumption in Libya varies depending on the region and level of economic development. The majority of electricity consumption is concentrated in the major cities, particularly Tripoli and Benghazi, where the population is highest and economic activity is concentrated. According to the World Bank, in 2019, the electricity consumption per capita in Libya was approximately 1,100 kWh, which is relatively low when compared to other countries in the region. This is partly due to the challenges faced by the electricity sector in Libya, including frequent power outages and the unreliable electricity supply. Besides, the cost of electricity for domestic use in Libya also varies depending on the region and the level of consumption. The Libyan government heavily subsidizes the cost of electricity, to provide affordable electricity to households and promote economic development. However, the subsidies have been a significant burden on the government budget, and there have been concerns about the sustainability of the subsidies in the face of ongoing economic challenges. The cost of electricity for domestic use in Libya was approximately 0.09 Libyan dinars per kWh, which is equivalent to approximately 0.06 US dollars. This is relatively low compared to other countries in the region, where the cost of electricity is often higher due to lower levels of government subsidies. However, the reliability of the electricity supply remains a significant challenge, and households may need to rely on alternative sources of energy, such as diesel generators, to meet their electricity needs during power outages. The use of diesel generators as an alternative source of energy can be expensive and may not be feasible for households with limited financial resources. In addition to the challenges of cost and reliability, there have also been concerns about the environmental impact of the electricity sector in Libya. The heavy reliance on fossil fuels, particularly natural gas, for electricity generation, has contributed to GHG emissions and air pollution. The development of renewable energy sources, such as solar power, could address these environmental challenges, while reducing the reliance on fossil fuels and promoting energy independence.

As mentioned above, Libya is a major oil-producing country and has historically been a net exporter of energy.

However, due to the ongoing political and security instability in the country and the damage to the oil infrastructure during the country's civil war, Libya has at times needed to import energy to meet its own domestic needs. According to the US Energy Information Administration (EIA), Libya imported an average of 2,000 barrels per day of petroleum products in 2020. This was a significant decrease from the previous year when the country imported an average of 13,000 barrels per day. It is worth noting that these import figures may not fully capture the extent of Libya's energy needs or imports, as some imports may occur through informal channels or may not be reported to the official statistics agencies. Additionally, the situation in Libya remains volatile and subject to change, and future energy import needs could fluctuate depending on a variety of factors.

B. Literature Review related to Renewable Energy in Libya

Libya has a significant potential for renewable energy resources, particularly solar and wind power. The country receives abundant sunshine throughout the year, and its coastal areas experience consistent winds. However, the development of renewable energy in Libya has been hindered by political instability, security concerns, and the reliance on fossil fuels. Notwithstanding these challenges, there have been some efforts to develop renewable energy in Libya. In 2012, the country's National Renewable Energy Authority (NREA) was established to promote the development of renewable energy projects. The NREA has identified several potential sites for wind and solar power plants and has signed agreements with international companies to develop renewable energy projects. In 2019, Libya's first commercial-scale solar power plant, the 10 MW Ubari Solar Power Station, was inaugurated. The plant is located in the southwestern part of the country, an area with high levels of solar radiation. The Ubari plant was developed by a consortium of companies from Italy, China, and Libya.

Libya has significant potential for wind energy, particularly along its coastal regions. The country's location along the Mediterranean Sea and its extensive coastline provide abundant opportunities for wind power generation. However, despite this potential, the development of wind energy in Libya has been limited, largely due to political instability and the lack of investment in renewable energy. The coastal areas of Libya experience consistent winds, particularly in the eastern part of the country, where wind speeds can reach values up to 10 m/s. This makes the region an ideal location for wind energy development, as high wind speeds are necessary to generate electricity efficiently. Wind energy has the potential to contribute significantly to Libya's electricity mix, as the country continues to rely heavily on fossil fuels for power generation. In 2014, the European Union's Joint Research Centre (JRC) published a study on the wind energy potential in the Mediterranean region, including Libya. The study estimated that the total wind energy potential for the Mediterranean region was 766 GW, with Libya accounting for 35 GW of this potential. Additionally, Libya has an estimated wind energy potential of around 10 GW, which is equivalent to the country's current electricity demand according to the Renewable Energy and Energy Efficiency Authority (REEEA) in Libya. Recently, the Libyan government has shown interest in developing its renewable energy sector, including wind power. The country's first wind farm, the Al-Fataiah Wind Farm with a capacity of 1.25 MW, was inaugurated in 2018. Plans are also underway to build several other wind farms along the coast and in other regions of the country [11, 12]. Furthermore, several studies have investigated the potential of wind energy potential in Libya [13-28]. For instance, Authors in [13] estimated the wind power potential Tripoli, Nault, and Esspeea using the Weibull distribution function. The results showed that Nault has the highest mean actual wind power ($50.3 W/m^2$) at a height of 10m. Authors in [17] evaluated the wind power potential wind energy potential in Al-Fattaih-Darnah. The results showed that the annual wind power density of the selected locations is categorized into class 3. Authors in [26] estimated the wind energy potential in Espiaa, Msallata, Alqatrun, and Adirsiyah, also using the Weibull distribution function. The results indicated that Msallata has the highest value of wind power potential (444.74 W/m^2 at a height of 60m) compared to other cities.

Libya has a high potential for solar energy due to the Sahara desert region, which experiences long hours of sunshine throughout the year. In recent years, there have been several studies conducted on the solar energy potential in Libya. According to NREA [29], the country had a total solar energy potential of 6.5 $kWh/m^2/day$, which is among the highest in the world. Additionally, the JRC published a study on the solar energy potential in the Mediterranean region, including Libya [30]. The study estimated that the total solar energy potential for the Mediterranean region was 332 TWh/year, with Libya accounting for 20% of this potential. The International Renewable Energy Agency (IRENA) concluded that North Africa had a total solar energy potential of 2,600 TWh/year, with Libya accounting for 1,050 TWh/year of this potential [31]. In addition, there have been some private-sector initiatives to develop solar energy in Libya [32, 33]. These projects are expected to contribute significantly to the country's electricity mix and reduce its dependence on fossil fuels.

