INTRODUCTION

In 2015, Saudi Arabia released its 2030 strategic plan designed to diversify the country's economy by enhancing business investments and opportunities.\(^1\) Saudi Arabia's economy has traditionally relied heavily on oil. An element of the 2030 plan therefore was to reduce the Saudi economy's dependence on oil revenues by diversifying the economy by making the kingdom suitable for foreign investors and by increasing the use of renewable energy sources.\(^2\) As part of that goal, the establishment of a new advanced city called NEOM in the northwestern part of the kingdom was announced in October 2017. NEOM will use only renewable energy for its electric power, and 500 billion USD will be invested into building the new megacity.\(^3\) Such a project requires a study of the wind energy potential, especially since—as of April 2019—the only wind farm in Saudi Arabia is in Turaif city, near the border of Jordan.\(^4\) Hence, the objectives of this paper are to describe the expected winds for the location of NEOM city with a proper probability density function (PDF), select a wind turbine that will generate the least levelized cost of energy (LCOE), and estimate the potential annual carbon dioxide savings.

One way to estimate the viability of a specific wind farm is by determining the average power density per swept area. Manwell et al\(^5\) defined seven classes of wind power. Sites of Class 4 or higher, which have a power density exceeding 200 W/m\(^2\) at a height above 10 m, are considered suitable for commercial operation. A 3.2-MW wind turbine, which is optimal for this location, has a capacity factor varying from 31.9% to 41.4% and LCOE that ranges from 6.99¢ to 8.32¢ per kWh. The 320-MW wind farm has a positive net present value, a simple payback period of 13.8 years, and a LCOE of 6.6¢ per kWh. By installing this farm, potential annual savings of CO\(_2\) are around 10\(^6\) metric tons.

Abstract

This paper provides an analytical assessment of the feasibility of wind energy for Saudi Arabia's envisioned NEOM city, which plans to use only renewable energy. A probability density function was fit to winds simulated for the NEOM region during 2014-2018. Using this distribution, the optimal wind turbine was selected as the one with the largest capacity factor and smallest levelized cost of energy (LCOE). Financial, environmental, and risk analysis of a wind farm consisting of 100 of these units was also performed. A Weibull distribution determined by changing the shape and scale parameters to minimize the mean squared error offered the best fit to the measured wind speeds at this location. The estimated power density showed that the NEOM site warrants a Class 3 classification, which means wind energy systems would be suitable for commercial operation. A 3.2-MW wind turbine, which is optimal for this location, has a capacity factor varying from 31.9% to 41.4% and LCOE that ranges from 6.99¢ to 8.32¢ per kWh. The 320-MW wind farm has a positive net present value, a simple payback period of 13.8 years, and a LCOE of 6.6¢ per kWh. By installing this farm, potential annual savings of CO\(_2\) are around 10\(^6\) metric tons.

KEYWORDS
capacity factor, levelized cost of energy, NEOM, power density, Weibull distribution, wind energy, wind speeds
commercial wind farm installations. Class 3 sites, which have power density between 150 and 200 W/m², are suitable only for commercial use at great heights. Class 2 sites, which have power density between 100 and 150 W/m² at 10 m, are marginal, and those with smaller power density are not suitable for commercial wind turbines.

Classifying a site in terms of power density requires an estimate of the distribution of wind speeds. Probability density functions such as the lognormal, Rayleigh, logistic, and Weibull distributions are fit to measured or simulated data to describe the magnitude and variability of the wind speeds. For example, a study of Johannesburg, South Africa, showed that, of these four distributions, the Weibull distribution fit best in all seasons; it also identified the optimal wind turbine size. The capacity factor, or the ratio of the actual produced energy and the maximum energy that the wind turbine can produce during the same period, plays an important role in determining the LCOE. The wind speed resources, the efficiency of the wind farm equipment, and the quality of operation (eg, alignment of wind turbines with the wind and other aspects of control) determine the capacity factor. In 2017, the global weighted average capacity factor was 29%, and the LCOE had a global weighted average of $0.06 per kWh.

