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RESEARCH ARTICLE

Techno-Economic Analysis for Wind Energy Projects: A Comparative Study With Three Wind Turbines Based on Real-Site Data

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ABSTRACT

The majority of the techno-economic studies in literature utilize the meteorological stations data or satellite data which generally underestimate the wind energy production potential. This leads to a low reliability in economic decisions. This study is unique in the sense that it uses real-site data which comes from an operating wind power plant and derives economical results based on this real-site data. The current data were obtained from 12 wind locations in Bursa, Turkey, at 10-min intervals, at 100-m hub height over 2 years. Weibull, turbulence, and power density parameters were calculated. Wind energy investigations were performed based on three alternative wind turbine types. High scale parameters (7.6-9.1) were observed in all locations. Low shape parameters (1.3-2.9) and high standard deviation resulted in high turbulence index (0.54 on average). Monthly mean wind speed varied between 4.6 and 11.7 m/s. The financial calculations show that the lowest levelized cost of energy (LCOE) belongs to the alternative with Goldwind turbine alternative. The models used for investment decision in this study have both macro- and microlevel implications. The political actors can require site-specific measurements from the wind project applications while economic actors should reshape their decision-making policies based on site-specific site measurements and alternative economic analysis such as LCOE.

Index Terms—Electricity generation, LCOE, techno-economic analysis, wind turbine

I. INTRODUCTION

In order to bring climate change under control, increasing the efficient renewable energy systems is essential [1]. Uncertainty of global climate models has the most substantial impact on projecting renewable energy generation potential [2].

For wind energy projects, the main determinants in a feasibility study are the wind energy technical potential and the economic assumptions. The wind energy potential can be estimated by site-specific measurements, correlation with the nearest meteorological masts, and satellite data.

While in practice, several project developers measure site-specific data by installing wind measurement masts, the academicians usually make their calculations based on the correlation with the existing meteorological stations or satellite-based data. The data except on-site measurements usually underestimate the potential and this can lead to poor decisions. This study will be using real-site data from an existing operational wind power plant in the Bursa region. This power plant has 12 wind turbines (WTs) and each turbine's specific wind data is recorded in the power plant's SCADA system. The data used in this study are obtained for every 10 min during 2 years from these 12 locations. The first step of the analysis is the wind potential calculation. Following the energy analysis, an economical assessment is done. The financial costs and cost of electricity generation of three different WT models with the same capacity were calculated and the best turbine is selected under different models.

The main goals of this study are as follows:

1. to provide a road map for wind energy investment decisions;
2. to analyze the influence of the annual, monthly, and daily (daytime (DT)/nighttime (NT)) characteristics of the wind speed and power potential;
3. to evaluate the influence of the Weibull parameters and turbulence index (TI);

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4. to calculate the electricity generation amount and the capacity factors; and
5. to conduct a feasibility analysis using three commercial WTs.

In consequence, the contribution of this work is the development of an in-depth techno-economic study of the onshore wind farms in Bursa, Turkey. This study also shows the unreliability of studies conducted with meteorological data by comparing the results of this study which is based on real on-site and 100 m height measured data with the study conducted for the same region with meteorological data.

The study is composed of six sections including this introduction section. The following part is the literature review where a summary of world and local studies are summarized. The study continues with a brief info about Turkey's wind sector. In the fourth section, materials and methods were evaluated followed by the results of the conducted analysis. The last part is the conclusion where the policy implications are discussed.

II. LITERATURE REVIEW

So far, several local wind potential energy studies have been performed. However, most of them are restricted to the determination of mean wind speed (MWS) and some statistical characteristics like annual or monthly Weibull parameters [3].

For Northwest Africa, Mexico, South Korea, Japan, Havana and Brazil, several studies have been conducted mostly using meteorological data. The variations of the wind potential in Northwest Africa are investigated for the feasibility analysis of the energy production in a study. The research was the first to appraise the spatiotemporal influence of wind energy production in Mauritania [3]. In another study, the small WT energy production of Mexico Metropolitan Area is investigated using 3 years' data of the meteorological system. A methodology is developed for 18 locations. Two WT and location models provided positive net present values (NPVs) [4]. Similar to this study, ten potential onshore wind farm sites for South Korea have been identified using the data obtained from meteorological systems at 10 m height. Appropriate type of WTs has been recommended for each site [5]. The wind speed data are analyzed for four populous cities of the Turkish Republic of Northern Cyprus. The data were collected on a monthly basis for the year 2018 and then each city was compared in terms of highest, lowest, and annual average wind speed. They found the system economically viable [6]. Based on the Japanese 55-year Reanalysis dataset, the spatiotemporal variations of wind resources were analyzed in the South China Sea [7]. The wind energy potential in Havana at 10 and 30 m is investigated in another study by obtaining the statistical wind speed, the wind rose, and the power density [8]. Annual energy produced (AEP) is estimated in a study in the northeast region of Brazil. Optimal locations for a hypothetical wind farm with 50 WTs are obtained to predict the power generation [9].

Main Points

- Annual, monthly, and daily wind parameters are evaluated for a real wind power plant.
- Data are obtained at 10-min intervals for 2 years at 100 m height.
- Three commercial wind turbines are compared for 12 locations.
- Site-specific data are found to be more accurate instead of meteorological station data.
- Cost values showed to be the main determinant for the turbine selection for Turkey.

For Turkey, several studies can be mentioned. Wind power potential for the 1980–2013 period over Turkey was studied in a study using the hourly wind speed data obtained from the Turkish State Meteorological Service. Highest hourly average wind speed values equal or larger than 3.80 m/s were found in Gökçeada, Çanakkale, and Mardin [10]. Other studies conducted in Bursa, Turkey, were based on the Nasa Prediction of Worldwide Energy Resource. The average wind speed is calculated as 3.88 m/s for a rural village. Different turbine models have been studied and an optimal hybrid design was suggested using hydro and solar resources [11] and [12]. The literature review is listed in Table I [3-12].

