4E analysis of the horizontal axis wind turbine with LCA consideration for different climate conditions

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Abstract

Rising concerns about greenhouse gas emissions from fossil fuels have made it important to pay attention to renewable energy sources. In this regard, using wind turbines to use the potential of wind energy as a source of clean energy is being developed. This study developed a numerical model of a horizontal axis wind turbine in MATLAB software. A multicriteria analysis based on energy, exergy, economic, and environmental analysis has been performed to policy-making and evaluate the potential of wind energy systems. Six cities of Buenos Aires, Harare, Madrid, Melbourne, Shiraz, and Washington have also been analyzed as a case study to examine the impact of different climates on the result of these criteria. According to energy analysis, Melbourne is the best choice with Temperate Oceanic Climates and average energy efficiency of 17.1%. From an exergy point of view, Harare, which has Oceanic Subtropical Highland Climates, is the best choice, with an average exergy efficiency of 11.6%. In terms of the Levelized cost of energy, Melbourne is also known as the most economical city, with an energy cost of $0.14 per kWh. Also, based on the environmental aspect of the analysis, which represents the carbon footprint, Shiraz, with the Cold–Summer Mediterranean Climate and the lowest carbon emission per year, is the most optimal option.

KEYWORDS

4E analyses, environmental analysis, horizontal wind turbine, life cycle assessment

1 | INTRODUCTION

The progress of human societies in social, economic, and industrial terms has led to an increase in energy needs in various dimensions. This increase in energy consumption has resulted in concerns about environmental pollution, extensive climate change, and energy resource depletion.1,2 Therefore, using clean fuels and energy has become more crucial to reducing carbon dioxide emissions (one of the most destructive greenhouse gases) while providing the energy demand.3,4 Among the various types of renewable energy, such as solar, geothermal, and tidal energy, wind energy has drawn the attention of many countries due to its unlimited source, relative stability, and easy access.5 The most common way to use wind energy is to employ wind
turbines, which can convert wind kinetic energy directly into electrical energy, as presented in Figure 1.6

In recent years, due to the development of human society and the increase in energy demand, more attention has been drawn to renewable resources, particularly wind energy.7 The growing trend of using wind energy potential is illustrated in Figure 2.

Wind turbines are divided into two general categories: vertical and horizontal. Since horizontal axis turbines have higher power coefficients and torque than vertical axis types, this turbine type is more common.9 The production capacity of horizontal axis turbines is strongly affected by the wind intensity in the site where the turbine is located. Therefore, choosing the geographical location of these turbines is vital.10 Also, each geographical region has a specific climate that affects the turbine's efficiency by determining the weather conditions such as wind speed and intensity, relative humidity, and altitude.11 Therefore, based on the region's geographical conditions, intensity, and wind potential, it is necessary to use a suitable turbine compatible with the local conditions.12

According to Köppe's classification, the world's climate is divided into five general classes: Zone A (tropical or equatorial zone), Zone B (arid or dry zone), Zone C (warm/mild temperate zone), Zone D (continental zone), and Zone E (polar zone).13

Due to the different climates and environmental conditions, studies must be conducted on the impact of climatic conditions on wind turbines' performance. On the other hand, the wind turbine's performance can be described using concepts such as energy, exergy, economic, and environmental analyses. The energy analysis is related to the amount of power produced by the wind turbine.14 Exergy analysis is the maximum theoretical work that results from the interaction between the system and the environment until they both (system and environment) reach equilibrium.15 The economic analysis is a levelized cost of energy (LCE) analysis per kWh. The environmental analysis is the amount of carbon dioxide a system releases (carbon footprint).12 In this regard, several studies have been conducted to evaluate produced power parameters, energy and exergy analysis, and economic and environmental considerations (4E analysis).

In the field of energy and exergy analyses, Omer Baskut et al. presented a model for predicting the system efficiency of a wind turbine power plant by considering temperature change, humidity, and atmospheric pressure. For different operating conditions, the plant's exergy efficiency was between zero to 68.2%.16 Al-Sulaiman performed an exergoeconomic analysis of an ejector-augmented shrouded horizontal axis turbine and improved turbine performance by increasing the input area ratio of the ejector and the wind speed, LCE significantly decreases per kWh.17

Various parameters have been studied in terms of economic analysis. Hence, Friedman presented a method for determining the economic efficiency of a wind turbine and considered the parameters of annual operating cost, interest rate, turbine's life, and energy cost are effective in this method.18 In another study, Li et al. proposed a method to accurately evaluate the economic viability of a small-scale wind turbine.19 Ryan Wiser et al. researched the economic performance of wind energy in the United States. Using innovative

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**FIGURE 1** Power generation process by wind turbine
methods, they obtained a profit-to-cost ratio of 18 to 1 and an internal rate of return of 15.4%. Grieser et al. studied the economic potential of employing small-sized wind turbines for domestic use in Germany. Their experimental studies found that a minimum average wind speed of 4–4.5 m/s is required, and the best place to install these turbines is on the outskirts of cities and rural areas due to lower building density.

Regarding the technical aspect of wind turbines and wind energy potential, Farhan Khahro et al. compared the experimental data with the results of Weibull’s and Rayleigh’s distribution functions used for the calculation of wind power density, by which they selected the GE45.7 wind turbine with a capacity factor of 0.56, and has an annual energy production capacity of 11.20 GWh. Dabbaghian et al. studied wind energy potential in Bushehr city to use wind turbines effectively and efficiently. They employed the Weibull distribution function to calculate the wind power density, and they found Bord Khun City, with an average wind power density of 265 W/m² is the best place to use wind energy. From an economic point of view, Ali Mostafaeipour et al. studied wind energy potential in Zahedan. They used Weibull’s distribution function to obtain the site’s wind power and energy density. Then, by examining four different types of turbines, they chose the Proven 2.5 kW, which was more economical.

Regarding the environmental aspect of using wind turbines, Uddin and Kumar studied greenhouse gas emissions and evaluated the environmental effects of a vertical axis wind turbine and a horizontal axis wind turbine (HAWT) using the LCA method. Wang et al. evaluated the LCA method’s greenhouse gas emissions on onshore and offshore wind turbines. They found that the onshore system is the most environmentally friendly.