The use of wind power to generate electricity has economic and environmental advantages. The declining LCOE makes wind energy cost-effective. While the cost of traditional sources of energy is subject to uncertainty in the market and fuel prices, wind energy is sold at fixed price over its lifetime and it comes from a free source of fuel. Wind energy also mitigates many of the environmental harms that other sources such as coal and thermal power cause. Wind energy saves millions of gallons of water every year because water is not required for cooling or generating power. In 2017 alone, water consumption was by 95 billion gallons reduced due to wind energy. Wind energy also reduces carbon dioxide emission, which has increased by a factor of 15 in the energy generation sector over a 20-year period. In 2018, wind energy generation reduced the carbon dioxide emissions by 200 million tons, or approximately the CO₂ emission from 43 million cars. Previous studies determine the potential CO₂ savings of energy production from renewable sources by computing the CO₂ emission from producing the same amount of energy from conventional sources. For example, a wind energy system to pump water in six locations in Nigeria would reduce CO₂ emissions by 4.3-22.9 tons/y.

Before a large project such as NEOM can be started, a preliminary study of the wind energy potential in this part of Saudi Arabia is needed. To classify NEOM city regarding wind energy, we evaluate four different methods for estimating the PDF of the wind and use the most suitable distribution to estimate power and energy densities and the characteristics of wind speeds at the site. The LCOE is computed and analyzed to determine the economic feasibility of wind energy at NEOM. Finally, the financial and environmental benefits are also evaluated.

## 2 METHODS

### 2.1 Data source and description

Because of a lack of historical measured data at the site, a simulated historical weather dataset developed by Meteoblue.com was used. NEOM will be placed on flat land near the Gulf of Aqaba surrounded by discontinuous and dry mountains as high as 6000 feet above sea level. Meteoblue uses
The CDF gives the probability of occurrence of wind speeds below a given value.

Two other PDFs were used to model the wind speed. The Rayleigh distribution is a special case of the Weibull distribution [Equation (1)] with $k = 2$:

$$f_r(v) = \frac{v}{\sigma^2} \exp \left[ -\frac{v^2}{2\sigma^2} \right]$$

The lognormal distribution, which is given by Zaharim et al., is

$$f_l(v) = \frac{1}{\sqrt{2\pi} \sigma v} \exp \left[ \ln \left( \frac{v}{\bar{v}_m} \right) \right]^2$$

where $\bar{v}_m$ and $\sigma$ are the mean and standard deviation of $\ln(v)$, respectively. To evaluate the performance of the distributions, the coefficient of determination ($R^2$) and absolute percent error of power density of the four different methods were calculated.

These PDFs can be used to compute the most probable wind speed and the ideal wind speed, or, respectively, the wind speed that occurs the most and the wind speed that produces the most wind energy. For example, the Weibull distribution yields a most probable wind speed $v_p$ of

$$v_p = c \left( \frac{k-1}{k} \right)^{1/2}$$

and an ideal wind speed $v_{id}$ of

$$v_{id} = c \left( \frac{k+2}{k} \right)^{1/2}$$

The selection of the wind turbine’s rated speed $v_r$ or the speed at which the turbine produces its maximum rated capacity, should be based on the calculated ideal speed. One of the disadvantages of the Weibull distribution is that it does not show the probability of zero speed. However, this disadvantage is not that significant in practice because no wind energy is produced below the cut-in speed $v_{ci}$, which ranges from 3 to 4 m/s.