Recently, several studies have investigated the potential of solar energy in different locations in Libya [34-39]. For example, authors in [34] found that the city had an average solar radiation of 5.38 $kWh/m^2/day$, which can be supported by the installation of photovoltaic (PV) panels with a total capacity of 508 MW. Besides, authors in [37] concluded that Benghazi had an average solar radiation of 5.8 $kWh/m^2/day$, which could support the installation of PV panels with a total capacity of 313 MW. Additionally, authors in [39] found that the Sabha in southern Libya was found to have an average solar radiation of 6.93 $kWh/m^2/day$. This indicates that there is a potential for the installation of PV panels with a total capacity of 270 MW.

C. Importance of the Current Study

The present study is of great importance due to the current situation in Libya. It is imperative to conduct a comprehensive study on the economic and environmental aspects. This study will serve as a roadmap for the investment of wind energy in Libya. The figures presented in this study provide a summary of the economic and energetic analysis conducted, while the environmental impact of the electricity crisis in the country has already been assessed.

II. MATERIALS AND METHODS

A. Dataset

Choosing locations with suitable wind speeds requires obtaining wind information for the region, thus, an atlas map was utilized. In general, wind speed and global solar radiation are essential criteria for installing wind and solar power plants at specific locations. In general, there is a lack of instruments used to measure wind speed due to the Civil War in Libya. Anyhow, several studies have evaluated the potential of wind energy at specific locations using satellite data such as the NASA power dataset [13, 40-46]. The NASA Prediction of Worldwide Energy Resource (POWER) dataset is a comprehensive set of meteorological data used for research and analysis of renewable energy resources, particularly solar and wind energy. It is provided by the NASA Langley Research Center's Atmospheric Science Data Center (ASDC) and is freely available to the public [47]. The dataset contains hourly, daily, and monthly data on a range of meteorological variables such as solar radiation and wind speed. The data are derived from a combination of satellite observations, reanalysis models, and ground-based measurements [47]. Therefore, the monthly data (collected from the NASA POWER dataset), including wind speed at a height of 50 m, are used to assess the economic feasibility of large-scale wind power projects to generate electricity in the country.

TABLE I. INFORMATION REGARDING THE SELECTED AREAS

Location No.	Region	Latitude	Longitude	Altitude
L#1	Al Butnan	29.742	24.515	11
L#2	Al Jabal al Akhdar	32.487	21.709	683
L#3	Al Jabal al Gharbi	30.705	13.223	579
L#4	Al Jifarah	23.986	45.185	872
L#5	Al Jufrah	27.983	16.912	515
L#6	Al Kufrah	24.198	23.294	396
L#7	Al Marj	32.485	20.833	336
L#8	Al Marqab	32.646	14.244	58
L#9	Al Wahat	29.157	21.75	47
L#10	An Nuqat al Khams	32.854	12.239	4
L#11	Az Zawiyah	32.884	13.185	17
L#12	Benghazi	32.119	20.087	7
L#13	Darnah	32.700	22.681	250
L#14	Ghat	26.020	10.434	594
L#15	Misratah	32.375	15.092	9
L#16	Murzuq	24.535	15.259	614
L#17	Nalut	30.613	10.671	545
L#18	Sabha	26.996	15.107	467
L#19	Surt	29.971	16.677	315
L#20	Tripoli	32.773	13.332	71
L#21	Wadi al Hayat	26.423	12.718	683
L#22	Wadi ash Shati'	27.56	14.449	346

B. Weibull Distribution

Wind speed (v) characteristics play a crucial role in the design and operation of wind energy systems. Probability distribution models are commonly used to analyze wind speed data and estimate the probability of different wind speeds occurring at a particular location. Generally, examining the Wind Speed Characteristics (WSC) is considered the first step for the evaluation of the wind energy potential at a specific location. Different distribution functions have been suggested to represent wind speed data in particular areas. The 2-parameter Weibull (2p-W) is commonly utilized for studying the distribution of wind speed at a specific region [48]. The Weibull distribution function is frequently used to model wind speed frequency due to its ability to accurately, simply, and efficiently fit a wide range of data [49]. The Weibull distribution function is defined below:

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

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

where $f(v)$ is the probability distribution function, $F(v)$ is the cumulative distribution function, c is the scale parameter in m/s, and k is the shape factor of the distribution.

In general, several methods can be used to estimate the parameters of the 2p-W, such as maximum likelihood estimation (MLS), the method of moments, etc. [50]. In this study, MLS, a widely used method for estimating the parameters of the Weibull distribution function, is used for estimating the parameters of the 2p-W.

$$k = \left(\frac{\sum_1^n v_i^k ln(v_i)}{\sum_1^n v_i^k} - \frac{\sum_1^n ln(v_i)}{n}\right)^{-1} \quad (3)$$

$$c = \left(\frac{1}{n}\sum_1^n v_i^k\right)^{1/k} \quad (4)$$

C. Wind Power Density

Generally, the amount of air flowing across the area of interest determines how much electricity a wind turbine can generate [51]. Wind Power Density (WPD) is a measure of the amount of power that can be harnessed from the wind in a specific location. It is defined as the ratio of the power present in the wind to the area swept by the wind turbine. WPD is also referred to as wind power potential or wind power per unit area, and it provides a numerical representation of the energy potential in a given region. It can be expressed as [68]:

$$\frac{\bar{P}}{A} = \frac{1}{2}\rho c\Gamma\left(1 + \frac{3}{k}\right) \quad (5)$$

where $\bar{P}$ is the mean WPD in W, $\bar{v}$ is the mean wind speed in m/s, A is the swept area in m^2, and ρ is the air density (ρ=1.225 kg/m^3).