Several studies performed wind turbines’ 4E analyses. Allouhi evaluated wind energy utilization and considered the same condition in two coastal areas in the north and south of Morocco with distinct climates for the plant. The results showed that the southern region, with a stability index of 1.74 (7.4% higher than the northern region) and lower electricity costs of $13.42/kWh, and lower environmental degradation (42.73 TonCO₂/kW reduction), had better conditions to use the wind potential. In another study, Ehyaei et al. analyzed a wind turbine’s energy, exergy, and economics. They performed the analysis for two cities, Manjil and Tehran, and they observed that Manjil with an energy efficiency of 3.33%, and exergy efficiency of 1.80%, and an energy cost of $0.078/kWh in comparison to Tehran, with an energy efficiency of 1.08%, and exergy efficiency of 6.43% and an energy cost of $0.23/kWh is a better option to use wind energy potential. The results of the carried out multicriteria for other energy systems are listed in Table 1.

The point to consider in previous studies is that in research, all aspects of wind turbines have not been studied and have been addressed on a case-by-case basis. Therefore, there is a lack of comprehensive research that examines all aspects of turbine operation. This issue can greatly help energy policymakers discuss the location...
and feasibility of the construction of wind farms. According to experimental and numerical research conducted on wind turbines (including technical analysis, optimization, energy, exergy, economic and environmental analyses, wind energy potential, and environmental conditions) in this study, the effect of climate change on the performance of wind turbines in the context of multicriteria analyses including 4E aspects are analyzed, and to classify the appropriate climate in each area, and the obtained results are compared. To achieve the primary purpose of this study, six cities in six different continents of the world and with distinct climates are selected as representative of their content to study the factors of energy and exergy efficiencies, energy cost balance, and amount of produced carbon dioxide (considering the life cycle of the system and the cost of produced carbon dioxide based on incentive and punitive policies).34

In conclusion, a general classification is presented from the perspective of each of the four categories of energy, exergy, economic, and environmental. Therefore, the main objective of this paper is to find the optimum (concerning the efficiency of energy and exergy, environmental impacts, economic effects, and climate conditions) place for constructing a wind turbine power plant. Finally, the novelty of this paper is analyzing the effect of different climate conditions on the performance of HAWT using simultaneous 4E analyses. Given that global warming has a remarkable effect on climate change, and according to the point that greenhouse gas emissions, especially carbon dioxide, have the most significant impact on global warming, environmental analysis in this study is done from the perspective of Carbon emission.

| Author         | Year | Principles | Type of system          | Result                                                                 |
|----------------|------|------------|-------------------------|------------------------------------------------------------------------|
| Caliskan30     | 2015 | Energy     | Solar PV                | For the same 20 kW production power, natural gas base plants and wind turbine plants are the most energy and Exergy efficient for nonrenewable and renewable energy resources, respectively. |
| Ehyaei et al.31| 2019 | Energy     | Parabolic solar collectors | The final optimized value of energy, exergy efficiencies, and the cost is 29.22%, 35.55%, and 0.0142 $/kWh.                               |
| Abuska et al.32| 2017 | Energy     | V-groove solar air collector | The copper v-groove collectors are preferable due to their performance and the payback period of 4.3 to 4.6 years, which is much longer than the lifetime of the collector with an enviro-economic cost value of 4.5 to 5.77 $/year. |
| Caliskan33     | 2018 | Energy     | Parabolic solar collectors | In solar collectors, the major portion of the energy is lost by radiation. The energy efficiency is 25.40% which is higher than the corresponding 0.732% exergy efficiency. EXEN result, which is 0.0727 kg CO₂/day, is lower than the corresponding 0.0777 kg CO₂/day environmental one. Consequently, the enviroeconomic result is 0.00112 $/day, and EXENEC result is 0.00105 $/day. So, the exergy-based EXENEC method is more reliable. |

2 | BACKGROUND

2.1 | Location description

Due to the greater potential of wind energy and greater adaptability of wind turbines in warm and temperate climates, to evaluate the effect of climates on the performance (4E analyses) of the wind turbines, six cities as representatives of the six continents and six distinct climates were selected from the warm and temperate climates (class C). The climatic characteristics of each city and its geographical coordinates are presented in Table 2.

Other climate variables affecting the 4E analyses of wind turbines, such as the wind speed and the monthly measurements of wind speed range, are presented in Figure 3 separately for each city.
Also, the working hours of the turbine based on the type of turbine in a specific range of speed, which leads to power generation, is demonstrated in Table 3.

### 2.2 System description

To study the effect of climate change on energy and exergy efficiencies and to calculate energy cost balance and environmental and economic studies, it is necessary to select a wind turbine with a specific size as a numerical modeling reference. Therefore, the Bergey Excel S 10 kW horizontal axial wind turbine, previously used in studies of Ehyaei et al., is chosen as a numerical modeling reference. The general properties of the Bergey Excel S wind turbine are illustrated in Table 4. These properties include geometric dimensions, turbine operating range speeds, turbine tolerable temperature range, and gearbox specifications.

The system of this study includes a volume control from which the input stream (wind energy) enters from its borders, and while transferring power, it makes the turbine blades rotate, and the output stream with the wasted energy is removed from it. The schematic of the system control volume is demonstrated in Figure 4.

### 3 Mathematical Modeling

#### 3.1 Energy analysis

The sensitivity of the power generated by the wind turbine to the wind speed is significantly high that only
in a specific range of speeds the turbine’s output power is equal to its nominal value. The high sensitivity of the output power to wind speed should be related to the wind’s kinetic energy. Wind kinetic energy is a function of the third power of wind speed. Therefore, small speed changes should significantly change its kinetic energy, and as the output power of the turbine is directly related to kinetic energy, this sensitivity to wind speed is reflected in the output power of the turbine. An excessive increase in wind speed also leads to a sharp increase in the turbine blades’ centrifugal force, damaging the turbine physically. Therefore, at high furling wind speed, the turbine is taken out of the circuit, or in other words, a no-load condition is enforced on it.

