Wind Power Potential Assessment at Different Locations in Lebanon: Best–Fit Probability Distribution Model and Techno-Economic Feasibility

Youssef Kassem
Department of Mechanical Engineering, Engineering Faculty, Near East University, Cyprus | Energy, Environment, and Water Research Center, Near East University, Cyprus
yousseuf.kassem@neu.edu.tr
(corresponding author)

Huseyin Gokcekus
Department of Civil Engineering, Civil and Environmental Engineering Faculty, Near East University, Cyprus | Energy, Environment, and Water Research Center, Near East University, Cyprus
huseyin.gokcekus@neu.edu.tr

Ahmed Mohamed Salah Essayah
Department of Environmental Education and Management, Ataturk Faculty of Education, Near East University, Cyprus
20215635@std.neu.edu.tr

Received: 15 January 2023 | Revised: 19 February 2023 | Accepted: 28 February 2023

ABSTRACT

The objective of the current paper is to evaluate Lebanon's wind energy generation potential as an alternative solution to the electricity supply to households and to enhance sustainable technological development. Firstly, the paper aims to investigate the appropriateness of 44 distribution function models for the evaluation of wind speed characteristics and compared them with popular models at 12 locations in Lebanon for the first time. The results showed that Wakeby and Beta distribution functions gave the best fit to the actual data for most locations. Secondly, the techno-economic and environmental feasibility assessment for 10MW grid-connected wind farms was developed based on variations in financial parameters using RETScreen Experts software. The findings demonstrate that the proposed power plant is both technically and financially feasible. It was found that Ain ed Dabaa is the most viable location for the installation of a wind farm.

Keywords-Lebanon; distribution function; wind energy potential; grid-connected; RETScreen

I. INTRODUCTION

Wind energy has known increasing exploitation in power generation [1]. The use of wind as an energy source is imperative nowadays due to the lack of fossil fuel resources, particularly in developing countries like Lebanon. Wind energy is a clean, inexhaustible, and environmentally friendly energy source. The generation of electricity from wind energy will be an essential part of Lebanon's future development.

In general, analyzing wind speed characteristics is essential to assess the potential of wind energy in a given location. Probability Distribution Models (PDMs) are utilized to describe wind speed observations [2]. Thus, finding the most suitable PDM is considered the first step for evaluating the wind power potential at a specific location. Two-parameter Weibull and Rayleigh distribution functions are the most used for modeling the wind speed at specific locations [2]. Many studies focus on analyzing wind characteristics using various distribution models. Authors in [3] utilized parametric models, mixture models, and one non-parametric model to evaluate the potential of wind energy in the United Arab Emirates. The results demonstrated that one-component parametric distributions provided the best fit to the wind speed data for all sites. Authors in [4] analyzed the distribution of wind speed in Northern Cyprus using 2-parameter Weibull (2p-W), Gamma

(G), Lognormal (Ln), Logistic (L), Log-Logistic (LL), Inverse Gaussian (IG), Generalized Extreme Value (GEV), Nakagami (Na), Normal (N), and Rayleigh (R) distribution functions. The authors found that GEV showed the best fit for most selected locations. Authors in [5] evaluated the wind energy potential at different locations in Pakistan using various distribution functions and GEV was identified as the best. Authors in [6] analyzed the wind speed characteristics of 5 locations in Iran using 8 PDMs. The authors concluded that Na and 2p-W gave the best fit to the actual data. Authors in [7] used 2p-W, G, and Inverse Gamma (IG) to study the characteristics of wind speed in Peninsular, Malaysia. G and 2p-W gave the best fit for the actual data. Authors in [8] utilized 37 distribution functions for evaluating the wind energy potential at the Güzelyurt region in Northern Cyprus. The authors concluded that Burr (4P), Wakeby, and GEV provided the best fit. Authors in [9] assessed the wind speed distribution at different locations in India using 9 PDMs. The results showed that GEV provided the best fit for the majority of the sites. Authors in [10] evaluated the wind energy potential at 17 locations in Sudan using 37 PDMs. The authors found that the Wakeby distribution function provided the best fit for the wind speed data for all locations. Authors in [11] studied the accuracy of several PDMs for modeling the wind speed distribution at different locations in Algeria. The results showed that the GEV and Gamma models were the most appropriate. Wais [12] studied the accuracy of 2p-W and 3-parameter Weibull (3p-W) in analyzing the wind speed characteristics at 3 locations in Poland. The author concluded that 3p-W gave a better fit to the wind speed data.

TABLE I. PREVIOUS STUDIES RELATED TO WIND ENERGY POTENTIAL IN LEBANON

Ref.	Location	PDMs used	Best
[13]	Klaiaat, Cedars, Daher El Baydar, Marjyoun, and Quaraoun	2p-W	-
[14]	Beirut, Sidon, and Tripoli	2p-W, G, Ln, L, LL, IG, GEV, Na, N and R	LL
[15]	Klaiaat, Les Cedres, Daher El Baydar, Quaraoun, and Marjyoun	2p-W	-
[16]	Rayak	2p-W	-
[17]	Beirut, Zahleh, Sour, and El-Abdeh	R	-
[18]	Beirut, Sidon, and Tripoli	2p-W	-
[19]	Younine, Birket Aarous, Ain ed Dabaa, Mqaybleh, Ras Ouadi Ed Darje, Kfardebian, Qaraoun, Khartoum, Iskandarounah and Beirut	2p-W	-
[20]	Abboudiye, Tal keri, Darine, Heke El Dahri, Saadine, Semmaqiye, TalAbbas and Tal El Bireh	G, 3p- G, IG, 3p-IG, LL, 3p-LL, Ln, 3p-Ln, Na, 2p-W, 3p-W	3P-W and 3p-LL
[21]	Akkar, Baalbek, Beirut, Zahlé, Baabda, Nabatieh, Tripoli, and Sidon	2p-W	-
[22]	Qlaiat, Ksara, Cedres, Dahr El Baydar, Marjayoun, Beirut, Khaldeh, Tripoli, Riaq	2p-W	-

Numerous studies have evaluated the wind energy potential in Lebanon using various distribution models as shown in Table I. Based on the findings, the most used distribution function for analyzing the wind speed distribution is 2p-W. Moreover, wind energy has been widely utilized globally to generate electricity and reduce greenhouse gas emissions. Authors in [4] conducted a techno-economic analysis for the generation of power utilizing a small-scale vertical axis wind turbine in 8 locations in Northern Cyprus. Authors in [13] assessed and analyzed the electricity that 116 wind turbines in Lebanon might produce.

The number of studies related to the analysis of wind speed characteristics using various distribution functions is limited. Furthermore, as a continuation of our study on the statistical investigation of wind characteristics in Lebanon, the present paper aims to evaluate for the first time the best-fit distribution function to describe the wind speed data at 12 locations in Lebanon. To fulfill this objective, 44 distribution functions were used to model the wind speed characteristics at the selected locations. The parameters of these distribution functions were estimated using the maximum likelihood method. Additionally, 3 goodness-of-fit test statistics were applied to determine the best-fit PDFs. The present study was performed on power produced by a wind turbine at a maximum of 10MW that may be installed in Lebanon.