As seen in Table I, majority of the studies in the literature are conducted using the data obtained from meteorological stations. The wind assessment report of the Karacabey Wind Project whose data are used in this study states that meteorological stations have shown decreasing trend in MWSs [13]. Because the data measured in the meteorological stations are usually at low heights and they are far from being representative of 100 m of hub height. Unfortunately, the locations of the stations are usually in the city centers where surrounding buildings create an obstacle for the wind flow and the wind speed could be measured as lower than the real figure.

For the case of Bursa, there are 29 meteorological stations [14]. A study was conducted using the meteorological data of 77 locations in Turkey. They calculated the average wind speed of Bursa, Turkey, as 2.9 m/s [10]. Homer software also gives low wind speed values for the Bursa site, that is, 3.88 m/s as in [11] and [12]. This is far lower than the real values which is measured from the real data of this study. According to this current study, the average wind speed is obtained as 7.4 m/s for a rural area of Bursa. Therefore, in order to calculate the wind power potential, wind speed data together with the other parameters obtained from real sites should be used instead of meteorological data or satellite data. Furthermore, no comprehensive study of wind power potential has been conducted in the Northwest of Turkey so far using real site data, which is the region with the highest wind potential in Turkey. It is clear that there is an important gap in literature in using real site data at 100 m height.

III. WIND POWER SECTOR IN TURKEY

The Republic of Turkiye has a big wind potential of around 47 849 MW [15]. The aim of Turkey is to reach 20 000 MW installed wind energy power plant capacity by the end of 2023 [16].

This potential can be utilized by using 1.3% of the total land of Turkey. Two cities (Çanakkale and Balıkesir) located at the border of Bursa account for approximately 23.5% of the country's wind

TABLE I.
LITERATURE REVIEW

Source	Location	Data	Data Source	Estimated Variables
[3]	Africa	1 year 10 min data for 8 sites	Measured at site	AEP, COE, NPV, wind potential, CF, Weibull, turbulence indices
[4]	Mexico	3 years hourly data for 18 sites	Meteorological system	AEP, Rayleigh parameters, CF, NPV, CO_2 mitigation
[5]	South Korea	17 years 10 min data for 10 sites	Meteorological system	AEP, CF, LCOE, NPV
[6]	Northern Cyprus	RETScreen software, sensor	RETScreen software	AEP, LCOE, NPV, PBP
[7]	China	55 years 6 h data, 19 sites, 10 m	Meteorological system	AEP, rate of change, CF
[8]	Cuba	10 years hourly data for 1 site	Meteorological system	AEP, CF, LCOE
[9]	Brazil	2 years 10 min data for 5 sites	Measured at site	AEP, CF, refined mesoscale models
[10]	Turkey	33 years hourly for 335 stations	Meteorological system	Weibull, wind speed, power density
[11] and [12]	Turkey	1 year 1 site	Homer software	Wind speed, AEP, NPV, CoE

AEP, annual energy produced; CF, Capacity Factor; COE, Cost of Energy; LCOE, levelized cost of energy; NPV, net present value.

energy potential [17, 18]. Bursa has a border with Balıkesir and is located in a high-potential region for WTs. By the end of September 2022, the total installed wind capacity of Turkey was 11 199 MW [17]. In the last 10 years until 2021, Turkey has increased its wind energy capacity by tenfold. Turkey is ranked among the top five European countries that invested the most in the wind energy sector in 2020 [18]. As a result, the installed renewable energy capacity of Turkey is 6th in Europe and 13th in the world and this is expected to increase in the coming decades. Therefore, increasing the reliability and availability of WTs in Turkey is of significant importance [16].

IV. MATERIAL AND METHODS

In this section, the methods followed during evaluations are given. The study is composed of two parts: technical and economical. In the first step, technical data are obtained from a company which is operating WTs. The data are analyzed in terms of power density, Weibull distribution and TI. The technical output of the study is the generation values for three types of turbines. The economical parts have two components: levelized cost of energy (LCOE) and NPV calculations. The turbines were evaluated with technical and economical aspects, and the turbine which has the lowest LCOE and highest NPV is determined. The outline of the method used in the study is given in Fig. 1.

A. Data Acquisition From the Sites and Meteorological Stations

Hourly electricity production and wind speed data are obtained from 12 units of 2.5 MW turbines [19] located in Karacabey, Bursa [20]. These locations are technically determined by Deutsches Windenergie Institut (DEWI) [13] in a special report prepared for the investor company. The investor company had installed turbines in these locations, and in this study, the data from the existing turbines of these locations are used. Two years' (2017–2018) turbine power, wind speed, and direction data recorded at a height of 100 m (40°18'26.8"N 28°21'25.9"E) have been used for analysis. The locations of 12 WTs are given in Fig. 2.

Hub height, rotor diameter, swept area, and power density of N100/2500 turbines are 100 m, 100 m, 7854 m², and 3.15 m²/kW, respectively.

In this study, Vestas V136, 4.5 MW; Goldwind GW 136, 4.8 MW; and GE Cypress Model, 4.8 MW are compared. Properties of turbines are given in Table II.

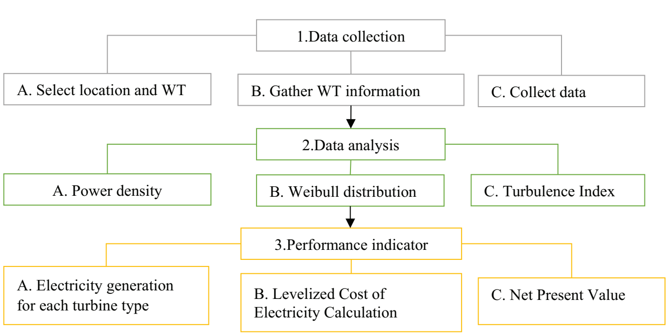

Fig. 1. The outline of the method used in the study.