### 2.3 Wind power and energy output

The available wind power density is calculated from the kinetic energy. For a wind turbine with swept area $A$, the kinetic energy resulting from wind of duration $t$ is

$$KE = \frac{1}{2} \rho Av^3 t$$

where $\rho$ is the density of air. We take the density of air to be 1.225 kg/m$^3$, the value at a mean temperature of 15°C, and a pressure of 1 atm at sea level. Although the density will vary,
For a fixed wind speed $v$, the power density $p$ is then computed from Equation (10) by dividing by the time and swept area:

$$p(v) = \frac{1}{2} \rho v^3$$  \hspace{1cm} (11)

When the probability density distribution is introduced to account for variability in wind speed, the power density becomes:

$$p(v) = \int_{0}^{\infty} \frac{1}{2} \rho v^3 f(v) \, dv$$  \hspace{1cm} (12)

For example, if the Weibull distribution PDF is used, the power density is

$$p(v) = \frac{1}{2} \rho c^3 \frac{\Gamma(1 + \frac{3}{k})}{\Gamma}\left(1 + \frac{3}{k}\right)$$  \hspace{1cm} (13)

The energy density for a duration $t$ is then calculated as $E(v) = p(v)t$.

When time series of wind speed are available, the energy output of a wind turbine is calculated using its power curve, which shows the power output as a function of wind speed. The power curve is typically provided by wind turbine manufacturers in a fashion similar to Figure 1. Above the cut-in speed $v_{ci}$, the wind turbine starts to produce energy, and when the wind speed reaches the rated speed $v_r$, which is typically 10-11 m/s, the wind turbine produces energy at its maximum rated capacity. Above the cutout speed $v_{co}$, the turbine stops producing energy. The power $P$ actually produced at time $t$ can be calculated from the time series using:

$$P(t) = P_r \left( \frac{v_r^2 - v_{ci}^2}{v_r^2 - v_{co}^2} \right) \left( v_{ci} \leq v_t \leq v_r \right)$$  \hspace{1cm} (14)

where $P_r = \frac{1}{2} \rho A C_p v_r^3$ is the rated power of the wind turbine, $v_t$ is the wind speed at time $t$ at the height of the hub, and $C_p$ is the coefficient of performance, or the ratio of the rated power and the potential power in the wind. The theoretical maximum value of the coefficient of performance is the Betz limit of 59.3%. The energy power output can be calculated using:

$$E(t) = \int P(t) \, dt \approx \sum_{i=1}^{N} P_i \Delta t$$  \hspace{1cm} (17)

where $P_i$ is the power produced in the $i^{th}$ interval, $N$ is the number of intervals, and $\Delta t$ is the duration of the interval (1 h). The capacity factor of the wind farm can be calculated using:

$$\text{CF} = \frac{E}{P_r N \Delta t}$$  \hspace{1cm} (18)

The capacity factor measures the fraction of the maximum available energy at the rated capacity that was utilized by the wind turbines.

2.4 Levelized cost of wind energy

The economic evaluation of a wind project determines whether the project is viable. The average LCOE is determined with:

$$\text{LCOE} = \frac{\text{CC} \cdot \text{CRF} + c_{FOM} + c_{VO&M}}{T \cdot \text{CF}} + c_{VO&M}$$  \hspace{1cm} (19)
where CC is the total capital cost per unit of power (e.g., kW) of installing the wind farm, CRF is the capital recovery factor, T is the time of operation (e.g., in a year), \( c_{\text{FO\&M}} \) is the fixed cost of operation and maintenance per unit of power, and \( c_{\text{VO\&M}} \) is the fixed variable cost of operation and maintenance per unit of energy. The capital recovery factor depends on the discount rate \( i \) and the number of payments \( n \):

\[
\text{CRF} = \frac{i (1+i)^n}{(1+i)^n-1} \quad (20)
\]

The calculation of LCOE assumes a discount rate of 5% and adopts several values from IRENA: a wind turbine lifetime of 25 years, CC = $1477 per kW, \( c_{\text{FO\&M}} = $58 per kW per year, and \( c_{\text{VO\&M}} = 2.5¢ per kWh. The LCOE was evaluated for a variety of wind turbine models with rated capacities that ranged from 1.5 MW to 3.6 MW (Table 1).

### 2.5 Case study for a wind farm

An economic and environmental evaluation of installing a wind farm in NEOM city was performed with RETScreen software, which evaluates the energy production and the financial and environmental aspects of new and existing renewable energy projects to help decision-makers. The rated capacity of the wind farm is assumed to be above 100 MW. Therefore, the number of wind turbines was assumed to be 100.