II. MATERIALS AND METHODS

A. *Study Area and Data Collection*

The wind speed characteristics of 12 locations in Lebanon should be fully understood in order to evaluate the wind power potential (Figure 1). Table II lists the geographical coordinate's latitude, longitude, and elevation of the selected locations. The monthly wind speed data from 2010 to 2017 were collected from the meteorological service.

B. *Probability distribution functions*

In this study, 44 Probability Distribution Functions (PDFs) are utilized to represent the wind speed frequency distribution (Table III). The number of parameters for the selected PDFs is within the range of 1-4. The probability density functions of the selected PDFs can be found in [8-10, 23].

Fig. 1. Map showing the selected locations. © Mapa GISrael.

TABLE II. INFORMATION ON THE SELECTED LOCATIONS IN LEBANON

Location	Latitude [°N]	Longitude [°E]	Elevation [m]
Younine	34.0776	36.2750	1198
Birket Aarous	34.2911	36.1456	2766
Ain ed Dabaa	34.4431	35.8992	296
Mqaybleh	34.6460	36.3577	330
Ras Ouadi Ed Darje	34.2533	36.5775	1555
Kfardebian	34.0017	35.8349	1670
Qaraoun	33.5669	35.7193	913
Khartoum	33.4079	35.3751	305
Iskandarounah	33.1550	35.1685	53
Beirut	33.8938	35.5018	40
Khiam	33.3294	35.6148	697
Hekr El Dahri	34.6306	36.0237	10

C. *Goodness-of-Fit Test*

In this research, Kolmogorov-Smirnov (K-S) test is employed to select the best-fit DF. The description of these tests is given below [10].

$$D = \max_{1\leq i\leq n}\left(F(x_i) - \frac{i-1}{n}, \frac{i}{n} - F(x_i)\right) \qquad (1)$$

where:

$$F_n(x) = \frac{1}{n} \times (\text{Number of observations} \leq x) \qquad (2)$$

TABLE III. SELECTED DF MODELS AND NUMBER OF PARAMETERS (NP)

Model No.	Model Name	NP	Model No.	Model Name	NP
DF#1	Beta	4	DF#23	Log-Gamma	2
DF#2	Burr	3	DF#24	Logistic	2
DF#3	Burr	4	DF#25	Log-Logistic	2
DF#4	Cauchy	2	DF#26	Log-Logistic	3
DF#5	Dagum	3	DF#27	Lognormal	2
DF#6	Dagum	4	DF#28	Lognormal	3
DF#7	Erlang	2	DF#29	Log-Pearson 3	2
DF#8	Erlang	3	DF#30	Nakagami	2
DF#9	Exponential	1	DF#31	Normal	2
DF#10	Exponential	2	DF#32	Pareto	2
DF#11	Gamma	2	DF#33	Pareto 2	2
DF#12	Gamma	3	DF#34	Pearson 5	2
DF#13	Generalized Extreme Value	3	DF#35	Pearson 5	3
DF#14	Generalized Gamma	3	DF#36	Pearson 6	3
DF#15	Generalized Gamma	4	DF#37	Pearson 6	4
DF#16	Generalized Logistic	3	DF#38	Pert	3
DF#17	Generalized Pareto	3	DF#39	Rayleigh	1
DF#18	Gumbel Max.	2	DF#40	Rayleigh	2
DF#19	Gumbel Min.	2	DF#41	Reciprocal	2
DF#20	Inverse Gaussian	2	DF#42	Wakeby	5
DF#21	Inverse Gaussian	3	DF#43	Weibull	2
DF#22	Kumaraswamy	4	DF#44	Weibull	3

D. *RETScreen*

A techno-economic assessment was made for the generation of electricity using 3 wind turbines with various specifications in the selected locations using RETScreen software. RETScreen Expert is a clean energy management tool developed by the Canadian government. It is a decision support tool that is utilized to determine the potential of energy, costs, savings, greenhouse gas (GHG) emission reduction, and economic viability. The RETScreen utilizes the long-term monthly average meteorological data from the National Aeronautics and Space Administration (NASA) database as a source of meteorological information for the specific location. Recently, RETScreen has been commonly employed to explore the feasibility of grid-connected wind and PV power systems. Capacity factor, annual power production, GHG reductions, and economic indicators are determined using RETScreen [10].

III. RESULTS AND DISCUSSION

A. *Description of Wind Speed Data at a Height of 10m*

The descriptive statistics of each location are listed in Table IV. Moreover, the monthly variation of wind speed for all the selected locations is illustrated in Figure 2. It is found that the mean wind speed varied between 2.81m/s and 4.90m/s (Table IV). The values for mean speed and standard deviation (SD) indicate that the wind behavior is quite consistent. The coefficients of variation (CV), which range between 6.52 and 17.25%, are relatively low. The minimum and maximum values are recorded in Younine and Ain ed Dabaa, respectively. 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 -1.46 to -0.19, and they are also moderately low.

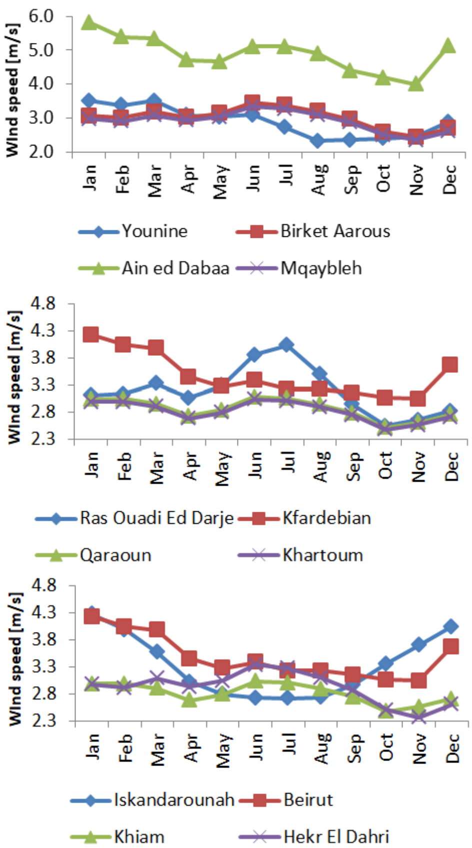

Fig. 2. Monthly average wind speed for the selected locations (2010-2017).