D. Extrapolation of Wind Speed Data

The power law model is commonly utilized in wind energy evaluations to extrapolate wind speed to various hub heights. The model is represented by (6):

$$\frac{v}{v_{10}} = \left(\frac{z}{z_{10}}\right)^{\alpha} \quad (6)$$

where v is the wind speed at the wind turbine hub height z, v_{10} is the wind speed at the original height z_{10}, and α is the surface roughness coefficient, which depends on the characteristics of the region. The wind speed data in this analysis were gathered at a height of 10 m above the ground level. Therefore, the value of α can be determined by [52]:

$$\alpha = \frac{0.37 - 0.088ln(v_{10})}{1 - 0.088ln(z_{10}/10)} \quad (7)$$

E. Design of Wind Farms

A wind turbine is a device that converts the kinetic energy of the wind into mechanical energy, which can then be used to generate electricity. There are two main types of wind turbines: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). HAWTs are more traditional. They have a rotor mounted horizontally on a tower and the blades rotate around a horizontal axis perpendicular to the wind direction. They are commonly used in large-scale wind farms and are well-suited for locations with strong and consistent winds. In general, designing a wind farm involves several considerations, including selecting an appropriate site, choosing the right type and size of turbines, and determining the optimal layout and spacing of turbines. According to [53, 54], the first step in designing a wind farm is to select a suitable site with high wind speeds and low turbulence. Additionally, authors in [55] report that the choice of turbine depends on the site conditions and the energy requirements of the project. Furthermore, the layout and spacing of the turbines will affect the performance of the wind farm [56]. The turbines should be spaced far enough apart to avoid the effects of wake, which is the turbulence created by the rotor blades as they rotate [57, 58]. If the turbines are spaced too closely, the wake effect can reduce the efficiency of downstream turbines. The wake effect occurs when the rotor blades of a wind turbine disrupt the air flow behind them, creating turbulence that can reduce the efficiency of downstream turbines [57, 58]. Regular cleaning and maintenance procedures are considered important factors [59, 60].

TABLE II. SPECIFICATIONS OF THE SELECTED WIND TURBINES

Specification	Turbine#1	Turbine#2	Turbine#3
Hub height [m]	80	75	80
Rated power [W]	2000	500	1500
Cut in speed [m/s]	4.0	3.0	4.0
Rated speed [m/s]	13.0	10.0	11.6
Cut out speed [m/s]	-	25.0	25.0

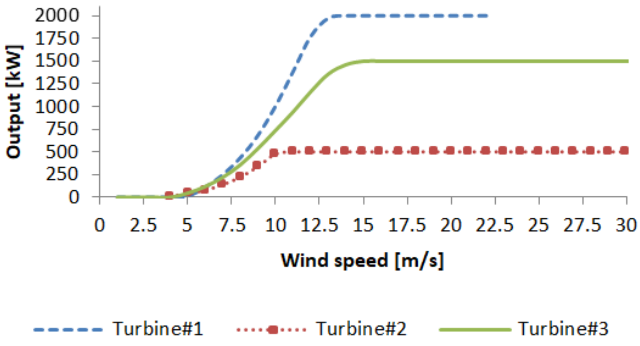

Fig. 1. Power-speed curve for the selected wind turbines.

In this study, three wind turbines (Turbine#1: AAER-A-2000 – 80m, Turbine#2: EWT-DW 52 - 500kW - 75m, and Turbine#3: AW-70/1500 Class I - 80m) are considered. The power-speed curve and the specification of the selected turbines are shown in Figure 1 and Table II, respectively. The capital, operation, and maintenance costs are assumed based on [61-66]. Moreover, various types of losses are taken into consideration for the evaluation of energy production.

F. Software Tool for Feasibility Study

During the recent years, numerous simulation tools have been available for assessing the performance of wind farms, including RETScreen and HOMER. RETScreen Expert is a comprehensive clean energy management software tool developed by the Canadian government that allows users to evaluate the energy production, savings, and costs of various types of renewable energy and energy efficiency technologies. It provides users with a suite of tools and databases that can be used to analyze renewable energy and energy efficiency projects. It includes a database of over 1,000 pre-built energy efficiency and renewable energy measures, as well as a variety of performance and financial analysis tools. It can be used to evaluate the performance of various renewable energy technologies. Moreover, it includes a suite of financial analysis tools that can be used to estimate the costs and financial returns of energy projects, including cash flows, net present value, and internal rate of return. Several researchers have utilized RETScreen for the evaluation of the techno-economic feasibility of wind farms. For instance, authors in [13] utilized RETScreen to evaluate the economic viability of a 50 MW grid-connected wind farm. Authors in [41] evaluated the feasibility of a 100 MW grid-connected wind farm in Saudi Arabia using RETScreen. Authors in [49] estimated the economic viability of wind farms in Ghana using RETScreen. Consequently, RETScreen Expert is used for evaluating the economic and environmental viability of wind farms in the current study. The mathematical equations for the calculation of the capacity factor, the annual power production, GHG reductions, and economic indicators are discussed in [53].

III. RESULTS AND DISCUSSION

A. Wind Power Potential at 50 m Height

To evaluate the wind power potential at a specific location, the WSC should be evaluated based on the value of daily, monthly, or annual wind speed. In the current study, the average monthly wind speeds values were gathered over a period of 30 years. The descriptive statistics of wind speed data of each location are listed in Table III. In addition, the monthly variation in wind speed for each of the chosen locations is shown in Figure 2. The mean wind speed is ranged between 5.66 m/s and 6.56 m/s at a height of 50 m. The values for mean speed and Standard Deviation (SD) indicate that the wind behavior is quite consistent. The Coefficients of Variation (CVs), which are within the range of 5.97-14.72%, are relatively low. The minimum and maximum values of 4.51 m/s and 7.68 m/s are recorded in L#15 (Misratah) and L#13 (Darnah) during August and February, respectively, as shown in Figure 3. For the majority of the chosen locations, the Skewness (S) values are negative, indicating that all distributions are left skewed. Additionally, the values of Kurtosis (K) vary from -1.65 to -0.56, and they are also moderately low as shown in Table III.

The parameters of the 2p-W distribution functions were estimated using monthly mean wind speed with the MLS. Table IV presents the annual Weibull distribution parameters of the selected locations. For all 22 locations, the calculated annual Weibull scale parameter varies from 5.84 to 6.88 m/s and the range of the annual shape parameter is 8.78 to 21.49. The lowest and highest shape parameter is found at L#8 (Al Marqab) and L#14 (Ghat), respectively.

The graphic representation of the Weibull probability is presented in Figure 3. Furthermore, the WPD is calculated for a year using (5). It should be noted that the average air density yearly values were determined using the ideal gas law. Throughout the investigation period, the air temperature and pressure values were gathered for this purpose. The average annual WPD at three hub heights is presented in Table V. It can be seen that the WPD values are within the range of 111.30-172.91 W/m^2. The minimum and maximum WPD values are recorded at L#1(Al Butnan) and L#13 (Darnah) as 111.30 W/m^2 and 172.91 W/m^2, respectively. It can be concluded that despite the unsuitability of the region's wind power potential for high-capacity wind turbines, it may still be feasible to harness wind power through the use of small-scale wind turbines in the area.