#### 2.5.1 Financial analysis

The initial cost and the O&M cost are determined from a database on the RETScreen based on the rated capacity of the project. For projects with rated capacity larger than 100 MW and smaller than 1 GW, the initial cost is equal to 2100 $/kW and the O&M cost is 64$/kW-year. The financial parameters were selected similar to the financial parameters from previous studies (Table 2).

#### 2.5.2 Risk analysis

RETScreen performs risk analysis by using Monte Carlo simulations within the range of the parameter’s uncertainty in order to produce a frequency distribution of financial indicators. The risk analysis was performed on the LCOE. The parameters are assumed to be independent, and the range of the parameters was set to be ±30%. To get 90% confidence intervals, the level of risk was set to be 20%.

### 2.5.3 CO2 emission savings

The amount of carbon dioxide saved can be calculated by estimating the amount of emission that would have been produced if fossil fuel generators were used instead. We calculate the CO2 footprint only during electricity production and do not account for the carbon dioxide footprint from producing the materials of the wind turbines. Because most power plants in Saudi Arabia use liquid oil to produce electricity, the energy output is estimated as

\[
E_{\text{gen}} = \eta_d k_d V_d \quad (21)
\]

where \( V_d \) is the volume of diesel required to generate energy. The efficiency \( \eta_d \) of power plants in Saudi Arabia is assumed to be approximately 31.9%, and the volume of diesel per unit of energy \( k_d \) is 10.29 kWh/L. Then by equating \( E_{\text{gen}} \) to the annual energy output for the wind farm, the equivalent mass of CO2 emitted was computed with

\[
M_{\text{CO2}} = \frac{K_{\text{p}} E(t)}{\eta_d k_d} \quad (22)
\]

where \( K_{\text{p}} \), the weight of CO2 per volume of diesel, is 2.66 kg/L.

### Table 1

| Model         | GE 1.5s – 70.5 | GE 1.85 – 82.5 | GE 2.5 – 88 | GE 3.2 – 130 | GE 3.6s – 104 |
|---------------|----------------|----------------|-------------|--------------|---------------|
| Rated power (kW) | 1500           | 1850           | 2500        | 3200         | 3600          |
| Rotor diameter (m) | 70.5           | 82.5           | 88          | 130          | 104           |
| Swept area (m²)   | 3904           | 5345           | 6082        | 13 273       | 8495          |
| Cut-in wind speed (m/s) | 4              | 3              | 3           | 2            | 3.5           |
| Rated wind speed (m/s) | 13             | 13             | 14          | 12           | 15            |
| Cut out wind speed | 25             | 25             | 25          | 25           | 25            |

### Table 2

| Parameter                  | Value |
|----------------------------|-------|
| Inflation rate (%)         | 3     |
| Discount rate (%)          | 5     |
| Project life (y)           | 25    |
| Debt ratio (%)             | 3     |
| Debt interest rate (%)     | 0     |
| Debt term (y)              | 20    |
| Electricity export escalating rate (%) | 3     |
greenhouse gas emission factors for many countries including Saudi Arabia, and it asks the users to enter the transmission and distribution losses, which were assumed to be 11.48%.

3 | RESULTS AND DISCUSSION

3.1 | Evaluation of statistical distributions and power and energy densities

The Weibull distribution fit the empirical distribution of wind speeds the best (Figure 2A). In particular, the method of minimizing the mean squared error (MSE) is the best option among the four methods. It has the maximum coefficient of determination, with a range of 0.94-0.97, for all of the years that were evaluated (Figure 3). The Weibull distribution fit using Equation (2) has $R^2 > 0.9$ in all cases as well, and the Rayleigh distribution has similar values of $R^2$. The lognormal distribution has $R^2 \leq 0.9$ in all cases.