TABLE IV. DESCRIPTIVE WIND SPEED DATASET

Location	Mean	SD	CV	Min	Max	S	K
Younine	2.90	0.45	15.37	2.32	3.51	0.03	-1.46
Birket Aarous	3.01	0.31	10.14	2.44	3.45	-0.56	-0.26
Ain ed Dabaa	4.90	0.53	10.79	4.00	5.82	-0.15	-0.41
Mqaybleh	2.91	0.30	10.14	2.36	3.34	-0.56	-0.26
Ras Ouadi Ed Darje	3.19	0.45	14.05	2.54	4.03	0.52	-0.19
Kfardebian	3.48	0.41	11.66	3.04	4.22	0.82	-0.75
Qaraoun	2.86	0.19	6.52	2.51	3.08	-0.54	-0.81
Khartoum	2.81	0.18	6.52	2.47	3.03	-0.54	-0.81
Iskandarounah	3.32	0.57	17.25	2.72	4.27	0.42	-1.46
Beirut	3.48	0.41	11.66	3.04	4.22	0.82	-0.75
Khiam	2.81	0.18	6.52	2.47	3.03	-0.54	-0.81
Hekr El Dahri	2.91	0.30	10.14	2.36	3.34	-0.56	-0.26

B. Wind Resource Assessment at a Height of 10m

The deep assessment of wind resources using various wind speed probability functions at 12 locations in Lebanon is investigated in this paper. According to [24], selecting the best-fit DF is an essential step in determining the average wind turbine power production. Therefore, the most suitable distribution that best fits the actual wind speed is assessed using the K-S test. Figure 3 shows the statistic value of K-S for all the selected distributions. It should be noted that the best fit to the wind speed has the lowest statistic value of K-S. Based on the K-S test (Figure 3 and Table V), Wakeby distribution has the lowest value, so it is considered the best distribution function to study the average monthly wind speed characteristics for Younine, Birket Aarous, Mqaybleh, and Hekr El Dahri. Moreover, Beta is among the distributions giving better fits to investigate the distribution of wind speed at Khiam, Iskandarounah, Khartoum, and Qaraoun. Gumbel Min and Gen. Logistic provide the best fit to wind speed at Ain ed Dabaa and Ras Ouadi Ed Darje, respectively. Additionally, to explore the distribution of the average monthly wind speed at Kfardebian and Beirut, 3p-Log-Logistic is one of the distributions offering the best fit for wind speed.

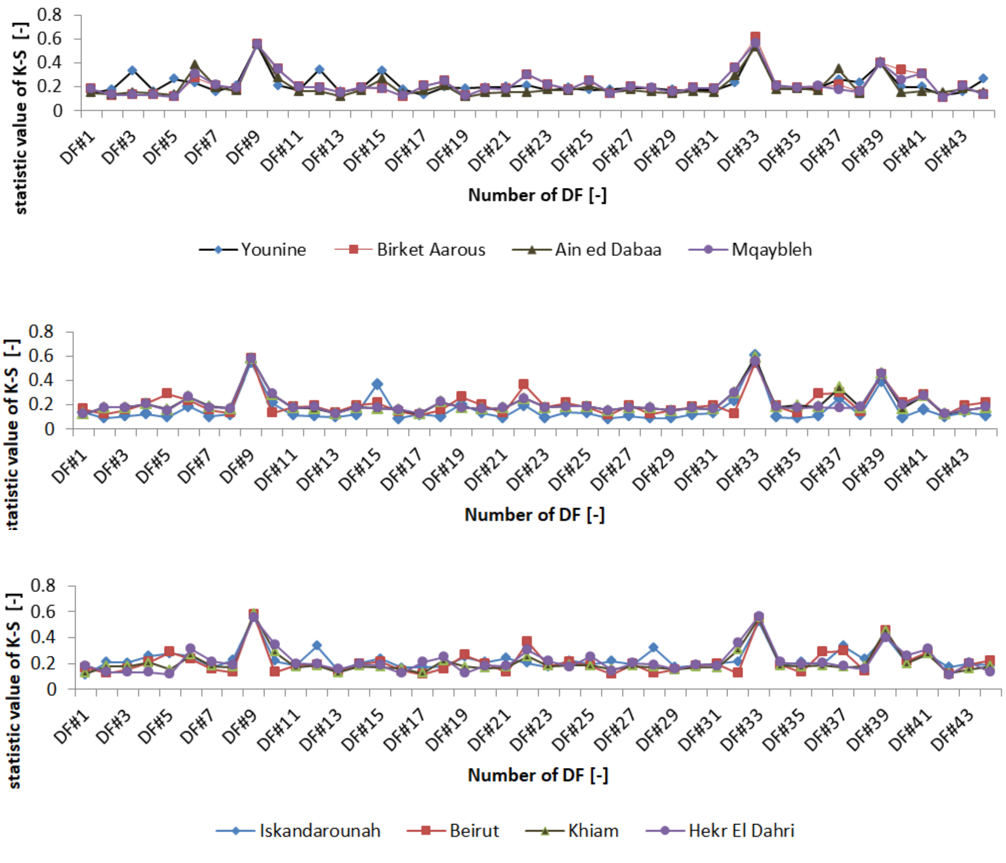

Fig. 3. Statistic and rank for various locations based on K-S value.

The essential characteristic of skewness (S), which is defined as the third central moment, measures asymmetry [11]. When the long tail is on the peak's negative (positive) side, there is a negative (positive) skew. Kurtosis (K) is a measure of tailedness, defined as the fourth central moment, if the data have higher [11]. A higher (lower) K value indicates that there are more (fewer) extreme values or fatter tails (middles) on the data curve. Table V compares the S and K values calculated using the best DFs distributions. These values are compared with widely used DFs (Weibull, Rayleigh, and GEV) to show the efficacy of the selected DF models. Some PDF figures can be seen in Figure 5.

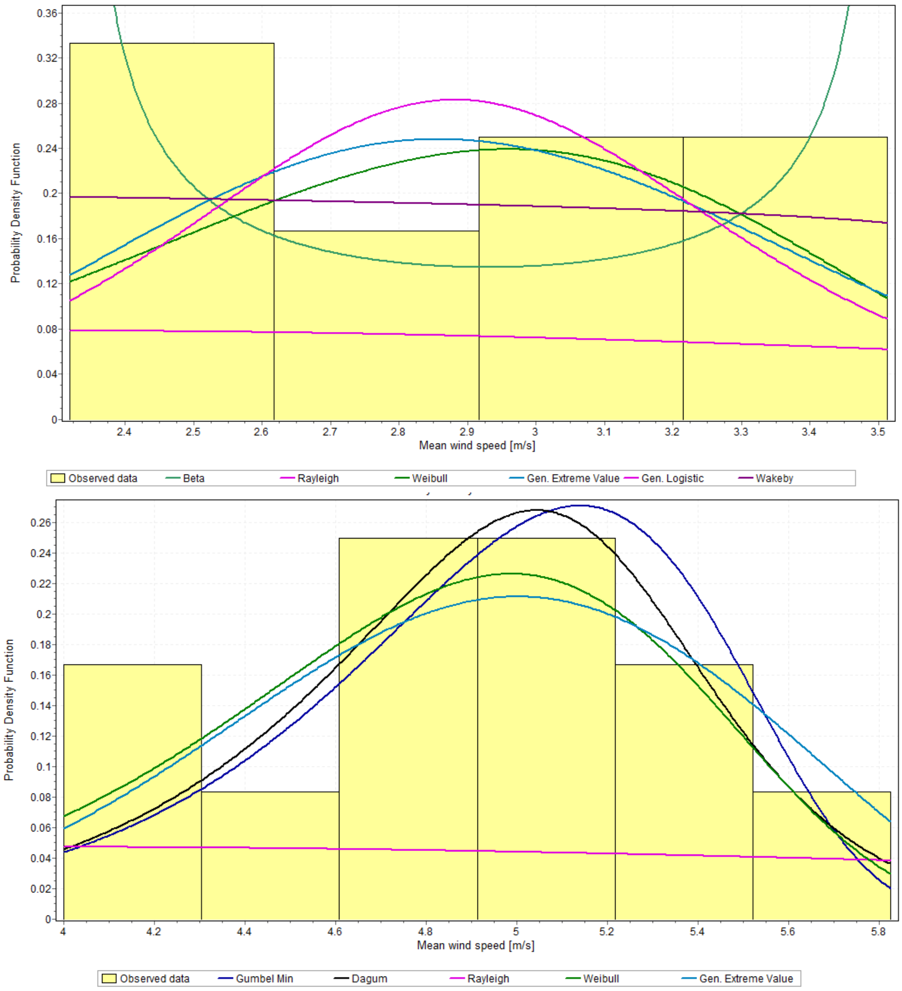

Fig. 4. Statistic and rank for various locations based on K-S values.