Fig. 2. The locations of 12 wind turbines in Karacabey, Bursa, Turkey.

TABLE II.
WIND TURBINES USED IN THIS STUDY

Manufacturer	Model	Power Density, m²/kW	Swept Area, m²	Hub Height, m	Rated Power, kW	Cut-in Speed, m/s
Goldwind	GW136/4800	3.03	7263	100	4800	2.5
Vestas	V136/4.5MW	3.19	7157	100	4500	3
GE Energy	4.8-158	4.09	9803	101	4800	3

B. Weibull Function

The Weibull function is commonly used to characterize the wind speed distribution of a region. The probability density function is given as (1) [21].

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

In this equation, *f* is the probability of wind speed, *c* is the scale factor (m/s), *k* is the shape factor, and *v* is the wind speed (m/s). Shape parameter *k* is calculated by (2) [22].

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad (2)$$

In this equation, σ is the standard deviation and v_m is the mean speed obtained by (3).

$$v_m = \frac{1}{n} \times \sum_{i=1}^{n} V_{h(i)} \quad (3)$$

In this equation, *n* is the number of observations and $V_{h(i)}$ is the wind speed at hub height at time *i*. Then, standard deviation is calculated by using (4).

$$\sigma = \sqrt{\frac{1}{n-1} \times \sum_{i=1}^{n} (V_{h(i)} - v_m)^2} \quad (4)$$

Using the value of *k* obtained in (4), the scale parameter (*c*) is obtained by (5).

$$c = \left[\frac{1}{n} \times \sum_{i=1}^{n} V_{h(i)}^{k}\right]^{1/k} \quad (5)$$

Wind power density (WPD) is calculated using the Weibull probability function by (6).

$$WPD = \frac{1}{2} \times D \times v^3 \times \text{“} \times \frac{1+3}{k} \quad (6)$$

In this equation, Γ is the gamma function [21]. *D* is the air density and calculated by (7).

$$D = \frac{p}{R \times T} \quad (7)$$

In this equation, *p* is the average air pressure (Pa), *R* is the gas constant [287 J/(kg K)], and T is the temperature (K).

Turbulence index is obtained by (8).

$$I_n = \frac{\sigma}{v_m} \quad (8)$$

C. Wind Turbine Power Output Estimation

Power generated by the WT is obtained by (9),

$$P = \frac{1}{2} \times D \times v^3 \times A \times Cp \quad (9)$$

In this equation, *D* is the density of air (kg/m³), *v* is the speed at hub height (m/s), *A* is the swept area (m²), and C_p is the coefficient of performance.

D. Wind Speed Regime of the Region

The MWS, WT power, the Weibull parameters, and the TI of sites were calculated for each season and characterized daily to evaluate the potential during DT and NT.

E. Capacity Factor

The capacity factor of a WT is the ratio of the average output power to potential output at rated capacity.

F. Techno-Economic Feasibility Analysis

To get the cost of the electricity generation from WTs, investment cost which is also known as the capital expenditures (CAPEX) and the operational costs (OPEX) which is the expenses incurred during the operation should be calculated. Capital expenditures include the Project Development, Equipment, and Installation Costs. Capital expenditures are the amount spent at the initial stage of the investments. Operational costs are the expenditures that are done during the commercial operation of the wind farm. In this study, the turnkey cost of a power plant with a total of 12 turbines is calculated and the LCOE is obtained.

1) Project Development Cost

In this study, the price is assumed as 870 USD/kW for Turkey which is the average of International Renewable Energy Agency (IRENA) price assumptions [23]. Average value of IRENA, that is, 5% of the total cost is accepted as the project development cost which makes 43.5 USD/kW. The project development costs for different turbine types are given in Table III.

Wind turbines make up between 64% and 84% of the total installed costs of an onshore wind project [24]. In this case, they would be

TABLE III.
PROJECT DEVELOPMENT COST CALCULATIONS FOR EACH TYPE OF TURBINE

Goldwind 4.8*12 Units (57.6 MW)	Vestas 4.5*12 Units (54 MW)	GE 4.8*12 Units (57.6 MW)
1 252 800 USD	1 174 500 USD	1 252 800 USD

making 71% of the total installed costs. For three types of WTs, the equipment and installation costs are calculated and results are provided in Table IV.

2) Operation and Maintenance Costs
According to IRENA [23], between 2016 and 2018, the operation and management (OM) costs for onshore wind have ranged from USD 33/kW per year to USD 56 USD/kW per year. The OM cost would be closer to the lower range of the interval (33 USD/ kW) for Turkey. Table V gives the OM.

3) Levelized Cost of Energy Calculation
The LCOE method has been used for numerous purposes of cost evaluation for renewable energy systems [25-29]. For the year 2020, the discount rate for Turkey was 15.7% [29]. However, here as the cost assumptions are based on USD and usually the WTs and balance of plant (BOP) quotations were given either in USD, we used US discount rate which was 3% [30].

The LCOE of renewable energy technologies is calculated by (10).

TABLE IV.
EQUIPMENT AND INSTALLATION COSTS FOR EACH TURBINE TYPE

USD	Goldwind 4.8*12 Units (57.6 MW)	Vestas 4.5*12 Units (54 MW)	GE 4.8*12 (57.6 MW)
WT cost	21 312 000	54 918 000	63 360 000
Electrical works and equipment	8 467 200	7 938 000	8 467 200
Civil works and equipment	7 200 000	6 750 000	7 200 000
Other costs	4 780 800	4 482 000	4 780 800
Total CAPEX	43 012 800	75 262 500	85 060 800
CAPEX per MW	746 750	1 393 750	1 476 750

CAPEX, capital expenditures; WT, wind turbine.