Although the results for power density are more mixed, the Weibull-MSE method still predicts power density well (Figure 4). Because the power density depends on the cube of the wind speed, a PDF that fits the large wind speeds accurately could reproduce power densities better than a PDF that fits the entire wind speed distribution well. For 2017, the Rayleigh distribution and Weibull distribution fit by matching the mean and standard deviation have smaller percent error (Figure 4). The Weibull distribution with minimized MSE has about 7% error for the 5-year dataset, and it works best in four of the five individual years. Therefore, the method of the Weibull distribution with minimized MSE was selected.

Wind speeds at NEOM are high and narrowly distributed. The scale parameter, which is proportional to the mean wind speed, ranged from 5.70 m/s in 2018 to 6.76 m/s in 2017 (Table 3). The shape parameter was about 2 for the individual years and the 5-year dataset. High values

**FIGURE 2**  A, Fit of the four models to the distribution of wind speeds measured at a height of 10 m: probability density function. B, Fit of the four models to the distribution of wind speeds measured at a height of 10 m: cumulative distribution function for the Weibull-MSE method.
of the shape parameter indicate small coefficient of variation (Equation 4), and winds with distributions with \( k > 2 \) are considered less variable.\(^{22}\) Wind speeds between 3 and 8 m/s occur with about 70% probability (Figure 2B). For the 5-year dataset, the scale parameter for NEOM city, which is on the coast, is much higher than that for Tabuk city, which is inland.\(^{7}\) Also, the scale parameter for the coastal city of Al Wajh\(^{7}\) is closer to that of NEOM, but it is still smaller than the scale parameter for NEOM, which indicates a higher mean wind speed.

NEOM is a suitable site for wind energy. The power density is in the range of 150-250 W/m\(^2\) for the evaluated individual years (Table 3), with a minimum of 153 W/m\(^2\) in 2018 and a maximum of 250 W/m\(^2\) in 2017. The annual energy density ranged from 1338 kWh/m\(^2\) in 2018 to 2189 kWh/m\(^2\) in 2017; the minimum and maximum energy densities correspond to the minimum and maximum power densities. Values were in the middle for the whole 5-year dataset, with an annual power and energy densities of 193 W/m\(^2\) and 1693 kWh/m\(^2\), respectively. Hence, the site can be classified at least as Class 3, or suitable for commercial use of wind turbines at great heights.\(^5\)

### 3.2 | Diurnal and monthly variation in wind speed

The wind speed follows a consistent diurnal pattern in each of the evaluated individual years (Figure 5). The highest hourly wind speeds occur after midnight and around noon. The wind reaches its maximum diurnal speed at around 2-3 AM with wind speed averages that ranged from 5.10 m/s in 2018 to 6.14 m/s in 2017. Then, the wind speeds decrease slightly before peaking again around noon. The wind speeds decline in the afternoon until they reach their minimum at around 8 PM when the average wind speed goes as low as 3.24 m/s.

The monthly mean wind speed is largest in the summer and smallest during the fall and winter (Figure 6, Table S1). In particular, June and September have the highest mean wind speed, while the minimum mean wind speed occurred in October, November, December, January, or February in the evaluated years. The mean wind speed ranged from 3.27 m/s in February 2018 to 7.07 m/s in June 2017, while the standard deviation varied from 1.59 m/s in November 2018 to 3.24 m/s in March 2015. Because the most probable wind speed ranges between 3.02 m/s in January 2015 and 8.12 m/s in June 2017,
wind speeds mostly exceed the typical cut-in speed of 3 m/s for wind turbines, and a wind farm is likely to be profitable at the site. The ideal wind speed, which ranged from 4.21 m/s in January 2014 to 11.78 m/s in March 2015 with an average of 8.38 m/s, shows that wind turbines with a rated speed of 8 m/s will perform better at the site. The ideal wind speed of 10.3 m/s reported in the NEOM fact sheet is in the high end of this range. The minimum power and energy densities occurred in January 2014, with the values of 28 W/m² and 21 kWh/m², respectively (Table S2). The maximum power and energy densities occurred in March 2015 with values of 441 W/m² and 328 kWh/m², respectively.