C. *Wind Power Density (WPD) Calculation at 10m Height*

WPD is the expected value for the potential wind energy at a specific location. WPD for a region can be calculated by:

$$\frac{P}{A} = \frac{1}{2}\rho v^3 f(v) \tag{3}$$

where P is wind power density (W), v is the wind speed (m/s), A is swept area (m^2), ρ is the air density (kg/m^3) and $f(v)$ is the PDF.

Additionally, the mean WPD can be determined by:

$$\frac{\bar{P}}{A} = \frac{1}{2}\rho \bar{v}^3 \tag{4}$$

where $\bar{P}$ is the mean wind power density and $\bar{v}$ is the mean wind speed.

In the literature, the air density value is 1.23kg/m^3. Using (4), the WPD was calculated and tabulated in Table VI. It is found that the value of WPD is within the range of 13.26 (Khiam and Khartoum) - 72.64 (Ain ed Dabaa)W/m^2. According to the wind power density classification [5], the wind energy potential in the selected locations is classified as class 1 (poor). Based on the findings, a small-scale wind turbine can use wind energy to generate electricity at the selected locations.

D. *Summary*

The findings of this study are significant for the installation of wind farms and many wind energy applications in the future. No single distribution can accurately describe the wind speed distribution based on the summary of previous scientific studies. The 2p-W is a common tool used in the assessment of wind energy for a specific region. Accordingly, the distribution function is chosen based on the available wind speed data and the utilized statistical methods. The main aim of this study is to evaluate the suitability of different probability functions for estimating wind speed characteristics at different locations in Lebanon. In this study, various distribution functions with a various number of parameters are utilized for the first time to estimate the characteristics of wind speed. Based on the findings, Wakeby, Beta, and GEV are considered effective, since they provide the best fits for the actual wind speed data for all locations. The annual values of WPD were calculated using the best distribution functions. Based on the findings, the WPD at the selected locations can be exploited using a small-scale wind turbine.

TABLE V. DESCRIPTIVE WIND SPEED DATASET

Location	DF	Parameter	Mean	V	SD	S	K	Statistic	Rank
Younine	Actual		2.90	-	0.45	0.03	-1.46	-	-
	Beta	α_1=0.38225 α_2=0.40879 a=2.32 b=3.512	2.90	0.20	0.45	0.06	-1.58	0.15	3
	Gen. Extreme Value	k=-0.25596 σ=0.4583 μ=2.7263	2.86	0.22	0.46	0.07	-0.26	0.16	5
	Gen. Pareto	k=-0.93858 σ=1.501 μ=2.1217	2.90	0.21	0.46	0.05	-1.18	0.13	1
	Rayleigh	σ=2.3107	2.90	2.29	1.51	0.63	0.25	0.40	6
	Wakeby	α=1.501 β=0.93858 γ=0 δ=0 ξ=2.1217	2.90	0.02	0.46	0.05	-1.18	0.13	2
	Weibull	α=6.5369 β=3.0351	2.83	0.26	0.51	-0.42	0.12	0.16	4
Birket Aarous	Actual		3.01	-	0.31	-0.56	-0.26	-	-
	Dagum	k=0.31321 α=33.389 β=3.2552	3.01	0.09	0.30	-0.83	1.52	0.12	2
	Gen. Extreme Value	k=-0.56484 σ=0.34662 μ=2.9426	3.01	0.11	0.32	-0.80	0.62	0.16	4
	Gen. Logistic	k=-0.14575 σ=0.17083 μ=3.0521	-	-	-	-	-	0.12	3
	Rayleigh	σ=2.4017	3.01	2.48	1.57	0.63	0.25	0.40	6
	Wakeby	α=3.8783 β=4.3227 γ=0.08856 δ=0.20184 ξ=2.1705	-	-	-	-	-	0.11	1
	Weibull	α=9.9843 β=3.1091	2.96	0.13	0.36	-0.64	0.57	0.21	5
Ain ed Dabaa	Actual		4.90	-	0.53	-0.15	-0.41	-	-
	Dagum	k=0.41765 α=25.218 β=5.2488	4.91	0.29	0.54	-0.50	1.22	0.13	3
	Gen. Extreme Value	k=-0.3961 σ=0.57967 μ=4.7359	4.90	0.30	0.55	-0.35	-0.15	0.12	2
	Gumbel Min	σ=0.41251 μ=5.1387	4.90	0.28	0.52	-1.14	2.40	0.12	1
	Rayleigh	σ=3.9101	4.90	6.56	2.56	0.63	0.25	0.41	5
	Weibull	α=10.146 β=5.0377	4.80	0.32	0.57	-0.64	0.59	0.18	4
Mqaybleh	Actual		2.91	-	0.30	-0.56	-0.26	-	-
	Dagum	k=0.31334 α=33.401 β=3.1518	2.92	0.09	0.29	-0.83	1.52	0.12	2
	Gen. Extreme Value	k=-0.56493 σ=0.33539 μ=2.8494	2.91	0.10	0.31	-0.80	0.62	0.16	4
	Gen. Logistic	k=-0.14579 σ=0.16529 μ=2.9553	-	-	-	-	-	0.12	3
	Rayleigh	σ=2.3256	2.91	2.32	1.52	0.63	0.25	0.40	6
	Wakeby	α=3.7758 β=4.3574 γ=0.08812 δ=0.19228 ξ=2.1008	-	-	-	-	-	0.11	1
	Weibull	α=9.9875 β=3.0105	2.86	0.12	0.34	-0.64	0.57	0.21	5
Ras Ouadi Ed Darje	Actual		3.19	-	0.45	0.52	-0.19	-	-
	Burr	k=0.73124 α=14.691 β=3.0386	3.19	0.22	0.47	1.19	4.69	0.09	3
	Gen. Extreme Value	k=-0.07482 σ=0.40347 μ=2.9829	3.19	0.22	0.47	0.75	0.88	0.10	4
	Gen. Logistic	k=0.12273 σ=0.25573 μ=3.1353	-	-	-	-	-	0.09	1
	Log-Logistic (3P)	α=5.5837 β=1.3577 γ=1.7727	3.20	0.25	0.50	2.04	15.48	0.09	2
	Rayleigh	σ=2.5435	3.19	2.78	1.67	0.63	0.25	0.39	6
	Weibull	α=8.2109 β=3.2847	3.10	0.20	0.45	-0.55	0.36	0.14	5
Kfardebian	Actual		3.48	-	0.41	0.82	-0.75	-	-
	Gen. Extreme Value	k=0.14286 σ=0.28756 μ=3.2647	3.48	0.22	0.46	-2.43	14.54	0.14	4
	Gen. Pareto	k=-0.16182 σ=0.58192 μ=2.9767	3.48	0.19	0.44	1.30	1.69	0.12	2
	Log-Logistic (3P)	α=1.4625 β=0.30081 γ=3.0211	3.79	-	-	-	-	0.12	1
	Rayleigh	σ=2.7747	3.48	3.30	1.82	0.63	0.25	0.45	6
	Wakeby	α=0.58192 β=0.16182 γ=0 δ=0 ξ=2.9767	3.48	0.19	0.44	1.30	1.69	0.12	3
	Weibull	α=9.3692 β=3.5804	3.40	0.19	0.43	-0.61	0.50	0.20	5
Qaraoun	Actual		2.86	-	0.19	-0.54	-0.81	-	-
	Beta	α_1=0.7163 α_2=0.45516 a=2.514 b=3.077	2.86	0.03	0.19	-0.42	-1.23	0.12	1
	Gen. Extreme Value	k=-0.61707 σ=0.21637 μ=2.8216	2.86	0.04	0.20	-0.94	0.98	0.13	4
	Gen. Pareto	k=-1.8226 σ=1.1791 μ=2.4405	2.86	0.04	0.19	-0.55	-0.97	0.13	2
	Rayleigh	σ=2.2806	2.86	2.23	1.49	0.63	0.25	0.46	6
	Wakeby	α=1.1791 β=1.8226 γ=0 δ=0 ξ=2.4405	2.86	0.04	0.19	-0.55	-0.97	0.13	3
	Weibull	α=15.456 β=2.9261	2.83	0.05	0.22	-0.80	1.03	0.16	5
Khartoum	Actual		2.81	-	0.18	-0.54	-0.81	-	-
	Beta	α_1=0.71911 α_2=0.45588 a=2.473 b=3.028	2.81	0.03	0.18	-0.43	-1.23	0.13	1
	Gen. Extreme Value	k=-0.61795 σ=0.21306 μ=2.7767	2.81	0.04	0.20	-0.94	0.99	0.13	4
	Gen. Pareto	k=-1.825 σ=1.1626 μ=2.4011	2.81	0.04	0.19	-0.55	-0.97	0.13	3
	Rayleigh	σ=2.2442	2.81	2.16	1.47	0.63	0.25	0.46	6
	Wakeby	α=1.8650E+5 β=77661.0 γ=1.1613 δ=-1.8236 ξ=0	-	-	-	-	-	0.13	2
	Weibull	α=15.442 β=2.8795	2.78	0.05	0.22	-0.80	1.03	0.16	5
Iskandarounah	Actual		3.32	-	0.57	0.42	-1.46	-	-
	Beta	α_1=0.28827 α_2=0.45156 a=2.719 b=4.27	3.32	0.33	0.57	0.44	-1.40	0.11	1
	Gen. Extreme Value	k=-0.00205 σ=0.48503 μ=3.0443	3.32	0.38	0.62	1.13	2.34	0.15	2
	Erlang	m=33 β=0.09894	3.27	0.32	0.57	0.35	0.18	0.17	3
	Weibull	α=5.9937 β=3.4797	3.23	0.39	0.63	-0.37	0.03	0.20	4
	Rayleigh	σ=2.6516	3.32	3.02	1.74	0.63	0.25	0.41	5