TABLE V.
OPERATION AND MANAGEMENT COST CALCULATIONS FOR EACH TYPE OF TURBINE

Goldwind 4.8*12 units (57.6 MW)	Vestas 4.5*12 units (54 MW)	GE 4.8*12 units (57.6 MW)
1 900 800 USD	1 782 000 USD	1 900 800 USD

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{10}$$

In this equation, LCOE is the levelized cost of energy generation, I_t is the investment expenditures, M_t is the operations and maintenance expenditures, F_t is the fuel expenditures, E_t is the electricity generation in the year t, r is the discount rate, and n is the life of the system.

In order to calculate the investment expenditures, total CAPEX is turned to annual CAPEX by using Capital Recovery Factor (CRF) which is calculated via (11).

$$CR\,Factor = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{11}$$

In this equation, n is the number of periods (same as the life of the system) and i is the interest rate. The CRF for a 20-year wind power plant (WPP) with 0.03 interest rate can be calculated as 0.05. Investment and OM expenditure calculation for turbines is given in Table VI.

With the above inputs LCOE of the wind power project is calculated using NREL [31].

4) Net Present Value Calculations
Net present value is a measure to determine the project's economic feasibility and evaluated by (12).

$$NPV = \sum_{i=1}^{n} \frac{values_j}{(1+rate)^j} \tag{12}$$

where value is the net value for time j, and i is the starting year.

TABLE VI.
INVESTMENT AND OM EXPENDITURE CALCULATIONS FOR TURBINES

	Goldwind 4.8	Vestas 4.5	GE 4.8
Installed capacity	57.6	54	57.6
Project development unit cost USD per MW	1 252 800	1 174 500	1 252 800
WT cost	21 312 000	54 918 000	63 360 000
Electrical works and equipment	8 467 200	7 938 000	8 467 200
Civil works and equipment	7 200 000	6 750 000	7 200 000
Other costs	4 780 800	4 482 000	4 780 800
Total CAPEX	43 012 800	75 262 500	85 060 800
CAPEX per MW	746 750	1 393 750	1 476 750
OM	1 900 800	1 782 000	1 900 800

CAPEX, capital expenditures; OM, Operation and Management; WT, wind turbine.

5) Future Research and Limitations

The prices of the WTs are obtained from public resources and reports. For future research when the market is more stabilized, a detailed cost analysis can be done by digging into the market prices, local taxes, local insurance and interest rates, etc. Another key determinant is capital cost. We assume that the project is 100% financed by capital. A detailed weighted cost of capital (WCCA) can be calculated and the LCOE analysis can be recalculated with a realistic WCCA. As a result of an amendment in licensing regulation, installing hybrid power plants become possible in Turkey.

V. RESULTS

A. Annual Characteristics

1) Wind Potential

Annual average MWS, scale parameter (*c*), shape parameter (*k*), WPD, TI, and standard deviation of the wind speed (σ) are given in Table VII for each site.

As it is clear from Table VII, due to the high standard deviation, TI is also high in all sites. Smaller shape parameter values correspond to more variable winds, and the higher scale values correspond to a higher potential [3]. Table VII shows the high potential of all sites due to high scale parameters that range between 7.6 and 9.1. Also, small shape parameters and high standard deviation show the variable wind speeds.

B. Seasonal Characteristics

Monitored data are analyzed to show the monthly distribution. Results are given in Fig. 3.

As seen from Fig. 3a, maximum power was generated during August whereas minimum was generated in April and July in all sites. Maximum and minimum powers are generated in sites 7 and 12, respectively, during the year. Fig. 3b shows the similarity between generated power (Fig. 3a) and MWS. The monthly MWS varies between 4.6 and 11.7 m/s which shows the available potential for electricity production.

Fig. 3c shows the maximum deviation was in March and September whereas minimum deviation was in July and October. Minimum TI was observed in August (Fig. 3d) during which maximum wind speed and power generation were observed. Maximum TI is observed in April (Fig. 3d) during which minimum wind speed and power generation were observed. Turbulence index varies between 0.3 and 0.8.

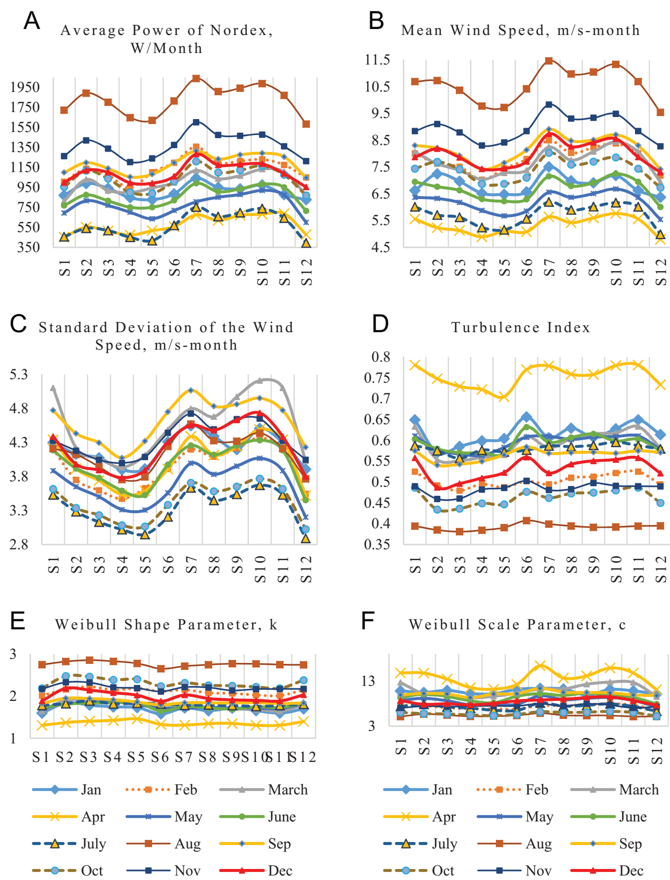

Fig. 3. Monthly wind potential characteristics on each site: (a) power of monitored turbine, (b) mean wind speed, (c) standard deviation of wind speed, (d) turbulence index, (e) Weibull shape parameter, (f) Weibull scale parameter.