Moreover, the turbine will be out of orbit when the speed limit exceeds the maximum speed allowed for the turbine or less than the minimum speed required to produce power. The power generated by the wind turbine can be calculated from the following equation:

\[
P_e = \begin{cases} 
0 & (u < u_c), \\
A + Bu^k & (u_c \leq u \leq u_r), \\
P_{er} & (u_r \leq u \leq u_f), \\
0 & (u > u_f), 
\end{cases}
\]

(1)

where \( P_{er} \) is the nominal power of the turbine and \( u_c \) is the minimum speed required to generate power, called cut-in speeds. \( u_r \) denotes the threshold speed for reaching the nominal power generation, called the rated speed. \( u_f \) presents the maximum speed used to generate power by the turbine, which is called furling speed. The coefficients \( a \) and \( b \) are derived from the below relations:

\[
a = \frac{P_{er}u_c^k}{u_c^k - u_r^k},
\]

(2)

\[
b = \frac{P_{er}}{u_r^k - u_c^k},
\]

(3)
$K$ is also the Weibull’s shape index parameter, and it is derived from below equation:

$$k = \left( \frac{\sigma}{u} \right)^{-1.086}.$$  \hspace{1cm} (4)

Equations (5) and (6) are used to calculate $\sigma$ and the mean velocity $\bar{u}$:

$$\sigma^2 = \frac{1}{n-1} \left[ \sum_{i=1}^{n} m_i u_i^2 - \frac{1}{n} \left( \sum_{i=1}^{n} m_i u_i \right)^2 \right],$$  \hspace{1cm} (5)

$$\bar{u} = \frac{1}{n} \sum_{i=1}^{n} m_i u_i,$$  \hspace{1cm} (6)

where, $m_i$ is the frequency of the calculated speed ($u_i$) among all the measured times ($n$), and the value of this parameter for each city and month is presented separately in Figure 3. Hence, by calculating the above relations, the useful output power of each speed was obtained, and by averaging the powers monthly, the efficiency of the wind turbine for each city is obtained as follows:

$$\eta_{\text{energy}} = \frac{P_{\text{r,ave}}}{P_{\text{r}}}.$$  \hspace{1cm} (7)

### 3.2 Exergy analysis

Generally, different types of exergy can be divided into four categories: physical, chemical, kinetic, and potential. Therefore, the total exergy is obtained from the sum of the above equations:

$$e_T = e_K + e_P + e_{ph} + e_{ch},$$  \hspace{1cm} (8)

where $e$ represents the specific exergy (kJ/kgK) and the subscripts $K, P, Ph,$ and $Ch$ represent the kinetic exergy, potential exergy, physical exergy, and chemical exergy, respectively. Due to the lack of height difference between input and output streams in horizontal axis turbines, the potential Exergy is negligible. To calculate the kinetic exergy changes in a wind turbine, the input and output of the kinetic exergy and the value of their difference are calculated according to the following equations:

$$e_{K,\text{in}} = \frac{1}{2} u_i^2,$$  \hspace{1cm} (9)

$$e_{K,\text{out}} = \frac{1}{18} u_i^2.$$  \hspace{1cm} (10)

The following equation is used to calculate the changes in physical exergy:

$$e_{ph} = (c_{pa} + \omega c_{pw}) T_0 \left[ \frac{T}{T_0} - 1 - \ln \left( \frac{T}{T_0} \right) \right] + (1 + 1.6078\omega) R T_0 \ln \frac{P}{P_0},$$  \hspace{1cm} (11)

where $c_{pa}$ denotes the thermal capacity of air at constant pressure and $c_{pw}$ is the thermal capacity of water vapor at constant pressure. Furthermore, $\omega$ is the moisture, and $R$ is the gas constant. $T_0$ and $P_0$ are standard temperature and pressure, which are 288.15 K and 1 atm, respectively. To calculate the inlet and outlet pressure of wind turbines, the below equation is used:

$$e_T = e_K + e_P + e_{ph} + e_{ch},$$  \hspace{1cm} (8)
The input and output of chemical exergy in wind turbines can be derived from \(35\):

\[
e_{\text{ch}} = RT_0 \left(1 + 1.6078\omega\right)\ln \left(\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega}\right) + 1 + 1.6078\omega \ln \left(\frac{\omega}{\omega_0}\right).
\] (13)

The below equation is used to calculate the amount of airflow that sweeps the turbine surface \(29\):

\[
m_\alpha = \frac{2}{3} \rho_\alpha A_s u,
\] (14)

where \(A_s\) is the area of swept and \(\rho_\alpha\) denotes the density of air. Hence, the exergy efficiency is derived from the relation \(35\):

\[
\eta_{\text{exergy}} = \frac{P_{\text{e,ave}} - Q_{\text{loss}}}{m_\alpha (e_{\text{T,in}} - e_{\text{T,out}})} = \frac{P_{\text{e,ave}}}{\frac{8760}{L}C_i I}\frac{1}{u_{\text{max}}^2}.
\] (15)

where \(u_{\text{max}}\) is the maximum speed in the month and \(Q_{\text{loss}}\) represents the waste heat of the turbine, and its value is derived from the relation (16). Since its value is minimal, it is not very important \(35\):

\[
Q_{\text{loss}} = m_\alpha C_p (T_{\text{out}} - T_{\text{in}}).
\] (16)

### 3.3 Economic analysis

In the economic analysis of wind turbines, the main purpose is to calculate the cost per kWh of energy produced by wind turbines, which cost is expressed as below \(29\):

\[
C_E = C_I + C_O + C_{\text{ins}},
\] (17)

where \(C_I\) represents the initial cost of equipment, \(C_O\) denotes the cost of maintenance and \(C_{\text{ins}}\) is the cost of insurance ($/kWh). The initial cost of equipment can be written as \(29\):

\[
C_I = \frac{CI}{8760P_{\text{e,ave}}}.
\] (18)

here, \(C\) is the initial cost of installing the equipment ($), and \(I\) is the coefficient of the equipment lifetime (\(L\)) and the interest rate \((i)\) and can be calculated as below \(29\):

\[
P = P_0 + \frac{u^2}{2}.
\] (12)

The wind turbine lifetime and interest rate values are presented in Table 4. Also, according to the available references, the total maintenance and insurance costs are 6% of the capital investment cost.

### 3.4 Environmental analysis

Environmental analysis in energy systems includes various aspects. For example, in the environmental analysis of wind turbines, carbon emissions, noise pollution, extinction of bird wildlife, and so on, can be examined. Therefore, carbon emission analysis is only part of the environmental analysis of wind turbines. However, given the international concerns about pollution caused by greenhouse gas emissions, which are known as the main cause of global warming, it can be said that the issue of carbon emissions (carbon footprint) is the most important and main environmental challenge of energy systems. Therefore, in this study, carbon emission (carbon footprint) is considered the main item of environmental analysis, and in all parts of environmental analysis, the goal is to calculate the carbon footprint.