Location	DF	Parameter	Mean	V	SD	S	K	Statistic	Rank
Beirut	Actual		3.48	-	0.41	0.82	-0.75	-	-
	Gen. Extreme Value	$k=0.14286$ $\sigma=0.28756$ $\mu=3.2647$	3.48	0.22	0.46	-2.43	14.54	0.14	4
	Gen. Pareto	$k=-0.16182$ $\sigma=0.58192$ $\mu=2.9767$	3.48	0.19	0.44	1.30	1.69	0.12	2
	Log-Logistic (3P)	$\alpha=1.4625$ $\beta=0.30081$ $\gamma=3.0211$	3.79	-	-	-	-	0.12	1
	Rayleigh	$\sigma=2.7747$	3.48	3.30	1.82	0.63	0.25	0.45	6
	Wakeby	$\alpha=0.58192$ $\beta=0.16182$ $\gamma=0$ $\delta=0$ $\xi=2.9767$	3.48	0.19	0.44	1.30	1.69	0.12	3
	Weibull	$\alpha=9.3692$ $\beta=3.5804$	3.40	0.19	0.43	-0.61	0.50	0.20	5
Khiam	Actual		2.81	-	0.18	-0.54	-0.81	-	-
	Beta	$\alpha_1=0.71911$ $\alpha_2=0.45588$ $a=2.473$ $b=3.028$	2.81	0.03	0.18	-0.43	-1.23	0.13	1
	Gen. Extreme Value	$k=-0.61795$ $\sigma=0.21306$ $\mu=2.7767$	2.81	0.04	0.20	-0.94	0.99	0.13	4
	Gen. Pareto	$k=-1.825$ $\sigma=1.1626$ $\mu=2.4011$	2.81	0.04	0.19	-0.55	-0.97	0.13	3
	Rayleigh	$\sigma=2.2442$	2.81	2.16	1.47	0.63	0.25	0.46	6
	Wakeby	$\alpha=1.8650E+5$ $\beta=77661.0$ $\gamma=1.1613$ $\delta=-1.8236$ $\xi=0$	-	-	-	-	-	0.13	2
	Weibull	$\alpha=15.442$ $\beta=2.8795$	2.78	0.05	0.22	-0.80	1.03	0.16	5
Hekr El Dahri	Actual		2.91	-	0.30	-0.56	-0.26	-	-
	Dagum	$k=0.31334$ $\alpha=33.401$ $\beta=3.1518$	2.92	0.09	0.29	-0.83	1.52	0.12	2
	Gen. Extreme Value	$k=-0.56493$ $\sigma=0.33539$ $\mu=2.8494$	2.91	0.10	0.31	-0.80	0.62	0.16	4
	Gen. Logistic	$k=-0.14579$ $\sigma=0.16529$ $\mu=2.9553$	-	-	-	-	-	0.12	3
	Rayleigh	$\sigma=2.3256$	2.91	2.32	1.52	0.63	0.25	0.40	6
	Wakeby	$\alpha=3.7758$ $\beta=4.3574$ $\gamma=0.08812$ $\delta=0.19228$ $\xi=2.1008$	-	-	-	-	-	0.11	1
	Weibull	$\alpha=9.9875$ $\beta=3.0105$	2.86	0.12	0.34	-0.64	0.57	0.21	5

TABLE VI. WPD (W/m^2) VALUE FOR EACH LOCATION (L)