Fig. 3e and 3f illustrate the Weibull parameters. The shape parameter (Fig. 3e) ranged from 1.3 to 2.9 which corresponds to the wide

TABLE VII.
ANNUAL WIND CHARACTERISTICS OF EACH SITE

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
MWS	7.03	7.54	7.31	6.89	6.95	7.24	8.06	7.65	7.78	7.99	7.56	6.75
c	7.94	8.52	8.27	7.79	7.86	8.16	9.11	8.65	8.78	9.02	8.54	7.63
k	2.05	2.03	2.04	2.00	1.98	1.87	1.94	1.91	1.90	1.89	1.87	1.96
TI	0.52	0.52	0.52	0.53	0.53	0.56	0.54	0.55	0.55	0.56	0.56	0.54
σ	3.64	3.92	3.79	3.63	3.70	4.07	4.39	4.22	4.31	4.45	4.26	3.64
WPD	570	709	645	554	580	700	922	801	845	920	789	541

σ, standard deviation of the wind speed; *c*, scale parameter; *k*, shape parameter; MWS, mean wind speed; TI, turbulence index; WPD, wind power density.

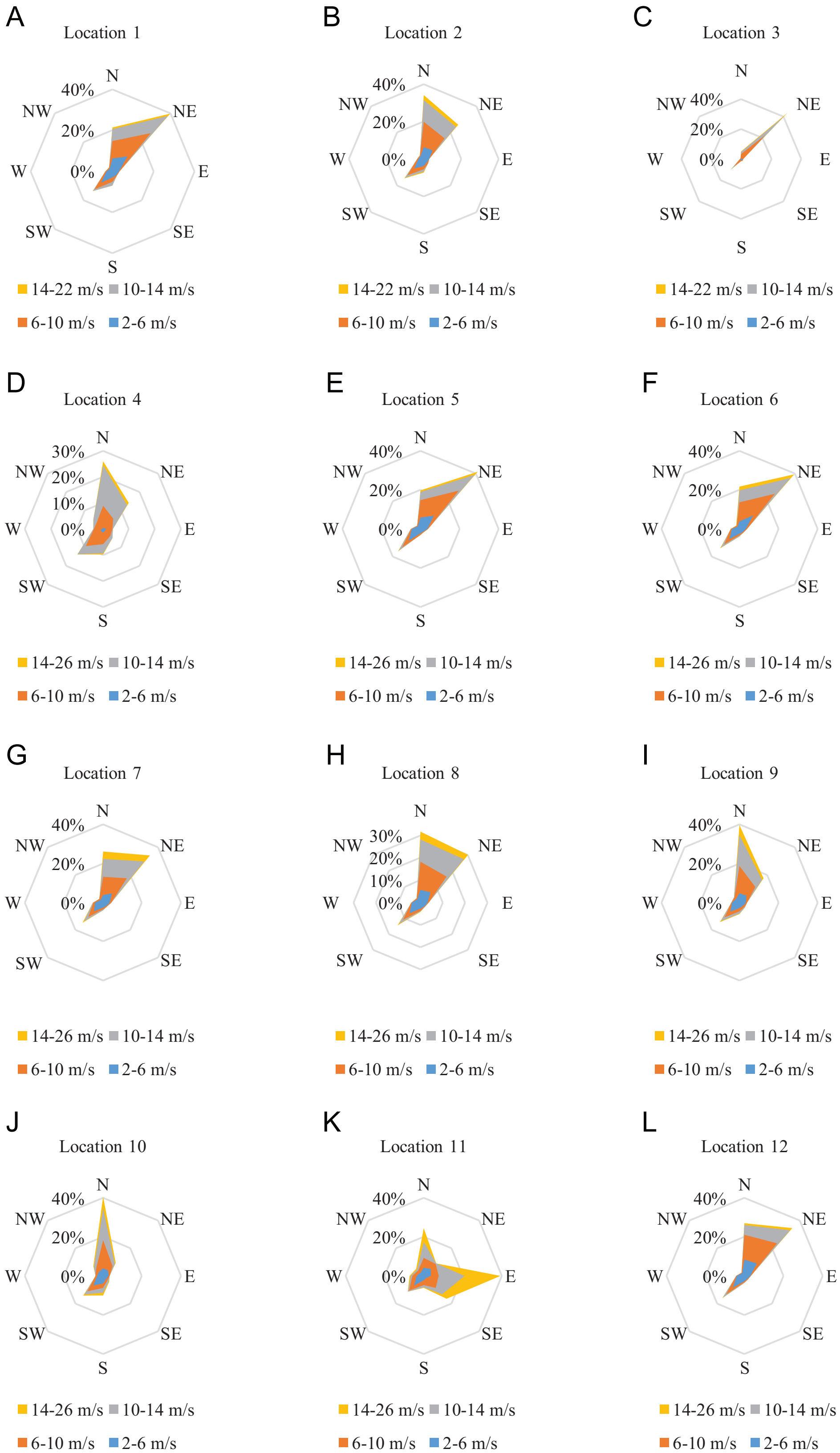

Fig. 4. Wind rose distribution on each site: (a) Location 1, (b) Location 2, (c) Location 3, (d) Location 4, (e) Location 5, (f) Location 6, (g) Location 7, (h) Location 8, (i) Location 9, (j) Location 10, (k) Location 11, (l) Location 12.