TABLE III. DESCRIPTIVE WIND SPEED DATASET

Location No.	Mean	SD	CV	Min.	Max.	S	K
L1	5.66	0.41	7.31	4.92	6.17	-0.68	-0.64
L2	6.49	0.49	7.54	5.63	7.20	-0.40	-1.01
L3	5.92	0.53	8.97	5.06	6.52	-0.37	-1.62
L4	6.04	0.37	6.13	5.52	6.66	0.31	-0.56
L5	6.42	0.41	6.45	5.76	6.96	-0.22	-1.21
L6	5.90	0.48	8.19	5.10	6.44	-0.61	-1.20
L7	6.52	0.58	8.82	5.75	7.41	0.12	-1.48
L8	6.19	0.91	14.72	4.64	7.25	-0.43	-1.18
L9	5.85	0.47	7.99	5.06	6.53	-0.35	-1.09
L10	5.84	0.52	8.93	5.03	6.46	-0.36	-1.51
L11	6.09	0.73	12.02	4.89	7.01	-0.37	-1.27
L12	6.40	0.69	10.74	5.55	7.43	0.22	-1.65
L13	6.56	0.74	11.30	5.40	7.68	-0.11	-1.26
L14	6.08	0.36	5.97	5.48	6.57	-0.38	-1.27
L15	6.02	0.87	14.41	4.51	7.02	-0.52	-1.13
L16	6.55	0.45	6.86	5.81	7.12	-0.43	-1.24
L17	6.41	0.41	6.45	5.81	7.02	0.01	-1.40
L18	6.08	0.50	8.23	5.27	6.69	-0.24	-1.43
L19	6.06	0.44	7.31	5.35	6.65	-0.10	-1.53
L20	6.09	0.73	12.02	4.89	7.01	-0.37	-1.27
L21	5.98	0.39	6.50	5.40	6.51	-0.17	-1.44
L22	6.08	0.49	8.12	5.35	6.73	-0.17	-1.00

B. *Feasibility of a 100 MW Wind Farm*

In this study, RETScreen was utilized to analyze the impact of Wake effects (array losses in %) and airfoil losses in the percentage on the output of wind farms, CF, GHG emissions, and financial viability. In the current study, 11 scenarios were based on a 100 MW wind power project. The inputs and calculations were conducted using the Level 3 analysis (Level 2 for financial) in RETScreen Expert, which provides the highest level of detail.

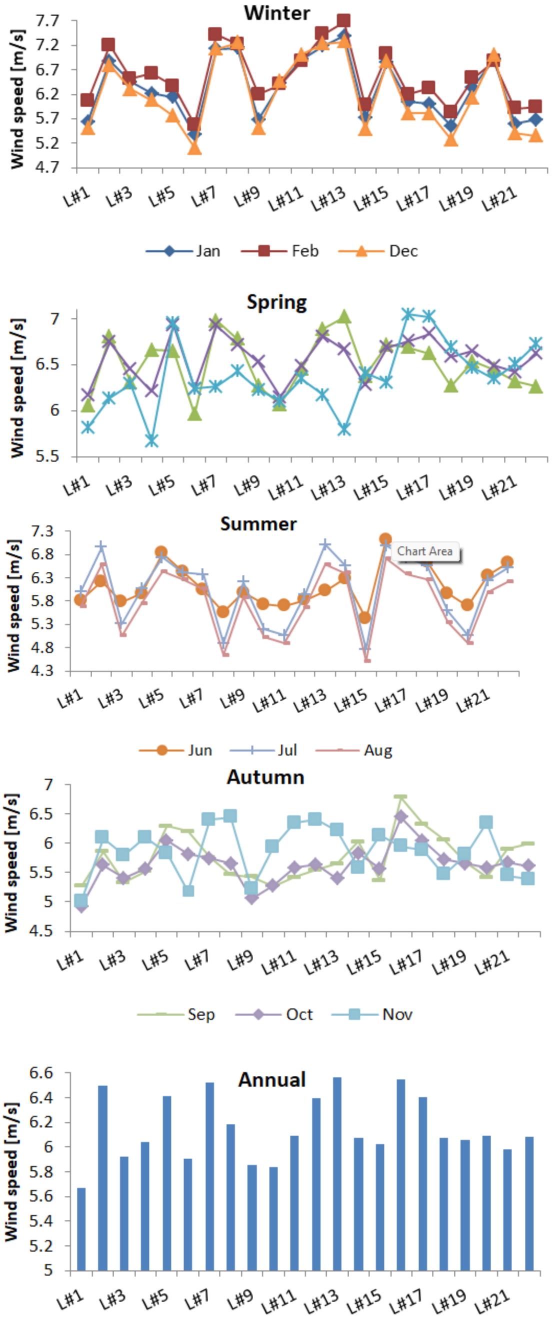

Fig. 2. Monthly average wind speed for all selected locations over 30 years at 50 m height.

Additional information about the scenarios and assumptions can be found in Table V. As mentioned above, the performance of the wind farms in terms of wind power output and CF depends on the geographic location and WSC. Based on the results, the maximum and minimum average monthly wind speed was recorded in Darnah and Al Butnan, respectively. Thus, the Electricity Exported to the Grid (EEG), the CF, and the economic viability and environment feasibility were estimated for all the selected regions.