L	DF	WPD	L	DF	WPD
Younine	Actual	14.94	Qaraoun	Actual	14.36
	Beta	14.94		Beta	14.36
	Gen. Extreme Value	14.34		Gen. Extreme Value	14.36
	Gen. Pareto	14.94		Gen. Pareto	14.36
	Rayleigh	14.93		Rayleigh	14.36
	Wakeby	14.94		Wakeby	14.36
	Weibull	13.92		Weibull	13.91
Birket Aarous	Actual	16.77	Khartoum	Actual	13.69
	Dagum	16.82		Beta	13.69
	Gen. Extreme Value	16.77		Gen. Extreme Value	13.69
	Gen. Logistic	-		Gen. Pareto	13.69
	Rayleigh	16.77		Rayleigh	13.69
	Wakeby	-		Wakeby	-
	Weibull	15.91		Weibull	13.26
Ain ed Dabaa	Actual	72.40	Iskandarounah	Actual	22.57
	Dagum	72.64		Beta	22.57
	Gen. Extreme Value	72.38		Gen. Extreme Value	22.57
	Gumbel Min	72.38		Erlang	21.41
	Rayleigh	72.38		Weibull	20.69
	Weibull	67.83		Rayleigh	22.57
Mqaybleh	Actual	15.23	Beirut	Actual	25.87
	Dagum	15.27		Gen. Extreme Value	25.87
	Gen. Extreme Value	15.23		Gen. Pareto	25.87
	Gen. Logistic	-		Log-Logistic (3P)	33.54
	Rayleigh	15.23		Rayleigh	25.87
	Wakeby	-		Wakeby	25.87
	Weibull	14.45		Weibull	24.10
Ras Ouadi Ed Darje	Actual	19.93	Khiam	Actual	13.69
	Burr	19.93		Beta	13.69
	Gen. Extreme Value	19.92		Gen. Extreme Value	13.69
	Gen. Logistic	0.00		Gen. Pareto	13.69
	Log-Logistic (3P)	20.24		Rayleigh	13.69
	Rayleigh	19.92		Wakeby	-
	Weibull	18.27		Weibull	13.26
Kfardebian	Actual	25.87	Hekr El Dahri	Actual	15.23
	Gen. Extreme Value	25.87		Dagum	15.27
	Gen. Pareto	25.87		Gen. Extreme Value	15.23
	Log-Logistic (3P)	33.54		Gen. Logistic	-
	Rayleigh	25.87		Rayleigh	15.23
	Wakeby	25.87		Wakeby	-
	Weibull	24.10		Weibull	14.45

E. Techno-Economic Feasibility

This section aims to encourage governments to develop wind farms to achieve sustainable energy infrastructures, particularly in developing countries like Lebanon. The investigation of changing tariffs influencing the wind energy market in Lebanon is discussed by proposing 9 scenarios as shown in Table VII. Moreover, the capital, operation, and maintenance costs associated with turbines can be assumed based on previous scientific studies [25]. In this study, the technical viability of 3 wind turbine models (WTMs) is evaluated. Generally, wind farm performance in terms of wind power production and capacity factor is affected by the geographic location and wind speed distribution. Thus, the Electricity Exported to the Grid (EEG) and the Capacity Factor (CF) were estimated for Younine (it has the lowest monthly wind speed) and Ain ed Dabaa (it has the maximum monthly wind speed) for the selected location. The mean EEG monthly value of for all the proposed models is shown in Figure 5. It is observed that the EEG is within the range of 604.38-3999.537MWh. The lowest value of EEG is recorded at Younine using WTM#1, while the highest value is recorded at Ain ed Dabaa using WTM#. It is noticed that WTM#2 produced the highest EEG. Moreover, for Younine location, the annual value of EEG of the proposed system is 14057.47MWh for WTM#1, 17152.08 for WTM#2, and 18268.02 for WTM#3. For Ain ed Dabaa, the annual value of EEG of the proposed system is 32030.96, 38252.56, and 37642.62MWh for WTM#1, 2, and 3, respectively. The annual CF was calculated for all wind turbines as shown in Figure 6. It is observed that the annual CF varied from 16.05% to 43.67%. The results demonstrate that among all wind turbines, the capacity factor of WTM#2 was the highest. These results can be supported by previous scientific studies. For instance, authors in [26] found that the CF values of the proposed wind farms varied from 9.79% to 51.93% and authors in [27] found that the CF values of the proposed farms were within the range of 5-42%. Authors in [28] found that the proposed farm projects in Pakistan have a CF ranging from 19% to 34%. The economic analysis is essential when one wants to know if the project is economically viable and sustainable. Thus, the techno-economic feasibility of the proposed projects was evaluated using RETScreen for different Scenarios as shown in Table VII. The used financial parameters include inflation rate (2.9%), discount rate (5.4%), reinvestment rate (9%), project life (25 years), debt ratio (70%), debt interest rate (8.9%), and debt payments (15 years) as input parameters, assumed based on previous studies. Based on these input parameters, NPV, ALCS, SP, EP, LCOE, and the internal rate of return (IRR) were estimated using RETScreen software.

TABLE VII. THE DEVELOPEPD THREE SCENARIOS TO SHOW THE IMPACT OF POLICY CHANGES ON THE FINANCIAL VIABILITY OF WIND POWER PLANTS IN LEBANON

Input	**Scenario A1**	**Scenario B1**	**Scenario C1**
Capacity	10MW		
Turbine model#1	AAER-A-2000 - 100		
Project Life	20 years		
Array Losses	4%		
Airfoil Losses	2%		
Miscellaneous Losses	6%		
Availability Factor	98%		
Electricity Export Cost [US Cents]	6.75	10.45	13.52
Input	**Scenario A1**	**Scenario B1**	**Scenario C1**
Capacity	10MW		
Turbine model#2	DW 52 - 500kW - 75m		
Project Life	20 years		
Array Losses	4%		
Airfoil Losses	2%		
Miscellaneous Losses	6%		
Availability Factor	98%		
Electricity Export Cost [US Cents]	6.75	10.45	13.52
Input	**Scenario A1**	**Scenario B1**	**Scenario C1**
Capacity	10MW		
Turbine model#3	W2E100/2000 - 100m		
Project Life	20 years		
Array Losses	4%		
Airfoil Losses	2%		
Miscellaneous Losses	6%		
Availability Factor	98%		
Electricity Export Cost [US Cents]	6.75	10.45	13.52

The NPV was determined for each location and each value of Electricity Export Rate (EER) and is illustrated in Figure 7. It is found that the value of NPV for each value of EER is positive, which indicated that the project is potentially feasible [29, 30]. Besides, it is noticed that there is a strong correlation between NPV and EER. Moreover, IRR is estimated to evaluate the economic viability of the project. The IRR provides the true return of interest over the life of the project. The results showed that increasing rate of exporting electricity led to an increase in the value of IRR. In addition, it is observed that the value of IRR of all locations is higher than the required rate of return of the project. Furthermore, ALCS is calculated by using NPV, discount rate, and project lifetime. It is found that ALCS is within the range of 67438-6790429 USD/year for all proposed projects.

According to previous scientific studies, the economic viability of a project is estimated by determining the payback period, which indicates the time required to recover the initial investments, with net positive income. Figure 7 shows the payback period including EP and SP for all selected locations based on various scenarios. It is found that the EP and SP are within the range of 1.1-16.1 and 2.9-15.7 years, respectively. WTM#2 has the lowest value of EP and SP compared to other models. The results reveal that the increase in EER will lead to a decrease in EP and SP. Moreover, the Electricity Production Cost (EPC) is found within the range of 0.038-0.104-0.038 USD/kWh. The EPC is lower compared to previous studies [25, 31] and the electricity tariff in the country [19].