### 3.3 Economic analysis of wind turbines

A 3.2-MW wind turbine is the optimal wind turbine (Figure 7). It produced the highest capacity factor, which resulted in producing the maximum energy output in all of the evaluated years—even more than GE 3.6-MW wind turbine (Figure 7, Table 4). As a result, the 3.2-MW wind turbine has the lowest LCOE. The annual capacity factor for this wind turbine ranged from 32% in 2018 to 41% in 2017, and the LCOE varied between 6.99¢ per kWh in 2017 and 8.32¢ per kWh in 2018 (Figure 7, Table 4). The monthly capacity

### TABLE 3 Shape and scale parameters and annual power and energy densities in NEOM city

| Year | k   | c (m/s) | p (W/m²) | E (kWh/m²) |
|------|-----|---------|----------|------------|
| 2014 | 2.03| 5.99    | 172      | 1504       |
| 2015 | 1.97| 6.12    | 190      | 1663       |
| 2016 | 2.03| 6.38    | 208      | 1828       |
| 2017 | 2.01| 6.76    | 250      | 2189       |
| 2018 | 1.98| 5.70    | 153      | 1338       |
| (2014-2018) | 1.99 | 6.18 | 193 | 1693 |

![FIGURE 5](image-url) Diurnal variation of wind speed (10 m data)

![FIGURE 6](image-url) Monthly variation of wind speed (10 m data)
factor, which reaches a peak of 53%, shows that the 3.2-MW wind turbine performs the best throughout the year (Figure 8). It has a higher swept area and lower cut-in and rated wind speeds (see Section 2.5). Therefore, the machine is able to capture more low wind speeds, and it can run at its maximum rated power for a longer time. In a different location where the mean wind speed is higher, the 3.6-MW wind turbine could be the optimal choice. Therefore, the 3.2-MW wind turbine is selected.

The levelized costs of energy in Table 4 are higher than the global average of 6¢ per kWh and the average cost of electricity in Saudi Arabia (as of June 2019) of 6¢ per kWh. The capital cost and the fixed and variable O&M costs could be high because they are based on global averages; the cost of labor in Saudi Arabia is much lower than in Europe and America. Also, wind energy revenues tend to grow as the electricity prices usually tend to increase. A study of a combination of 600 kW wind turbines in different cities on the west coast of Saudi Arabia showed that LCOE varies between 5.36¢ per kWh and 7.11¢ per kWh; the study assumed a discount rate of 5% and a capital cost of $958 per kW, which is similar to the assumptions made in this study. Moreover, the prices would be more precisely calculated when more wind farms are installed in the country and a trend of local prices is established.

The LCOE estimated for NEOM was very high compared to bids for a new 400-MW wind farm project called Dumat al-Jandal. This project, which is in the northern part of Saudi Arabia, received bids for the LCOE ranging from 2.13¢ to 3.38¢ per kWh. For NEOM, the LCOE was estimated based on the assumption that the capital cost of the wind turbine is the same as the global weighted average. As mentioned before, the total installed cost of wind turbines varies from $1000 to $2800 per kW. Also, the discount rate in Saudi Arabia varies in multiple studies between 0%, 5%, and 8%. The fixed O&M costs have a high range from $41 to $76 per kW. Figure 9 shows the capital cost needed to achieve a specified LCOE for a range of discount rate and fixed O&M cost. The global average LCOE of 6¢ per kWh can be matched in about 60% of the range considered (Figure 9A); capital costs would need to be smaller than the range mentioned for high discount rates and high fixed O&M costs. The bids for Dumat al-Jandal cannot be matched with the range of capital costs (Figure 9B); for fixed O&M costs below $36/kW, the bids can be matched, but the capital cost has to be smaller than about $300/kW.