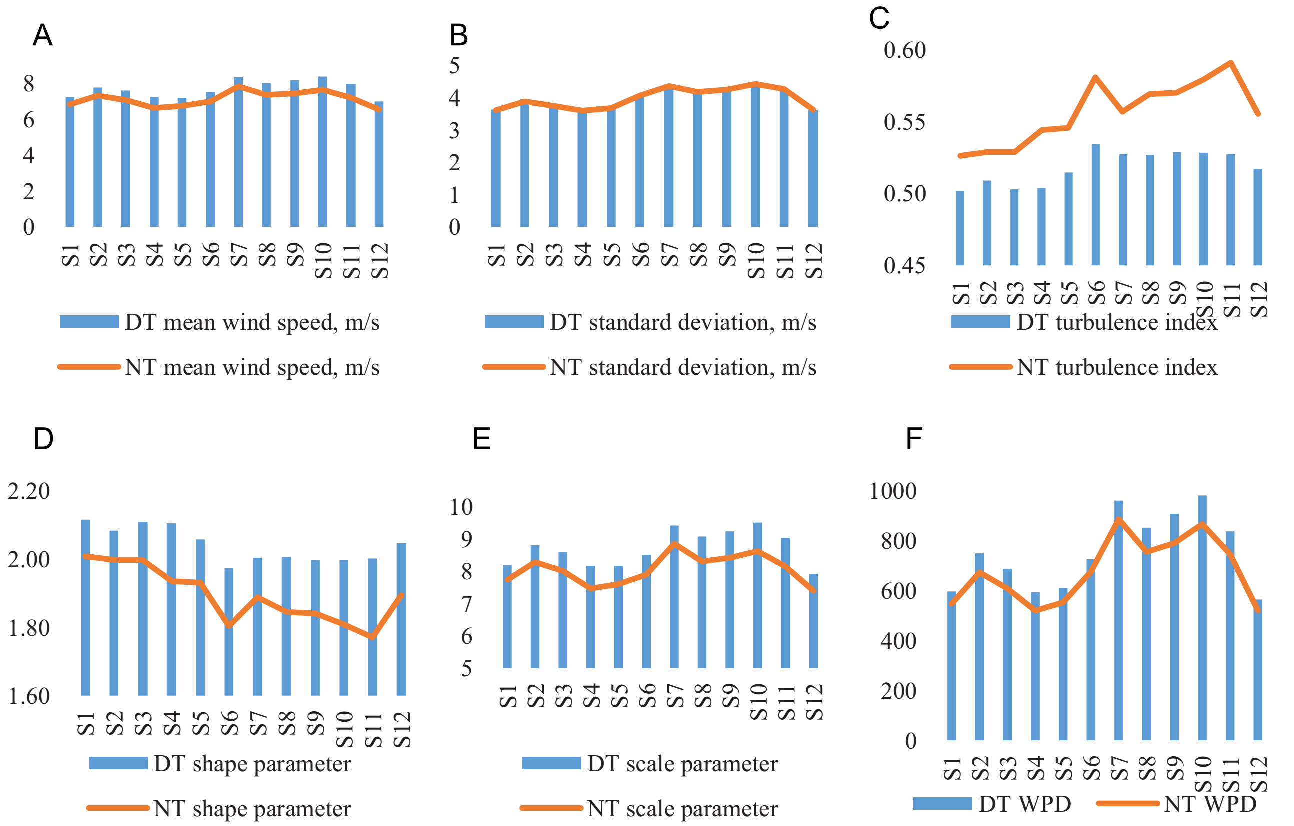

Fig. 5. Wind energy potential parameters during DT and NT: (a) mean wind speed, (b) Standard deviation, (c) Turbulence index, (d) shape parameter, € scale parameter, (f) WPD.

variation of the wind speed. The scale parameter (Fig. 3f) ranged from 5 to 16.4.

C. Seasonal Distribution of the Wind Speeds

1) Wind Rose Distribution

The wind rose is the presentation of the wind frequencies in a coordinate system. Wind rose diagrams were developed for 12 locations and are given in Fig. 4. It is seen in Fig. 4 that there are two dominating wind directions, north and northeast which remained fairly stable for all turbines except turbine 11.

2) Daily Characteristics of Wind Potential

Potential of the wind speed is investigated for DT (from 8:00 to 18:00 h) and NT (from 18:01 to 07:59 h). Fig. 5a and 5f show that the mean wind speed and the WPD are lower during the DT. Relatedly, the Weibull parameters are lower for the NT as seen in Fig. 5d and 5e. This will be explained by a more homogenous and less variable wind speed distribution in the DT. This result can also be observed in Figure 5c which represents the high TI during NT. The standard deviation is stable as seen in Fig. 5b.

D. Wind Turbines Energy Output and Economic Analysis

1) Annual Energy Produced

The current turbines installed are Nordex turbines with AEP of 106.9 GWh/year. The highest generation value is obtained from GE turbines with 166.7 GWh/year, followed by Vestas (137 GWh/year), and the lowest generation is from Goldwind turbines (134.7 GWh). Annual energy produced by each turbine type for each turbine is given in Table VIII.

2) Annual Capacity Factor

The theoretical full generation for 8760 h of 12*2.5 MW Nordex wind power plant is 262 800 MWh/year. Therefore, the capacity factor is 40.7%. The capacity factors of the wind farm are 0.26, 0.290, and 0.330 for Goldwind, Vestas, and GE, respectively

3) Cost Analysis of the Generated Energy (Levelized Cost of Energy)

The lowest LCOE belongs to the wind farm with Goldwind turbines. Although the capacity factor of this plant is the lowest, with the half CAPEX amount compared to the other two wind farm configurations, the resulting LCOE for Goldwind is 0.035 USD/kWh.