#### 3.4.1 EnergoEnvironmental (ENEN)

Faizal et al. \(41\) presented an environmental analysis of the system according to below equation.

\[
x_{\text{CO}_2} = y_{\text{CO}_2} \times P_{r} \times t_{\text{working}},
\] (20)

where \(x_{\text{CO}_2}\) is the amount of carbon dioxide released at the considered time and \(y_{\text{CO}_2}\) denotes the amount of CO2 emission (carbon footprint) of the reference energy system obtained from the life cycle assessment (LCA) method. \(P_{r}\) represents the nominal power of the reference system and \(t_{\text{working}}\) is the operating time of the system.

LCA is one of the widely used methods in the environmental assessment of processes and products. In fact, LCA is one of the environmental assessment methods that complete evaluations besides technical and economic assessment. \(41\) This method helps ensure that the subject is also environmentally safe in addition to technical and economic points of view. A general assessment of the product's environmental effects, from the extraction process to the disposal and recycling process, is performed in this method, leading to the calculation of the total pollution.
The value of $y_{CO_2}$ of a wind turbine is considered to be about 0.01 kgCO₂/kWh.\textsuperscript{42,43}

### 3.4.2 ExergoEnvironmental (EXEN) analysis

EXEN analysis is another method proposed for environmental assessment, which was presented by Kaliskan et al. and is given as\textsuperscript{33}:

$$x_{ex,CO_2} = y_{CO_2} \times \dot{E}_T \times t_{working}. \quad (21)$$

The difference between EXEN and ENEN analyses is that in exergoenvironmental analysis, the nominal power of the system is used ($P_{er}$), however, in EXEN analysis, the total exergy ($\dot{E}_T$) is employed.

### 3.4.3 EnergoEnviroEconomic analysis (ENENEC)

ENENEC analysis is presented in energy systems by Deniz et al.\textsuperscript{44} according to the below equation:

$$C_{CO_2} = x_{CO_2} \times c_{CO_2}, \quad (22)$$

where $C_{CO_2}$ is the enviroeconomic parameter and $c_{CO_2}$ denotes the carbon dioxide price. The obtained parameter is the cost of carbon dioxide emissions produced in the system, and it is considered a method for evaluating energy systems from an environmental perspective.\textsuperscript{45} To prevent climate change and other phenomena such as global warming, methods and policies are proposed to reduce carbon dioxide emissions as much as possible.\textsuperscript{46} With an economical approach, pricing the carbon method seeks to make environmental impacts more tangible for a more accurate analysis of the problem and reduces the environmental impact of energy systems by formulating incentive or punitive (financial penalty) policies. A schematic of the interaction of environmental parameters is illustrated in Figure 5. The cost of carbon emissions varies in different countries, and according to their policies, it ranges from 13$ to 16$ per ton of produced carbon dioxide (USD 13–16 per tonCO₂).\textsuperscript{47} In this study, considering the changes in the price range, the average value of 14.5 ($/ton) is assumed to be equal to 0.0145 ($/kg) of carbon dioxide.\textsuperscript{48}

Figure 5 represents the four environmental parameters and the relationship between them. This figure is designed to better understand the relationship between the environmental domain and sections of life cycle assessment and penalty policies.

### 3.4.4 ExergoEnviroEconomic analysis (EXENEC)

EXENEC analysis is similar to ENENEC analysis, except for the calculations based on exergy. For the exergoenviron-economic analysis of energy systems, the below equation is applied\textsuperscript{30}:

$$C_{ex,CO_2} = x_{ex,CO_2} \times c_{CO_2}, \quad (23)$$

where $x_{ex,CO_2}$ is derived from the EXENEC analysis of the system mentioned above.

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**Figure 5** Environmental analysis
To analyze the horizontal wind turbine, a numerical model in MATLAB software was developed, and the effect of climate change on energy, exergy, economic, and environmental perspectives was studied. The code was written using environmental and climatic data from the meteorological information site (https://rp5.ru/Weather), the frequency of each speed range in each month considering wind speed is calculated at the first step (Figure 3), and the operating hours of the turbine that leads to power generation is computed (Table 4). Afterward, the useful power of the turbine, energy and exergy efficiencies, the Levelized energy cost, environmental parameters (ENEN and EXEN), and enviroeconomic parameters (ENENEC and EXENEC) of each month and each city were calculated and presented, as can be seen in Figure 6.

As shown in Figure 6, at the primary stage of the utilized algorithm, all data from different perspectives (weather database, wind turbine parameters, environmental and economic parameters) are loaded into the RAM. The second stage is energy analysis. In this stage, as the first step, with the help of wind speed data acquired from the previous stage, it is checked whether the turbine is generating power or not. If the wind turbine is not generating power (i.e., the wind speed is too high or too low for the wind turbine), the algorithm goes to the next wind speed data. Additionally, if the wind turbine generates power, it is checked whether it generates nominal power or not. In the case of generating nominal power, its exact value will be used in future stages of the algorithm, and in the case of not generating nominal power, the generated power is calculated using the mathematical model. As the final step of this stage, the monthly average of the energy efficiency is calculated using the data achieved from the previous steps. The third stage is exergy analysis. In this stage, the exergy analysis is performed by using both the loaded values into the RAM and the values computed from the energy analysis stage. The fourth stage is economic analysis. In this stage, with the help of the wind turbine and economic parameters from stage 1, the unit cost of energy is calculated. Finally, the fifth stage is the environmental analysis. In this stage, the calculated values from the second and third stages are used to calculate ENEN, EXEN, ENENEC, and EXENEC parameters.

**FIGURE 6** Flowchart of numerical modeling
5 | VALIDATION

Modeling validation is integral to the study before presenting numerical modeling results. The results obtained from numerical modeling are compared with the information in the data provided by the company. Therefore, using each city's average wind speed, the turbine's output power is achieved using Figure 7, extracted from the company's catalog. Hence, it is compared with the results of numerical modeling.

Figure 7 shows the relationship between wind speed and turbine output power. This figure is taken from the results of experimental tests of the manufacturer and is a suitable reference for validating research results. To validate the results, the output power of the turbine is derived from numerical modeling in Table 5, which is compared to the results extracted from Figure 7.