TABLE IV. ANNUAL WEIBULL PARAMETERS AND WPD VALUES AT 50 M HEIGHT

Location	Shape	Scale [m/s]	WPD [W/m^2]	Locations	Shape	Scale [m/s]	WPD [W/m^2]
L1	18.46	5.84	111.30	L12	10.79	6.70	160.31
L2	16.86	6.71	167.63	L13	10.70	6.88	172.91
L3	14.58	6.15	126.97	L14	21.49	6.24	137.49
L4	17.74	6.21	134.68	L15	9.17	6.37	133.63
L5	19.11	6.60	161.76	L16	18.88	6.74	171.92
L6	16.65	6.11	125.90	L17	18.36	6.59	161.07
L7	13.25	6.77	169.64	L18	15.26	6.30	137.49
L8	8.78	6.56	144.98	L19	16.72	6.26	136.20
L9	15.78	6.05	122.62	L20	10.67	6.40	138.40
L10	14.46	6.06	121.79	L21	18.96	6.15	131.04
L11	10.67	6.40	138.40	L22	15.21	6.30	137.61

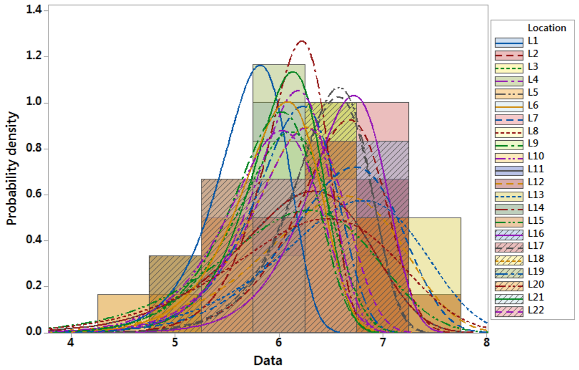

Fig. 3. Graphic representation of the Weibull probability for all the selected locations.

TABLE V. ASSUMED CASE, INPUTS TO THE TOOL

Wind farm capacity	100 MW	100 MW	100 MW
Turbine	Turbine#1: AAER-A-2000 Turbine#2: EWT-DW 52 - 500kW		
Project life	20 years		
Capital cost	2000 USD/kW		
Replacement cost	1600 USD/kW		
Operational and maintenance	50 USD/kW		
Array (Wake effects) losses	Ranged from 2% to 16% in step 4		
Airfoil soiling losses	Ranged from 2% to 10% in step 4		
Miscellaneous losses	6.00		
Availability factor	98.00		
Inflation rate	2.77		
Discount rate	9.52		
Debt ratio	70.00		
Debt interest rate	3.28		
Debt payments	15.00		
Electricity export escalation rate	5.00		

The mean monthly value of EEG for all the proposed scenarios (cases) is shown in Figure 4 for Darnah and Figure 5 for Al Butnan. It is observed that the EEG is within the range of 198888-31616.853 MWh for Turbine#1 and 27055.90-41458.69 MWh for Turbine#2. The lowest value of EEG is recorded for case#11 (array losses = 16% and airfoil soiling losses = 10%), while the highest value is recorded for case#1 (array losses = 2% and airfoil soiling losses = 2%). Also, it is noticed that Turbine#2 (cut-in speed = 3 m/s and rated wind speed = 10 m/s) produced higher EEG than Turbine#1 (cut-in speed = 4m/s and rated wind speed = 13 m/s). The results indicate that an increase in wake effect percentage resulted in reduced energy production from the wind farm. These results are supported by the findings in 69-73]. The power production from wind farms depends on the distance between the turbines and the operating condition of the upstream turbine. Also, they found that the wake effect can cause up to a 30% reduction in power output. Also, it is found that airfoil soiling losses can significantly impact the energy production of wind farms as shown in Figures 4 and 5. It has been shown [73-75] that even a small amount of soiling can cause a noticeable decrease in the power output.

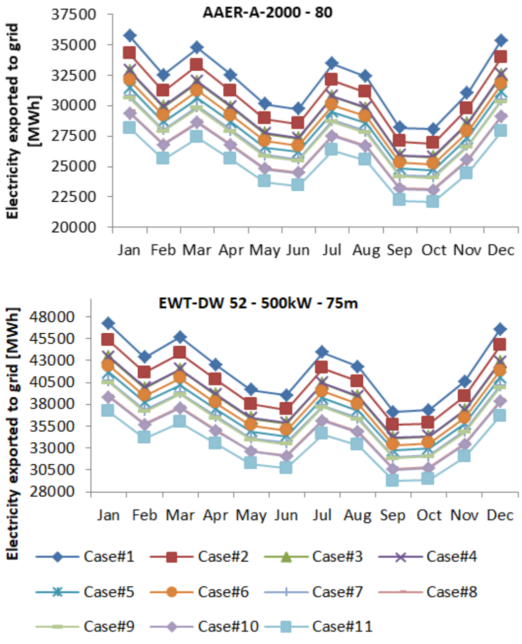

Fig. 4. Monthly variation of the EEG of all proposed cases for Darnah.

Furthermore, the annual CF was calculated for all cases as shown in Figure 6. The annual CF varied from 30.97% to 57.69%. The results are supported by previous scientific studies. According to [76], the CF of wind farms under consideration ranged from 9.79% to 51.93%. Authors in [77] reported that the CF of the proposed farms fell within the range of 5-42%. Authors in [78] found the CF of the proposed farm projects in Pakistan to range from 19% to 34%. In [79], the CF values were estimated to be within the range of 22.9-50.6% using different wind turbines. Assessing the economic viability and sustainability of a project is crucial, and one way to do so is through techno-economic feasibility analysis. In this regard, the feasibility of the proposed projects was evaluated using RETScreen, taking into consideration various financial parameters. The input parameters used for the analysis were based on previous studies and included an inflation rate of 2.77%, a discount rate of 9.52%, a reinvestment rate of 9%, a project life of 20 years, a debt ratio of 70%, a debt interest rate of 3.28%, and debt payment spread over 15 years. Based on these input parameters, NPV, ALCS, SP, EP, and LCOE were estimated using RETScreen. The NPV was determined for each case and is illustrated in Figures 7 for Darnah and Figure 8 for Al Butnan.