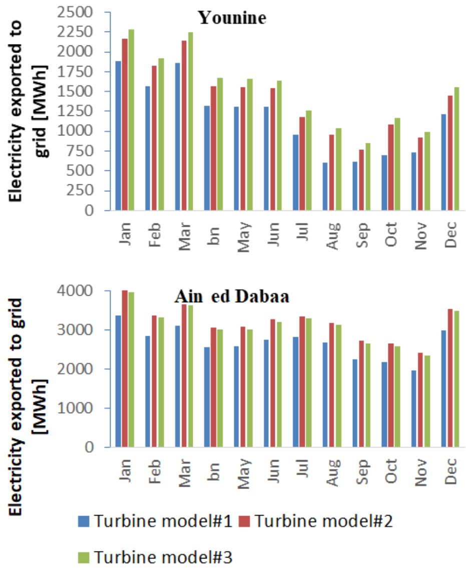

Fig. 5. Monthly average electric production.

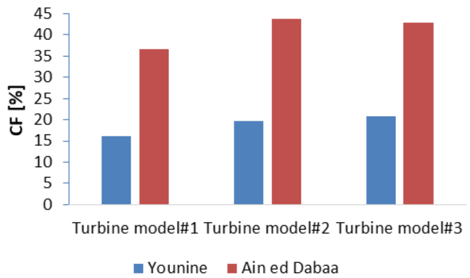

Fig. 6. Annual CF.

F. *Climate Co-benefit Assessment*

The climate co-benefits in terms of GHG emission reduction were calculated using RETScreen software for each location and are listed in Table VIII. The results indicate that a large amount of CO_2 emissions can be avoided by implementing the developed wind project in each location. It is noticed that the Wind Farm (WF) using WTM#3 (WF-WTM#3) has the highest amount of CO_2 emission reductions. The total amount of CO_2 emissions reduction for each location is determined based on the electricity generated annually [32].

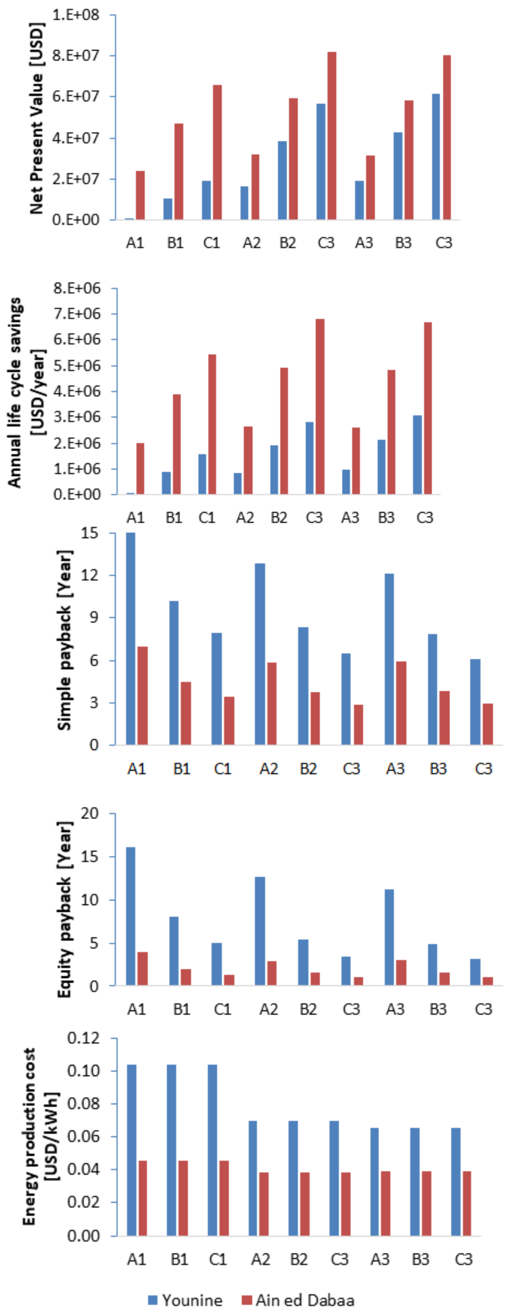

Fig. 7. Economic performance of the developed wind project in Younine and Ain ed Dabaa.

TABLE VIII. NET ANNUAL REDUCTION OF GHG EMISSIONS (tCO_2)

Location	WF-WTM#1	WF-WTM#2	WF-WTM#3
Younine	9244.15	11279.21	12013.05
Ain ed Dabaa	23142.37	27637.47	27196.79

IV. CONCLUSION

In this paper, the wind speed distribution and the potential of wind energy were assessed at 12 locations in Lebanon. For wind speed distribution, 44 distribution models were utilized to analyze the wind speed characteristics in the selected locations. The results demonstrated that Wakeby and Beta distribution functions gave the best fit to the actual data for most locations. Moreover, a 10MW wind farm's viability was examined for the climate conditions of various locations in Lebanon using RETScreen software. The results indicated that the proposed wind farms are feasible both technically and economically. Ain ed Dabaa is the most suitable location for installing a wind farm in the future.

The developed projects provide a significant insight into the economic feasibility of the project for all locations. Wind energy exploitation is able to solve the chronic problem of the lack of electricity and reduce the electricity import cost in Lebanon.

REFERENCES

[1] E. A. Al-Ammar, N. H. Malik, and M. Usman, "Application of using Hybrid Renewable Energy in Saudi Arabia," *Engineering, Technology & Applied Science Research*, vol. 1, no. 4, pp. 84–89, Aug. 2011, https://doi.org/10.48084/etasr.33.

[2] B. Memon, M. H. Baloch, A. H. Memon, S. H. Qazi, R. Haider, and D. Ishak, "Assessment of Wind Power Potential Based on Raleigh Distribution Model: An Experimental Investigation for Coastal Zone," *Engineering, Technology & Applied Science Research*, vol. 9, no. 1, pp. 3721–3725, Feb. 2019, https://doi.org/10.48084/etasr.2381.

[3] T. B. M. J. Ouarda *et al.*, "Probability distributions of wind speed in the UAE," *Energy Conversion and Management*, vol. 93, pp. 414–434, Mar. 2015, https://doi.org/10.1016/j.enconman.2015.01.036.

[4] M. M. Alayat, Y. Kassem, and H. Camur, "Assessment of Wind Energy Potential as a Power Generation Source: A Case Study of Eight Selected Locations in Northern Cyprus," *Energies*, vol. 11, no. 10, Oct. 2018, Art. no. 2697, https://doi.org/10.3390/en11102697.

[5] M. A. Khan, H. Camur, and Y. Kassem, "Modeling predictive assessment of wind energy potential as a power generation sources at some selected locations in Pakistan," *Modeling Earth Systems and Environment*, vol. 5, no. 2, pp. 555–569, Jun. 2019, https://doi.org/10.1007/s40808-018-0546-6.

[6] O. Alavi, K. Mohammadi, and A. Mostafaeipour, "Evaluating the suitability of wind speed probability distribution models: A case of study of east and southeast parts of Iran," *Energy Conversion and Management*, vol. 119, pp. 101–108, Jul. 2016, https://doi.org/10.1016/j.enconman.2016.04.039.

[7] N. Masseran, "Evaluating wind power density models and their statistical properties," *Energy*, vol. 84, pp. 533–541, May 2015, https://doi.org/10.1016/j.energy.2015.03.018.