According to the results, the average error value of the turbine's useful power is 3.28%, which proves the validation of numerical modeling performance.

6 | RESULTS AND DISCUSSION

According to the main purpose of this study, the effect of distinct climates on wind turbines, research with the main focus on fields of energy, exergy, economy, and environment is defined. Hence, a numerical model is developed based on Bergey's three-blade horizontal axis turbine, and the basic parameters are calculated as presented in Figure 8. The interaction of the defined parameters with the main fields of energy, exergy, economy, and the environment is also determined in Figure 8.

The items shown in Figure 8 are the study's objectives, which are summarized and described below. These parameters are presented in the form of four main areas: energy, exergy, economic, and environmental. Discussing the most effective climatic parameters on the wind turbine output power, such as speed and intensity, is necessary before presenting the results of 4E analyses and the two subdomains, EXENEC and ENENEC. Considering the six cities Buenos Aires, Harare, Madrid, Melbourne, Shiraz, and Washington as representatives of

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**FIGURE 7** Bergey excel S 10 kW power curve

**TABLE 5** Validation mathematical modeling

| Cities     | Power curve | Mathematical model | Error (%) |
|------------|-------------|--------------------|-----------|
| Buenos Aires | 0.82       | 0.837              | 2.07      |
| Harare     | 0.63       | 0.609              | 3.33      |
| Madrid     | 1.51       | 1.56               | 3.31      |
| Melbourne  | 1.65       | 1.71               | 3.44      |
| Shiraz     | 0.39       | 0.413              | 5.30      |
| Washington | 0.87       | 0.847              | 2.64      |
| Mean error |            |                    | 3.28      |
six continents with distinct climates of class C (warm and temperate), it is important to study the wind speed and stability of each climate in each month of a year. Therefore, the monthly average wind speed for each city is presented in Figure 9. Since the research has an annual view, all the presented data are calculated daily for each month.

Figure 9 values are calculated using the frequencies of each speed range. These values are calculated monthly, in accordance with Figure 3. The presented data in Figure 9 indicate that the lowest average speed is related to Shiraz, and the highest is for Melbourne. It is also observed that each city’s maximum average wind speed occurs in a particular month, depending on the geographical conditions. Mean speed and the ratio of speed distribution to mean speed are the most significant wind turbine analysis parameters. The lower the ratio, the better the wind turbine output can be expected. Furthermore, the maximum wind speed of each city each month is presented in Figure 10 to determine the ratio.

The values presented in Figure 10 show the scattering of the velocity data from their mean to max value. As can be seen, the highest difference between the maximum and average speed, or the highest standard deviation, occurs in Shiraz and the lowest in Washington.

### 6.1 Energy analysis

According to Figure 8 and for energy analysis, it is necessary to determine the energy distribution in the system. As mentioned in Figure 4, the distribution of energy in the system occurs when the wind energy enters the system borders as input, and part of it is wasted due to heat transfer, and finally, the remaining amount as useful power converts to electrical power. The useful power output of the turbine is demonstrated in Table 6.

Studying the impact of climate change in different months using energy balance and analyzing its parameters is time-consuming and difficult. Therefore, utilization of the concept of energy efficiency, which is the most
fundamental parameter to describe the system’s energy performance, is a better option. The energy efficiency of a horizontal wind turbine system in six cities: Buenos Aires, Harare, Madrid, Melbourne, Shiraz, and Washington during other months of the year is illustrated in Figure 11.

The purpose of Figure 11 is to show the behavioral trend of the energy efficiency chart on a monthly basis to understand this parameter’s behavior better. According to Figure 11, energy efficiency is experiencing a dynamic trend resulting from the changes in weather conditions each month. The remarkable point in this figure is that the wind turbine efficiency will reach 22% in the best case. This shows that the turbine converts only a small part of the wind energy potential into useful energy. However, to determine the most suitable climate from the energy point of view, the annual average energy efficiency for each city is demonstrated in Figure 12.

Figure 12, which is the average of the results of Figure 11, is drawn to create a reference for comparison.
between different climates so that it can be used to select the optimal climate from an energy perspective. As shown in Figure 12, Melbourne has the highest energy efficiency, and in contrast, Shiraz has the lowest value. The reason for this can be attributed to the higher average speed in Melbourne as well as the lower dispersion of wind speed data. In other words, these results show that wind speed values are always in the range of wind turbine power generation. It can be concluded that in terms of energy, Melbourne with Cfb climate (temperate oceanic climates) with an average energy efficiency of 17.1% is the best option.

### TABLE 6 Monthly generated power

| Months | January Generated power (kW) | February | March | April | May | June |
|--------|-----------------------------|----------|-------|-------|-----|------|
| Buenos Aires | 0.58 | 0.47 | 0.78 | 0.96 | 0.78 | 1.05 |
| Harare | 0.58 | 0.95 | 0.33 | 0.51 | 0.53 | 0.51 |
| Madrid | 1.14 | 1.78 | 1.95 | 2.01 | 1.44 | 1.53 |
| Melbourne | 1.42 | 1.50 | 1.60 | 1.54 | 1.65 | 1.32 |
| Shiraz | 0.42 | 0.47 | 0.64 | 0.62 | 0.46 | 0.50 |
| Washington | 1.41 | 1.06 | 1.11 | 1.01 | 0.48 | 0.70 |

| Month | July Generated power (kW) | August | September | October | November | December |
|-------|---------------------------|--------|-----------|---------|-----------|----------|
| Buenos Aires | 0.76 | 0.58 | 0.80 | 1.51 | 1.21 | 0.57 |
| Harare | 0.59 | 0.39 | 0.35 | 0.82 | 0.79 | 0.96 |
| Madrid | 1.65 | 1.24 | 1.30 | 1.13 | 1.90 | 1.64 |
| Melbourne | 2.07 | 1.99 | 1.83 | 1.77 | 2.10 | 1.73 |
| Shiraz | 0.51 | 0.41 | 0.35 | 0.31 | 0.19 | 0.09 |
| Washington | 0.57 | 0.63 | 0.57 | 0.76 | 0.97 | 0.88 |

**FIGURE 11** Monthly energy efficiency of different cities
6.2 Exergy analysis

To analyze the system's Exergy, a similar process of energy analysis has been adopted and, the exergy efficiency of wind turbines in six cities including, Buenos Aires, Harare, Madrid, Melbourne, Shiraz, and Washington during other months of the year is presented in Figure 13.