The second lowest LCOE belongs to GE turbines; 0.046 USD/kWh which can be attributed to the highest capacity factor among the other two. The third LCOE resulted from a wind farm with Vestas turbines. The lower capacity factor levels and higher CAPEX amounts are the main factors for this relatively higher LCOE. These relatively low values of LCOE can be attributed to the discount rate which is taken as 3%. If we make a small sensitivity analysis which doubles the

TABLE VIII.
ANNUAL ENERGY PRODUCED BY EACH TURBINE TYPE IN EACH SITE

Turbine	Goldwind 4.8, MWh/Year	Vestas 4.5, MWh/Year	GE 4.8, MWh/Year	Nordex 2.5, MWh/Year
T1	9751	10 020	12 377	8222
T2	11 570	11 788	14 348	9318
T3	10 690	10 930	13 409	8839
T4	9303	9554	11 810	7955
T5	9497	9722	11 956	8018
T6	10 773	10 953	13 323	8723
T7	13 585	13 709	16 421	10 236
T8	12 298	12 466	15 058	9566
T9	12 709	12 867	15 513	9845
T10	13 506	13 628	16 329	10 250
T11	12 108	12 284	14 871	9519
T12	8891	9115	11 266	7613
AEP	134 681	137 036	166 681	106 987

discount rate (to 6%), then the resulting LCOE would be 0.043, 0.061, and 0.056 USD/kWh for Goldwind, Vestas, and GE, respectively. For 20 year period of time, the lowest LCOE can be achieved by Goldwind turbines with 3.5 USD/kWh. GE ranks second place whereas Vestas has the highest LCOE.

Another point of perspective for investment decisions can be obtained from NPV calculations. The NPV with 20-year values is obtained as 83 945 583, 58 887 360, and 80 306 589 USD for Goldwind, Vestas, and GE, respectively.

The electricity sale price is the feed-in tariff value of 7.3 USD/MWh as regulated by Turkish renewable energy support law. The NPV analysis ranks the Goldwind turbines as the best place followed by GE and Vestas. It gives the same results as the LCOE ranking.

VI. CONCLUSION

In this study, for a more reliable wind assessment, the seasonal, daily, and turbulence variations of the wind characteristics in Bursa, Turkey, have been investigated using the 10-min interval data obtained in 12 locations, at 100-m height level over a 2-year period. Mean speed, Weibull parameters, TIs, power density parameters, and cost of energy were calculated based on seasonal and daily wind analyses.

The other literature studies give low wind speed values as 2.9 and 3.88 m/s for Bursa by using meteorological stations or satellite data, however, this study shows that the real wind speed is much higher than these calculations. According to this current study, the average wind speed is obtained as 7.4 m/s for a rural area of Bursa. Weibull scale parameters ranged between 7.6 and 9.1 which shows the high wind potential of the region. Weibull shape parameters were observed to be low (1.3 to 2.9) and the standard deviation was high which resulted in variable wind speeds. The dominating wind directions were north and northeast which remained fairly stable for all sites except site 11. The potential of the wind speed is investigated for DT and NT. Weibull shape and scale parameters were lower for the NT compared to DT on all sites.

After the determination of wind parameters, energy generation values are obtained. Three turbine manufacturers with the highest market share were (Goldwind, GE, and Vestas) compared for the sites. According to calculations of this study, the highest generation value is obtained from GE turbines with 166.7 GWh/year, followed by Vestas turbines (137 GWh/year) and the lowest generation is from Goldwind turbines (134.7 GWh).

Next, for the economical aspects, the costs are introduced into the analysis. The lowest LCOE for Goldwind is 0.035 USD/kWh. The second LCOE belongs to GE turbines with 0.046 USD/kWh which can be attributed to the highest capacity factor among the other two. The third LCOE resulted from Vestas turbines which was obtained as 0.05 USD/kWh. Both analyses point out that the wind farm with Goldwind turbine has the highest NPV and the lowest LCOE. In this case, the investor should select the Goldwind turbine for its project.

This analysis has both macro- and microlevel policy implications. At the macrolevel, with the concern for climate change, governments need to prioritize renewable energy investments. However, these investments should be based on reliable feasibility analysis. According to this study, the use of site-specific hub height data is crucial for decisions. The governments may require such analysis at the site before giving permissions to projects. Other countries can make such policies as well. In the micro level, the economic actors and the investors should have to use wisely their limited financial resources. While shaping their decision-making policies, they should be given the utmost importance to using site-specific measurement data in their investment analysis. The alternative cost analysis should also be employed to bring different economic perspectives. Otherwise, there could be over- or underestimation of the wind potential which would result in unexpected losses and infeasible investments.