[8] Y. Kassem, H. Gokcekus, A. Iravanian, and R. Gokcekus, "Predictive suitability of renewable energy for desalination plants: the case of guzelyurt region in northern Cyprus," *Modeling Earth Systems and Environment*, vol. 8, no. 3, pp. 3657–3677, Sep. 2022, https://doi.org/10.1007/s40808-021-01315-0.

[9] N. Natarajan, M. Vasudevan, and S. Rehman, "Evaluation of suitability of wind speed probability distribution models: a case study from Tamil Nadu, India," *Environmental Science and Pollution Research*, vol. 29, no. 57, pp. 85855–85868, Dec. 2022, https://doi.org/10.1007/s11356-021-14315-5.

[10] Y. Kassem and M. H. A. Abdalla, "Modeling predictive suitability to identify the potential of wind and solar energy as a driver of sustainable development in the Red Sea state, Sudan," *Environmental Science and Pollution Research*, vol. 29, no. 29, pp. 44233–44254, Jun. 2022, https://doi.org/10.1007/s11356-022-19062-9.

[11] N. Aries, S. M. Boudia, and H. Ounis, "Deep assessment of wind speed distribution models: A case study of four sites in Algeria," *Energy Conversion and Management*, vol. 155, pp. 78–90, Jan. 2018, https://doi.org/10.1016/j.enconman.2017.10.082.

[12] P. Wais, "Two and three-parameter Weibull distribution in available wind power analysis," *Renewable Energy*, vol. 103, pp. 15–29, Apr. 2017, https://doi.org/10.1016/j.renene.2016.10.041.

[13] G. Al Zohbi, P. Hendrick, and P. Bouillard, "Wind characteristics and wind energy potential analysis in five sites in Lebanon," *International Journal of Hydrogen Energy*, vol. 40, no. 44, pp. 15311–15319, Nov. 2015, https://doi.org/10.1016/j.ijhydene.2015.04.115.

[14] Y. Kassem, H. Gokcekus, and M. Zeitoun, "Modeling of techno-economic assessment on wind energy potential at three selected coastal regions in Lebanon," *Modeling Earth Systems and Environment*, vol. 5, no. 3, pp. 1037–1049, Sep. 2019, https://doi.org/10.1007/s40808-019-00589-9.

[15] G. Al Zohbi, P. Hendrick, and P. Bouillard, "Assessment of wind energy potential in Lebanon," *Research in Marine Sciences*, vol. 3, no. 4, pp. 401–414, 2018.

[16] Y. Kassem, H. Gokcekus, and W. Janbein, "Predictive model and assessment of the potential for wind and solar power in Rayak region, Lebanon," *Modeling Earth Systems and Environment*, vol. 7, no. 3, pp. 1475–1502, Sep. 2021, https://doi.org/10.1007/s40808-020-00866-y.

[17] M. Elkhoury, Z. Nakad, and S. Shatila, "The Assessment of Wind Power for Electricity Generation in Lebanon," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 32, no. 13, pp. 1236–1247, Apr. 2010, https://doi.org/10.1080/15567030802706754.

[18] Y. Kassem, M. M. Mizran, and S. M. Alsayas, "Evaluation of the Wind Energy Potential in Lebanon's Coastal Regions using Weibull Distribution Function," *International Journal of Engineering Research and Technology*, vol. 12, no. 6, pp. 784–792, 2019.

[19] Y. Kassem, H. Gokcekus, H. Camur, and A. H. A. Abdelnaby, "Wind Power Generation Scenarios in Lebanon," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9551–9559, Dec. 2022, https://doi.org/10.48084/etasr.5258.

[20] H. Gokcekus, Y. Kassem, and M. A. Hassan, "Evaluation of Wind Potential at Eight Selected Locations in Northern Lebanon Using Open Source Data," *International Journal of Applied Engineering Research*, vol. 14, no. 11, pp. 2789–2794, 2019.

[21] Y. Kassem, H. Camur, M. A. H. A. Abdalla, B. D. Erdem, and A. M. R. Al-ani, "Evaluation of wind energy potential for different regions in Lebanon based on NASA wind speed database," *IOP Conference Series: Earth and Environmental Science*, vol. 926, no. 1, Aug. 2021, Art. no. 012093, https://doi.org/10.1088/1755-1315/926/1/012093.

[22] B. Assaf and G. Zihri, "Reducing blackouts via wind power, a sparse grid case in Lebanon," *Lebanese Science Journal*, vol. 18, no. 1, pp. 106–121, Jun. 2017, https://doi.org/10.22453/LSJ-018.1.106121.

[23] "Visit Mathwave.com - EasyFit - Distribution Fitting Software." https://links.giveawayoftheday.com/mathwave.com.

[24] C. Jung, D. Schindler, J. Laible, and A. Buchholz, "Introducing a system of wind speed distributions for modeling properties of wind speed regimes around the world," *Energy Conversion and Management*, vol. 144, pp. 181–192, Jul. 2017, https://doi.org/10.1016/j.enconman.2017.04.044.

[25] S. O. Fadlallah, D. E. Benhadji Serradj, and D. M. Sedzro, "Is this the right time for Sudan to replace diesel-powered generator systems with wind turbines?," *Renewable Energy*, vol. 180, pp. 40–54, Dec. 2021, https://doi.org/10.1016/j.renene.2021.08.018.

[26] B. Bilal, K. H. Adjallah, K. Yetilmezsoy, M. Bahramian, and E. Kiyan, "Determination of wind potential characteristics and techno-economic feasibility analysis of wind turbines for Northwest Africa," *Energy*, vol. 218, Mar. 2021, Art. no. 119558, https://doi.org/10.1016/j.energy.2020.119558.

[27] A. S. Khraiwish Dalabeeh, "Techno-economic analysis of wind power generation for selected locations in Jordan," *Renewable Energy*, vol. 101, pp. 1369–1378, Feb. 2017, https://doi.org/10.1016/j.renene.2016.10.003.

[28] M. Adnan, J. Ahmad, S. F. Ali, and M. Imran, "A techno-economic analysis for power generation through wind energy: A case study of Pakistan," *Energy Reports*, vol. 7, pp. 1424–1443, Nov. 2021, https://doi.org/10.1016/j.egyr.2021.02.068.

[29] M. M. Riaz and B. H. Khan, "Techno-Economic Analysis and Planning for the Development of Large Scale Offshore Wind Farm in India," *International Journal of Renewable Energy Development*, vol. 10, no. 2, pp. 257–268, May 2021, https://doi.org/10.14710/ijred.2021.34029.

[30] A. M. H. A. Khajah and S. P. Philbin, "Techno-Economic Analysis and Modelling of the Feasibility of Wind Energy in Kuwait," *Clean Technologies*, vol. 4, no. 1, pp. 14–34, Mar. 2022, https://doi.org/10.3390/cleantechnol4010002.

[31] K. A. Adeyeye, N. Ijumba, and J. S. Colton, "A Techno-Economic Model for Wind Energy Costs Analysis for Low Wind Speed Areas," *Processes*, vol. 9, no. 8, Aug. 2021, Art. no. 1463, https://doi.org/10.3390/pr9081463.

[32] F. Leon and A. Ramos, "An Assessment of Renewable Energies in a Seawater Desalination Plant with Reverse Osmosis Membranes," *Membranes*, vol. 11, no. 11, Nov. 2021, Art. no. 883, https://doi.org/10.3390/membranes11110883.