According to Figure 13, Harare reported the maximum exergy efficiency value in a case study of the mentioned cities. The parameters of Equation (15), particularly the maximum speed that affects the total exergy, should be noticed for a better explanation. As illustrated in Figure 10, Harare has the lowest maximum speed value of all months. Even though in Table 6, the lowest output power values belong to
TABLE 7  Monthly total exergy

| Cities  | January Total exergy (kW) | February | March  | April    | May    | June    |
|---------|---------------------------|----------|--------|----------|--------|---------|
| Buenos Aires | 13,963.19                | 47,125.75| 18,585.00 | 30,677.12 | 13,963.19 | 18,585.00 |
| Harare  | 3016.05                   | 7149.15  | 3016.05 | 4789.37  | 3016.05 | 3016.05 |
| Madrid  | 68,601.13                 | 68,601.13| 68,601.13 | 95,773.49 | 38,314.98 | 38,314.98 |
| Melbourne | 57,193.21                | 68,601.13| 47,125.75 | 30,677.12 | 38,314.98 | 38,314.98 |
| Shiraz  | 10,179.16                 | 18,585.00| 13,963.19 | 13,963.19 | 18,585.00 | 10,179.16 |
| Washington | 24,128.38                | 24,128.38| 24,128.38 | 30,677.12 | 7149.15  | 13,963.19 |

| Cities  | July Total exergy (kW)  | August | September | October | November | December |
|---------|-------------------------|--------|-----------|---------|----------|----------|
| Buenos Aires | 18,585.00               | 10,179.16 | 18,585.00 | 57,193.21 | 24,128.38 | 18,585.00 |
| Harare  | 3016.05                 | 10,179.16 | 10,179.16 | 13,963.19 | 10,179.16 | 10,179.16 |
| Madrid  | 38,314.98               | 24,128.38 | 24,128.38 | 57,193.21 | 68,601.13 | 111,705.48 |
| Melbourne | 38,314.98               | 30,677.12 | 81,433.30 | 57,193.21 | 68,601.13 | 47,125.75 |
| Shiraz  | 10,179.16              | 10,179.16 | 129,313.06 | 7149.15  | 3016.05  | 7149.15  |
| Washington | 7149.15                 | 10,179.16 | 7149.15  | 18,585.00 | 18,585.00 | 18,585.00 |

FIGURE 14  Exergy efficiency of different cities

Harare, the total exergy rate has the lowest values, according to Table 7.

Hence, to compare cities and determine the best city and climate from the exergy point of view, the average exergy efficiency is presented annually for each city in Figure 14.

As demonstrated in Figure 14, the city of Harare has the highest exergy efficiency of all, and the city of Madrid has the lowest value. In analyzing the results, it should be stated that according to Equation (15), the exergy efficiency is inversely related to the third power of the maximum velocity, so in Harare, where the wind speed is
| Cities       | January | February | March | April | May | June |
|--------------|---------|----------|-------|-------|-----|------|
|              | Energy  | Exergy   | Energy| Exergy| Energy| Exergy|
|              | Efficiency (%) | Efficiency (%) | Efficiency (%) | Efficiency (%) | Efficiency (%) | Efficiency (%) |
| Buenos Aires| 5.83    | 4.18     | 4.70  | 1.00  | 7.77 | 4.18 |
| Harare       | 5.81    | 19.25    | 9.50  | 13.29 | 3.32 | 11.00|
| Madrid       | 11.39   | 1.66     | 17.78 | 2.59  | 19.46 | 2.84 |
| Melbourne    | 14.21   | 2.48     | 14.99 | 2.19  | 15.99 | 3.39 |
| Shiraz       | 4.17    | 4.09     | 4.69  | 2.52  | 6.41  | 4.59 |
| Washington   | 14.14   | 5.86     | 10.62 | 4.40  | 11.07 | 4.59 |

| Minnesota | July | August | September | October | November | December |
|-----------|------|--------|-----------|---------|----------|----------|
| heated    | Energy | Exergy | Energy | Exergy | Energy | Exergy |
| Buenos Aires | 7.58 | 4.08 | 5.78 | 5.68 | 8.05 | 4.33 | 15.09 | 2.64 | 12.06 | 5.00 | 5.74 | 3.09 |
| Harare    | 5.91 | 19.60 | 3.86 | 3.80 | 3.49 | 3.43 | 8.21 | 5.88 | 7.89 | 7.75 | 9.59 | 9.42 |
| Madrid    | 16.47 | 4.30 | 12.44 | 5.15 | 12.97 | 5.38 | 11.26 | 1.97 | 18.96 | 2.76 | 16.36 | 1.46 |
| Melbourne | 20.70 | 5.40 | 19.92 | 6.49 | 18.25 | 2.24 | 17.74 | 3.10 | 21.00 | 3.06 | 17.28 | 3.67 |
| Shiraz    | 5.08 | 4.99 | 4.11 | 4.04 | 3.47 | 0.27 | 3.13 | 4.38 | 1.86 | 6.16 | 0.91 | 1.27 |
| Washington | 5.67 | 7.93 | 6.31 | 6.20 | 5.73 | 8.01 | 7.57 | 4.07 | 9.74 | 5.24 | 8.85 | 4.76 |
low, the total exergy has lower values and the exergy efficiency has the highest value. Therefore, the city of Harare, with Cwb climate (oceanic subtropical highland climates) with an average exergy efficiency of 11.6%, is declared the best option in exergy.

To compare energy efficiency with exergy efficiency, the data is obtained from energy and exergy system analyses which are also presented in Table 8. Wind turbine systems’ energy and exergy efficiencies are considered separately for each city and month.

The data in Table 8 indicate the reverse behavior in the energy efficiency chart profile toward the exergy efficiency. Subsequently, in most cases where energy efficiency is significant, exergy efficiency is minimized, and vice versa. To analyze the results, it should be stated that according to the energy efficiency and exergy equations, energy efficiency is directly related to wind speed. In contrast, exergy efficiency is inversely related to wind speed, so these two parameters have different behaviors. For a better explanation, Figure 15 shows Madrid’s energy and exergy efficiencies diagrams simultaneously in different months of the year.