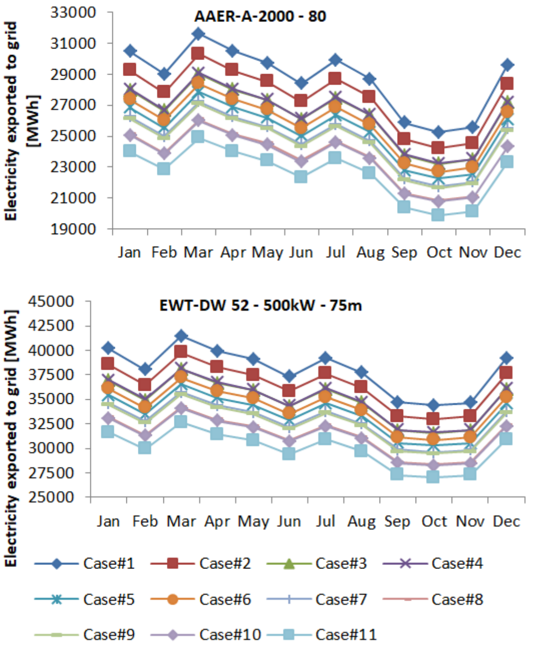

Fig. 5. Monthly variation of the EEG of all proposed cases for Al Butnan

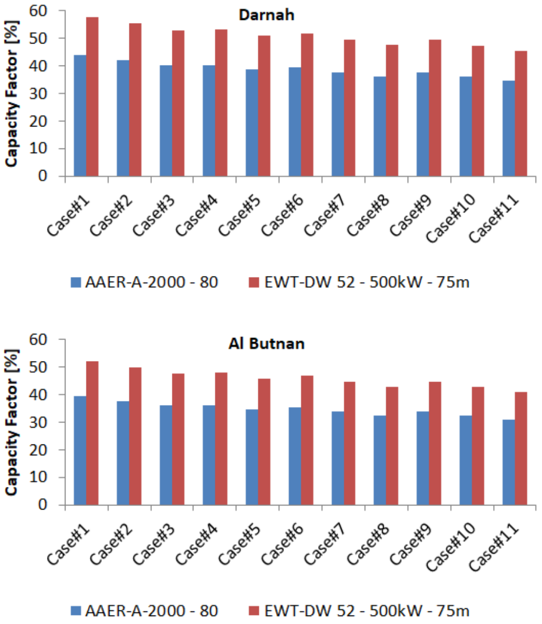

Fig. 6. Annual CF for the proposed cases suing different wind turbines.

C. *Feasibility of a 10 MW Installed Capacity Wind Farm*

In this study, the technical viability of Turbine#2 (DW 52 - 500kW - 75m) is evaluated for all the selected locations and the results were compared with Turbine#3 (AW-70/1500 Class I - 80m). As mentioned above, the wind power output and the CF of the wind farms depend on the geographic location and wind speed characteristics. Therefore, in this study, EEG and CF as well as the financial viability were estimated for all the considered locations with RETScreen.

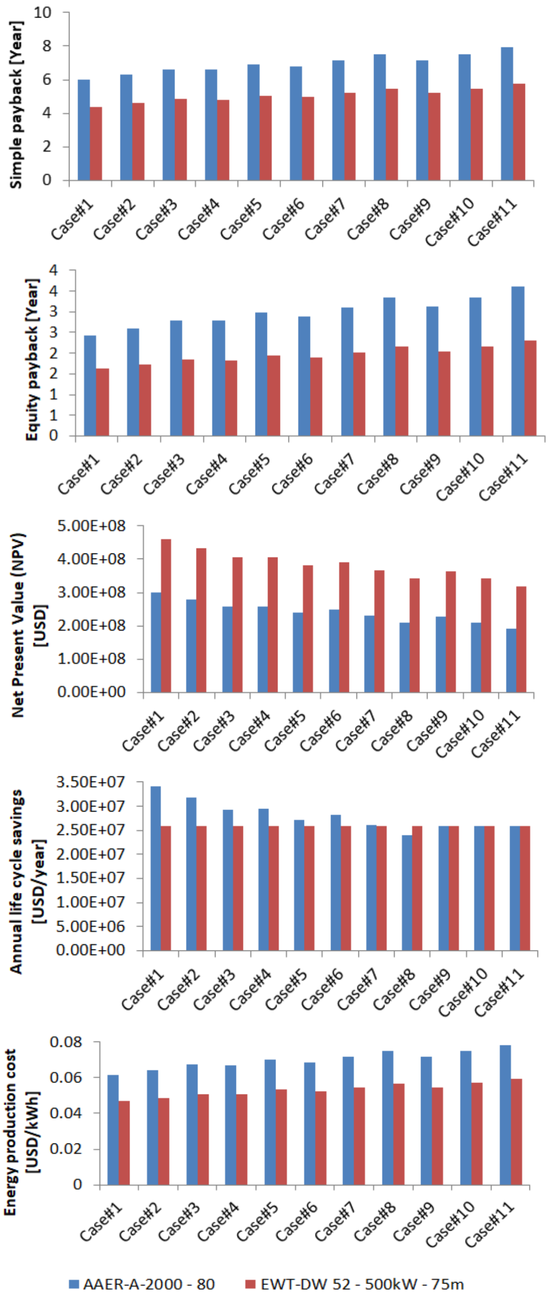

Fig. 7. Economic performance for the developed wind farms in Darnah.

Figure 9 shows the mean monthly EEG values for the proposed wind turbine models. It can be observed that the EEG ranges from 2165.497 to 4046.684 MWh for Turbine#3 and from 2279.643 to 4641.675 MWh for Turbine#2. It is noticed that Turbine#2 produced higher EEG than to Turbine#3. Figure 10 shows the calculated annual CF. The results indicate that the annual CF varies from 38.39% to 56.79%. The CF of Turbine#2 was found to be the highest. Previous studies [76-79] can be supported by these results.