### 3.4 Case study of a 320-MW wind farm

#### 3.4.1 Financial analysis

The financial indicators show that a wind farm consisting of 100 3.2-MW wind turbines is profitable. The LCOE for 100 units with a capacity factor of 41% is 6.6¢ per kWh, which is similar to the value in Table 4 in 2017. The net present value

**FIGURE 7** Annual capacity factor for different wind turbines (80 m elevation)

**TABLE 4** Energy output (MWh) and levelized cost of energy for the 3.2-MW wind turbine (80 m elevation)

| Year | E (MWh) | LCOE (¢/kWh) |
|------|---------|--------------|
| 2014 | 10 278  | 7.57         |
| 2015 | 10 132  | 7.64         |
| 2016 | 10 698  | 7.38         |
| 2017 | 11 611  | 6.99         |
| 2018 | 8 944   | 8.32         |
(NPV) is positive at $192,415,570, and the simple payback and equity payback are 13.8 and 10.2 years, respectively. Positive cash flows are expected from the 10th year onward (Figure 10). These results show that this type of project is profitable even without any government subsidy.

3.4.2 | Risk analysis

The median LCOE was 6.58¢/kWh, and the most frequent LCOE was 6.39¢/kWh with a frequency of 5.5% of the time. The 90% confidence interval shows that the LCOE for this type of wind farm with a capacity factor of 41% is within a range of 5.8 ¢/kWh to 7.5 ¢/kWh (Figure 11). Estimating the energy output and the capacity factor is most important to estimate the LCOE. The risk analysis of the LCOE shows that an increase in the electricity exported to grid can decrease the LCOE significantly with a standard deviation of relative impact of −0.82 (Figure 12). The second most important parameter in calculating the LCOE is the initial costs: Increasing the initial costs would increase the LCOE with a relative impact of parameter of +0.51. Similarly, increasing the O&M costs would increase the LCOE but with less effect than the initial costs.

3.4.3 | CO₂ emission and energy saved

Measured in terms of the savings of fossil fuel, the 100-turbine wind farm has substantial environmental benefit. The wind farm could annually save about 10⁶ metric tons of CO₂ that could have been produced by diesel generators. This mass of CO₂ saved is equivalent to not using 167,452 cars and light trucks or 207,793 acres of forest absorbing carbon or 2,126,254 barrels of crude oil not consumed.

**FIGURE 8** Monthly capacity factor for different wind turbines (80 m elevation)

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**FIGURE 9** A, Capital cost ($/kW) needed to achieve specified LCOE: LCOE = $0.06/kWh. The variable O&M costs are assumed to be fixed at 2¢ per kWh, and the capacity factor is assumed to be 41%. The vertical scales of the two subplots are different. B, Capital cost ($/kW) needed to achieve specified LCOE: LCOE = $0.03/kWh. The variable O&M costs are assumed to be fixed at 2¢ per kWh, and the capacity factor is assumed to be 41%. The vertical scales of the two subplots are different.
4 | CONCLUSION

We have assessed the feasibility of wind energy for the proposed city of NEOM in Saudi Arabia by fitting a PDF to modeled wind speeds, evaluating wind speed characteristics, determining the optimal rated capacity of wind turbines and their LCOE, and estimating the environmental and financial benefits. The method of minimizing the mean squared error of the difference between the Weibull distribution and the empirical distribution is the best method for representing the pattern of wind speeds in NEOM city. The shape parameter of the Weibull distribution for NEOM was similar to the coastal city of Al Wajh and inland city of Tabuk. However, the scale parameters of the Weibull distribution for NEOM were larger than those two cities. Wind speeds between 3 and 8 m/s occur with about 70% probability, and the ideal wind speed of 10.3 m/s reported on NEOM’s fact sheet is on the high end
of the range of ideal wind speeds determined from monthly averages. NEOM city can be classified as Class 3, or suitable for commercial use. A wind turbine with a rated capacity of 3.2 MW produced the highest capacity factor and lowest LCOE: The capacity factor is as high as 41%, and the LCOE is as low as 6.99¢ per kWh. The LCOE is higher than the global weighted average, but the assumptions in the analysis could have led to overestimating LCOE. The calculations for a 320-MW wind farm showed that installing a wind farm on this site is financially viable, and it can provide environmental benefits equivalent to not using 2 126 254 barrels of crude oil per year. As more wind energy is developed in the region, specifying the components of the cost with more certainty will be possible, and the uncertainty in the LCOE can be reduced.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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