Figure 15 shows the relationship between energy efficiency and Exergy in different months. The irregular pattern in the graphs is the effect of different wind velocities in different months.

Regarding the accuracy of the energy and exergy fields results, monthly velocity profiles and their dispersion can be used according to Figures 9 and 10. According to these figures, the higher the average wind speed is, the higher the useful power output, leading to higher energy efficiency. Also, the closer the average wind speed is to the maximum wind speed (in other words, the lower the scatter of wind speeds), the more power the system will have to produce energy, and as a result, the system will be more stable.

6.3 Economic analysis

Regarding the economic analysis of the wind turbine system, the unit cost of energy is discussed. According to the project’s lifetime and interest rates mentioned in Table 4 and other conditions such as maintenance cost and equipment and staff insurance, by dividing the total cost to the total energy produced by the turbine, the unit cost of energy ($/kWh) is calculated. Figure 16 illustrates the monthly cost of generated electricity per city.

As shown in Figure 16, considering the same total cost in all cities, the city that produces the most power will have a lower unit cost of energy. Therefore, according to Table 6, the highest amount of useful power...
is generally related to the city of Melbourne, while the levelized cost of energy (cost per unit of energy) in this city is the lowest. The average cost per unit of energy for each city is presented in Figure 17 for comparing cities and climates.

Figure 17 demonstrates that, Shiraz has the highest cost per unit of energy and Melbourne has the lowest. Therefore, from an economic point of view, Melbourne is the optimal city with a Cfb climate (temperate oceanic climates) and a levelized energy cost of 0.14 $/kWh.
| Months          | January ENEN (kg/month) | January EXEN (kg/month) | February ENEN (kg/month) | February EXEN (kg/month) | March ENEN (kg/month) | March EXEN (kg/month) | April ENEN (kg/month) | April EXEN (kg/month) | May ENEN (kg/month) | May EXEN (kg/month) | June ENEN (kg/month) | June EXEN (kg/month) |
|----------------|-------------------------|-------------------------|--------------------------|--------------------------|-----------------------|-----------------------|-----------------------|-----------------------|---------------------|---------------------|-----------------------|-----------------------|
| Cities         |                         |                         |                          |                          |                       |                       |                       |                       |                     |                     |                       |                       |
| Buenos Aires   | 1.65                    | 2.31                    | 1.22                     | 5.75                     | 1.26                  | 2.34                  | 1.13                  | 3.47                  | 1.38                | 1.93                | 1.11                  | 2.07                  |
| Harare         | 0.99                    | 0.30                    | 0.55                     | 0.39                     | 1.26                  | 0.38                  | 0.98                  | 0.47                  | 0.90                | 0.27                | 0.99                  | 0.30                  |
| Madrid         | 1.09                    | 7.49                    | 1.17                     | 8.04                     | 1.10                  | 7.56                  | 1.16                  | 11.08                 | 1.06                | 4.06                | 1.09                  | 4.20                  |
| Melbourne      | 1.69                    | 9.64                    | 1.79                     | 12.31                    | 1.58                  | 7.43                  | 1.47                  | 4.52                  | 1.93                | 7.40                | 1.63                  | 6.26                  |
| Shiraz         | 0.33                    | 0.34                    | 0.39                     | 0.72                     | 0.52                  | 0.73                  | 0.49                  | 0.68                  | 0.38                | 0.71                | 0.33                  | 0.34                  |
| Washington     | 1.41                    | 3.40                    | 1.26                     | 3.05                     | 1.51                  | 3.64                  | 1.50                  | 4.59                  | 1.34                | 0.95                | 1.42                  | 1.98                  |

| Months          | July ENEN (kg/month) | July EXEN (kg/month) | August ENEN (kg/month) | August EXEN (kg/month) | September ENEN (kg/month) | September EXEN (kg/month) | October ENEN (kg/month) | October EXEN (kg/month) | November ENEN (kg/month) | November EXEN (kg/month) | December ENEN (kg/month) | December EXEN (kg/month) |
|----------------|----------------------|----------------------|------------------------|------------------------|---------------------------|---------------------------|-------------------------|-------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Cities         |                       |                       |                        |                        |                           |                           |                         |                         |                         |                         |                         |                         |
| Buenos Aires   | 0.96                 | 1.78                 | 1.11                   | 1.13                   | 1.28                      | 2.38                      | 1.53                    | 8.73                    | 1.39                    | 3.36                    | 1.48                    | 2.75                    |
| Harare         | 0.83                 | 0.25                 | 1.42                   | 1.45                   | 1.48                      | 1.51                      | 1.66                    | 2.32                    | 1.53                    | 1.56                    | 1.20                    | 1.22                    |
| Madrid         | 0.98                 | 3.76                 | 0.81                   | 1.95                   | 1.10                      | 2.65                      | 0.67                    | 3.83                    | 1.19                    | 8.16                    | 1.11                    | 12.41                   |
| Melbourne      | 1.71                 | 6.56                 | 1.88                   | 5.78                   | 1.77                      | 14.38                     | 1.63                    | 9.35                    | 1.90                    | 13.05                   | 1.90                    | 8.98                    |
| Shiraz         | 0.36                 | 0.37                 | 0.27                   | 0.28                   | 0.24                      | 3.06                      | 0.21                    | 0.15                    | 0.10                    | 0.03                    | 0.06                    | 0.04                    |
| Washington     | 1.03                 | 0.73                 | 1.06                   | 1.08                   | 1.21                      | 0.87                      | 1.25                    | 2.32                    | 1.36                    | 2.53                    | 1.08                    | 2.01                    |
6.4 | Environmental analysis

According to the environmental analysis of the wind turbine system, the produced amount of carbon dioxide can be considered a fundamental parameter. Notably, the amount of carbon dioxide produced by renewable energy is much lower than fossil fuels. Therefore, the use of renewable energy has a significant role in reducing greenhouse gases. As the produced amount of carbon dioxide can be calculated based on total energy and exergy values, the analysis of the produced amount of carbon dioxide leads to the emergence of ENEN and EXEN parameters. By computing the amount of produced carbon dioxide in the life cycle of the system (from the moment of production to recycling and destruction), using total energy, the parameter ENEN is obtained, and by computing the amount of produced carbon dioxide in the life cycle of the system, using the total exergy, the parameter EXEN is gained. The ENEN and EXEN analyses for the six cities: Buenos Aires, Harare, Madrid, Melbourne, Shiraz, and Washington, respectively, by different months of the year, are illustrated in Table 9.