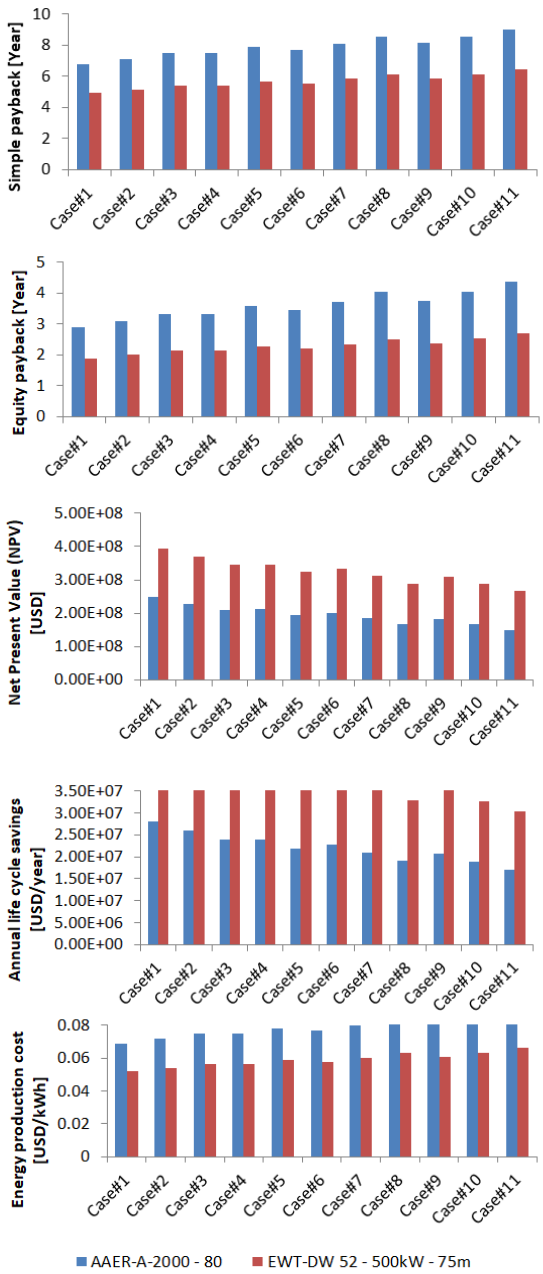

Fig. 8. Economic performance for the developed wind farms in Al Butnan.

Figure 11 shows the NPV calculated for each location and the Electricity Export Rate (EER), which indicated a positive value for each location, suggesting a potentially feasible project. Additionally, the IRR was estimated to evaluate the economic viability of the project, and it was found that the value for all locations was higher than the required rate of return. The ALCS was calculated using the NPV, discount rate, and project lifetime, and it was found to be in the range of 1798379 to 5640383 USD/year for all the proposed projects. The payback period, which represents the time needed to recover the initial investments made for the project, was also evaluated for all selected locations, as shown in Figure 11. The EP and SP were found to be within the range of 6.99 to 4.47 years and 3.36 to 1.66 years, respectively, with Turbine#2 having the lowest values. Additionally, the EPC was calculated to be within the range of 0.0707 to 0.0437 USD/kWh.

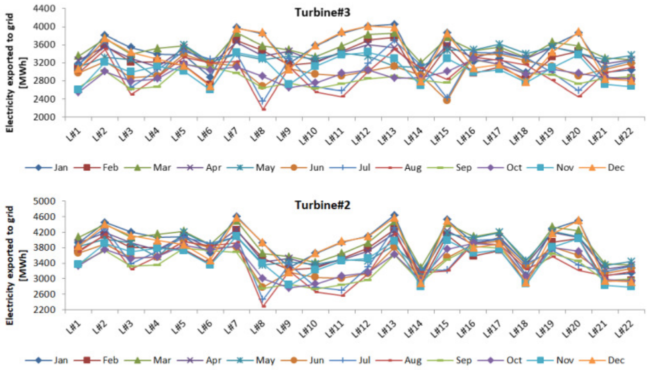

Fig. 9. Monthly variation of EEG for all the selected locations.

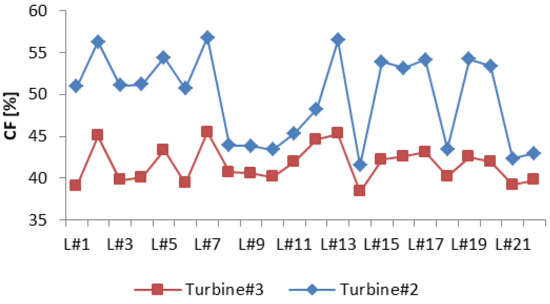

Fig. 10. CF value of the selected wind turbines.

D. Climate Co-benefit Assessment

Estimating the environmental benefits in terms of reduced GHG emissions of the proposed system is crucial. Calculation of the climate co-benefits in terms of GHG emission reduction was performed using RETScreen for each location and is presented in Figures 12 and 13 for 100MW and 10MW wind farms, respectively. The annual electricity generation was used to determine the total CO_2 emission reduction for each location. The results indicate that a large amount of CO_2 emissions can be avoided by implementing the developed wind farms.

IV. LIMITATIONS AND FUTURE WORK

Although the results of the present study were derived from RETScreen utilizing the NASA dataset, it is important to acknowledge that this study possesses certain limitations that could be explored and addressed in future research. First, the accuracy of the data from NASA for assessing the wind potential in Libya is not evaluated in this study, Therefore, wind resource assessment in Libya should be investigated using various gridded satellite data, and the results should be compared with the measured data to find the best-gridded satellite data. Second, terrain analysis was not considered in this study. Future research should focus on the site selection of wind energy power plants using GIS-multi-criteria evaluation. Third, the influence of weather parameters such as air temperature, and relative humidity were not considered.

Therefore, future research should examine the influence of temperature, relative humidity, and density on wind power generation. Finally, the impact of economic data, which is required for the techno-economic model on the performance of wind turbines, was not been investigated. Hence, it is recommended that future research concentrates on examining the impact of economic data on the performance of wind farms.