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REFERENCES

1. A. G. Olabi, and M. A. Abdelkareem, "Renewable energy and climate change," *Renew. Sustain. Energy Rev.*, vol. 158, p. 112111, 2022. [CrossRef]
2. Y. Yuchen, K. Javanroodi, and V. M. Nik, "Climate change and renewable energy generation in Europe—Long-term impact assessment on solar and wind energy using high-resolution future climate data and considering climate uncertainties," *Energies*, vol. 15, p. 1, 302, 2022.
3. B. Bilal, K. H. Adjallah, K. Yetilmezsoy, M. Bahramian, and E. Kıyan, "Determination of wind potential characteristics and techno-economic feasibility analysis of wind turbines for northwest Africa," *Energy*, vol. 218, p. 119558, 2021. [CrossRef]
4. O. Rodriguez-Hernandez, M. Martinez, C. Lopez-Villalobos, H. Garcia, R. Campos-Amezcua, and T.-E. Area, "Feasibility study of small wind turbines in the valley of Mexico Metropolitan area," *Energies*, vol. 12, p. 5, 890, 2019.
5. S. Ali, and C.-M. Jang, "Selection of best-suited wind turbines for new wind farm sites using techno-economic and GIS analysis in South Korea," *Energies*, vol. 12, no. 16, p. 16, 3140, 2019. [CrossRef]
6. F. Al-Turjman, Z. Qadir, M. Abujubbeh, and C. Batunlu, "Feasibility analysis of solar photovoltaic-wind hybrid energy system for household applications," *Comput. Electr. Eng.*, vol. 86, p. 106743, 2020. [CrossRef]
7. Y. Wen, B. Kamranzad, and P. Lin, "Assessment of long-term offshore wind energy potential in the south and southeast coasts of China based on a 55-year dataset," *Energy*, vol. 224, p. 120225, 2021. [CrossRef]
8. Y. S. Torres, and P. R. Ramos, "Techno-Economic Feasibility Study of Small Wind Turbines in Havana city," *Rev. Cuba. Ingeniería*, vol. 7, no. 1, pp. 47–57, 2021.
9. A. F. Gomes da Silva, C. Regina de Andrade, and E. L. Zaparoli, "Wind power generation prediction in a complex site by comparing different numerical tools," *J. Wind Eng. Ind. Aerodyn.*, vol. 216, p. 104728, 2021. [CrossRef]
10. H. Arslan, H. Baltaci, B. O. Akkoyunlu, S. Karanfil, and M. Tayanc, "Wind speed variability and wind power potential over Turkey: Case studies for Çanakkale and İstanbul," *Renew. Energy*, vol. 145, pp. 1020–1032, 2020. [CrossRef]
11. M. Purlu, S. Beyarslan, and B. E. Turkay, "Optimal Design of Hybrid Grid-connected Microgrid with Renewable Energy and Storage in a Rural Area in Turkey by Using HOMER," International Conference on Electrical and Electronics Engineering, *Bursa*, 2021.
12. M. Pürlü, S. Beyarslan and B. E. Türkay, "On-Grid and Off-Grid Hybrid Renewable Energy System Designs with HOMER: A Case Study of Rural Electrification in Turkey," *Turk J Electr Power Energy Syst*, pp. 75-84, 2022.
13. DEWI GmbH, *Site-Related Wind Potential Analysis and Enegy Yield Assessment at the Site Karacabey*. Wilhelmshaven: DEWI GmbH, 2010.
14. General Directorate of Meteorology, "Station information database". Available: https://mgm.gov.tr/kurumsal/istasyonlarimiz.aspx?il=Bursa. [Accessed: 21 11 2022].
15. T.R. Ministry of Energy and Natural Resources, *"Wind,"*. Available: https://enerji.gov.tr/eigm-yenilenebilir-enerji-kaynaklar-ruzgar. [Accessed:10 10 2022].
16. N. Sarma, P. M. Tuohy, O. Özgönenel, and S. Djurović, "Early life failure modes and downtime analysis of onshore type-III wind turbines in Turkey," *Electr. Power Syst. Res.*, vol. 216, p. 108956, 2023. [CrossRef]
17. TEIAS, "Power Plants Installed Capacity Reports," [Online]. Available: https://www.teias.gov.tr/kurulu-guc-raporlari. [Access: 21 10 2022].
18. *Wind Europe, "Turkey Reaches 10 GW wind energy milestone," 9 September 2021*. Available: https://windeurope.org/newsroom/news/turkey-reaches-10-gw-wind-energy-milestone/. [Accessed: 25 10 2022].
19. Nordex, "N100/2500,", 2020. Available: https://www.scribd.com/document/400033062/Nordex-GammaN100-2500-En. [Accessed: 29 09 2023].
20. *Arti Energy*. 2020. Available: http://www.artienerji.com.tr/index-eng.htm. [Accessed: 21 10 2022].
21. T.-P. Chang, F.-J. Liu, H.-H. Ko, S.-P. Cheng, L.-C. Sun, S.-C. Kuo, "Comparative analysis on power curve models of wind turbine generator in estimating capacity factor," *Energy*, vol. 73, pp. 88–95, 2014.
22. C. G. Justus, W. R. Hargraves, A. Mikhail, and D. Graber, "Methods for estimating wind speed frequency distributions," *J. Appl. Meteorol.*, vol. 17, no. 3, pp. 350–353, 1978.
23. IRENA, IRENA Renewable Power Generation Costs in 2021, 2021. Available: https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021 [Accessed: 12 10 2022].
24. IRENA, Renewable power generation costs in 2017, Abu Dhabi, 2018. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018_summary.pdf [Accessed: 12 10 2022].
25. K. Hansen, "Decision-making based on energy costs: Comparing levelized cost of energy and energy system costs," *Energy Strategy Rev.*, vol. 24, pp. 68–82, 2019. [CrossRef]
26. X. Ouyang, and B. Lin, "Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China," *Energy Policy*, vol. 70, pp. 64–73, 2014. [CrossRef]
27. S. Larsson, D. Fantazzini, S. Davidsson, S. Kullander, and M. Höök, "Reviewing electricity production cost assessments," *Renew. Sustain. En. Rev.*, vol. 30, pp. 170–183, 2014. [CrossRef]
28. R. Gross, W. Blyth, and P. Heptonstall, "Risks, revenues and investment in electricity generation: Why policy needs to look beyond costs," *Energy Economics*, vol. 32, no. 4, pp. 796–804, 2010. [CrossRef]
29. M. Purlu, and U. Ozkan, "Economic and environmental analysis of grid-connected rooftop photovoltaic system using HOMER," *Turk. J. Electr. Power Energy Syst*, vol. 3, no. 1, pp. 39–46, 2023. [CrossRef]
30. CEIC, *Turkey Central Bank discount rate*. Available: https://www.ceicdata.com/en/turkey/saving-discount-rate-and-interbank-rate/central-bank-discount-rate. [Accessed: 27 09 2022].
31. US Department of Energy, *US 2021 discount rates, 01 04 2021*. Available: https://www.energy.gov/sites/default/files/2021-04/2021discountrates.pdf. [Accessed: 01 10 2022].
32. NREL, Levelized Cost of Energy Calculator, Available: https://www.nrel.gov/analysis/tech-lcoe.html [Accessed: 25 09 2023].