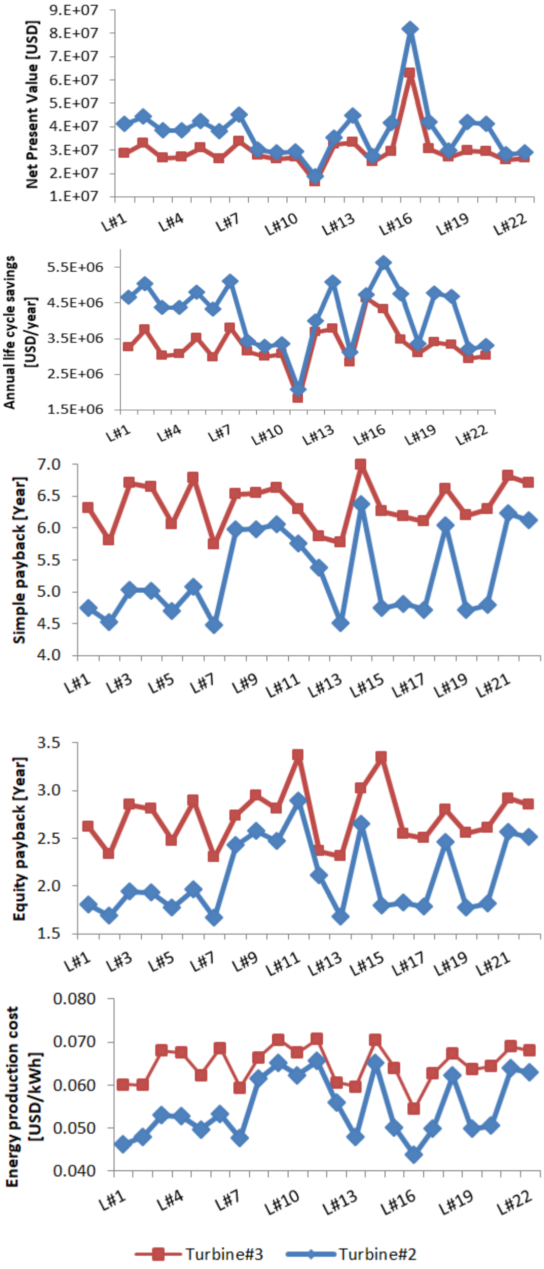

Fig. 11. Economic performance of the developed wind projects at the selected locations.

V. CONCLUSIONS

Libya faces a rising demand for electricity production due to its expanding economy and growing population. Renewable energy sources, particularly wind energy, emerge as a readily accessible energy solution to address this demand. According to the Global Wind Atlas, Libya is blessed with abundant wind energy resources at a hub height of 50 m. Accordingly, the main aim of the present study was to evaluate the wind potential at 22 locations over Libya. The results showed that Darnah has the maximum wind speed with a value of 7.68 m/s, while the minimum speed of 4.51 m/s was recorded in Misratah. Moreover, it was found that small-scale wind turbines are suitable for generating electricity in the country based on the value of WPD. Moreover, the techno-economic feasibility of 100 and 10 MW wind farms was investigated using RETScreen Expert. The impact of wake effect and airfoil losses on the performance of wind farms was assessed to provide valuable insight for policymakers in the country.

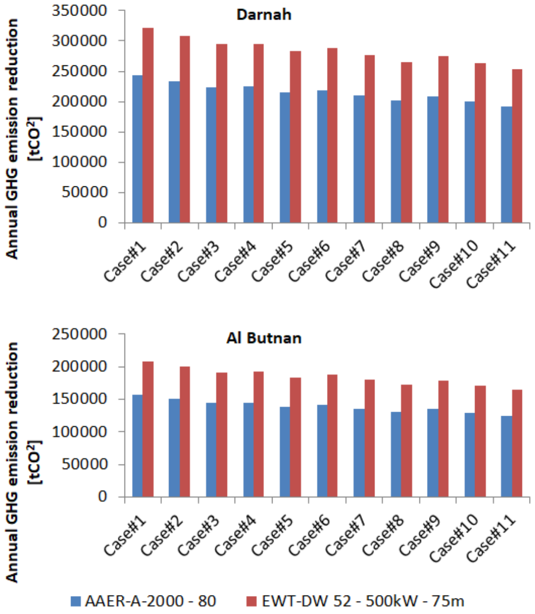

Fig. 12. GHG emission reduction potential from 100 MW wind farms.

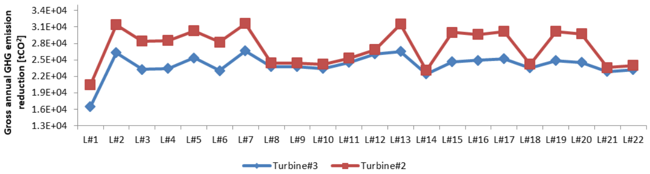

Fig. 13. GHG emission reduction potential from 100 MW wind farms.

The results demonstrated that the wake effect is an important factor in wind farm design and can be mitigated through careful spacing and turbine design. Additionally, airfoil soiling on wind turbine blades can have a significant impact on the energy production of a wind farm, reducing the efficiency of the turbine and lowering the amount of energy it can produce. Thus, wind farm operators typically implement regular cleaning and maintenance procedures to minimize the impact of airfoil soiling on energy production. Moreover, the results indicate that Turbine#2 (EWT-DW 52 - 500kW) can be a suitable turbine for a wind farm with various installation capacities in Libya.

VI. RECOMMENDATIONS

The wind energy potential in Libya is significant and could contribute significantly to the country's energy mix. However, the wind energy sector in the country faces several challenges, including inadequate infrastructure, inadequate investment, and policy gaps. Addressing these challenges would require a clear policy framework for the sector, increased investment, and a focus on developing local capacity.

- Inadequate infrastructure: One of the main challenges of wind energy production is inadequate infrastructure. The country's electricity infrastructure is inadequate, and this affects the wind energy sector, as there is a lack of suitable wind turbines and other equipment for wind energy generation. There is also a lack of suitable transmission and distribution networks for wind energy, which limits the ability to integrate wind farms into the national grid.

- Inadequate investment: The wind energy sector suffers from inadequate investment, with most of the investment going to the oil and gas sector. The lack of investment has limited the development of wind energy projects and has hindered the growth of the sector. The lack of investment has also resulted in a lack of research and development in, which limits innovation and the adoption of new technologies.

- Policy gaps: The wind energy sector also faces policy gaps, with no clear policy framework. The lack of a clear policy framework has resulted in a lack of incentives for wind energy development and a lack of regulations. This has limited the growth of the sector and has made it difficult for investors to enter the market.

- High capital costs: Wind energy projects require significant upfront capital investment, which can be a barrier for investors. The high capital costs of wind energy projects make it difficult for small and medium-sized enterprises to invest in the sector.

- Limited local capacity: There is a limited local capacity for wind energy in Libya, which means that the country has to rely on foreign expertise and technology for such projects. This increases the cost and limits the transfer of knowledge and technology to local communities.

- Lack of public awareness: There is a lack of public awareness about the benefits of wind energy in Libya. This lack of awareness makes it difficult to garner support for wind energy projects, so it is advised to educate the public about the potential of wind energy.

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