As seen in Table 9, the amount of released carbon dioxide from the exergy point of view is usually more significant than from the energy point of view. Therefore, it can be stated that in this case, the exergy analysis is more reliable. In other energy systems, including solar collectors, the energy analysis is reliable. The annual amount of carbon dioxide produced per capita of energy and Exergy by wind turbines for each city is presented in Figure 18 to analyze and compare different cities.

Figure 18 indicates that in Harare, due to its very low total exergy (Table 7), the predicted amount of released carbon dioxide by the exergy field is significantly higher than the amount predicted by the energy field. It can also be stated that, from the environmental point of view, Shiraz, with the least amount of released carbon dioxide (ENEN = 111 kg/year, EXEN = 224 kg/year), has the least damage to the environment. These results indicate that designs based on energy analysis are, in most cases, more cautious and reliable than exergy analysis.

6.5 | Enviroeconomic analysis

ENENEC and EXENE economic factors can clarify the environmental analysis since this analysis can create a better view of the problem. The difference between these analyses and the analysis of the previous section (results related to carbon footprint) is in the type of results. These analyses show the environmental's financial penalty, while the results of the previous section show the amount of carbon dioxide emissions. The financial performance of a system is related to the penalty costs of carbon dioxide emissions. In this regard, the ENENEC factor calculates the cost (depending on the incentive and
| Months Cities | January ENENEC ($/month) | January EXENEC ($/month) | February ENENEC ($/month) | February EXENEC ($/month) | March ENENEC ($/month) | March EXENEC ($/month) | April ENENEC ($/month) | April EXENEC ($/month) | May ENENEC ($/month) | May EXENEC ($/month) | June ENENEC ($/month) | June EXENEC ($/month) |
|--------------|--------------------------|--------------------------|---------------------------|---------------------------|----------------------|----------------------|-----------------------|----------------------|---------------------|---------------------|---------------------|---------------------|
| Buenos Aires | 0.024                    | 0.034                    | 0.018                     | 0.083                     | 0.018                | 0.034                | 0.016                 | 0.050                | 0.020               | 0.028               | 0.016               | 0.030               |
| Harare       | 0.014                    | 0.004                    | 0.008                     | 0.006                     | 0.018                | 0.006                | 0.014                 | 0.007                | 0.013               | 0.004               | 0.014               | 0.004               |
| Madrid       | 0.016                    | 0.109                    | 0.017                     | 0.117                     | 0.016                | 0.110                | 0.017                 | 0.161                | 0.015               | 0.059               | 0.016               | 0.061               |
| Melbourne    | 0.024                    | 0.140                    | 0.026                     | 0.179                     | 0.023                | 0.108                | 0.021                 | 0.066                | 0.028               | 0.107               | 0.024               | 0.091               |
| Shiraz       | 0.005                    | 0.005                    | 0.006                     | 0.011                     | 0.008                | 0.011                | 0.007                 | 0.010                | 0.006               | 0.010               | 0.005               | 0.005               |
| Washington   | 0.020                    | 0.049                    | 0.018                     | 0.044                     | 0.022                | 0.053                | 0.022                 | 0.067                | 0.019               | 0.014               | 0.021               | 0.029               |
| **July Cities** | **Buenos Aires** | **Harare** | **Madrid** | **Melbourne** | **Shiraz** | **Washington** | **Buenos Aires** | **Harare** | **Madrid** | **Melbourne** | **Shiraz** | **Washington** |
|              | 0.014                    | 0.026                    | 0.016                     | 0.016                     | 0.019                | 0.035                | 0.022                 | 0.127                | 0.020               | 0.049               | 0.022               | 0.040               |
|              | 0.012                    | 0.004                    | 0.021                     | 0.021                     | 0.022                | 0.022                | 0.024                 | 0.034                | 0.022               | 0.023               | 0.014               | 0.018               |
|              | 0.014                    | 0.055                    | 0.012                     | 0.028                     | 0.016                | 0.038                | 0.010                 | 0.056                | 0.017               | 0.118               | 0.016               | 0.180               |
|              | 0.025                    | 0.095                    | 0.027                     | 0.084                     | 0.026                | 0.209                | 0.024                 | 0.136                | 0.028               | 0.189               | 0.028               | 0.130               |
|              | 0.005                    | 0.005                    | 0.004                     | 0.004                     | 0.003                | 0.044                | 0.003                 | 0.002                | 0.002               | 0.001               | 0.001               | 0.001               |
|              | 0.015                    | 0.011                    | 0.015                     | 0.016                     | 0.018                | 0.013                | 0.018                 | 0.034                | 0.020               | 0.037               | 0.016               | 0.029               |
punitive policy) based on the energy aspect, and the EXENEC factor calculates the cost based on the exergy aspect. The enviroeconomic analysis data of the wind turbine system are presented in Table 10 monthly.

As expected, the data trend presented in Table 10 is the same as the data trend presented in Table 9 with financial statements. The cost of carbon dioxide emissions should be calculated annually to perform the final comparison. Figure 19 indicates the annual cost of produced carbon dioxide in the six energy-based ENENEC and exergy-based EXENEC cities.

As stated, since the results of Figure 19 are derived from the results of Figure 18, therefore the process is similar; however, there is an exception that in this figure, the concept of the penalty cost resulting from the annual carbon dioxide emission of a horizontal axis wind turbine is depicted. According to the report on the amount of emitted carbon dioxide, Shiraz is more environmentally friendly than other cities, with the lowest penalty cost resulting from the lowest emissions. The important point of Figure 19 is that, although the penalty cost of a wind turbine is small, considering the punitive policy and generalizing the calculations to the wind plants, it is essential to calculate the ENENEC and EXENEC parameters.

6.6 Results classification

By introducing the four main fields and analyzing the parameters, it is better to make a general classification from each point of view to compare the general cities and climates to determine the most appropriate option. To select the most appropriate option from each perspective of the four fields, which are energy, exergy, economic, and environmental, a general classification is presented in Figure 20. According to Figure 20, it can be stated that no situation can be identified as an optimal choice from the perspective of all four areas of energy, exergy, economy, and environment of a city. Therefore, in this case, the goals of policymakers must be specified. The results show that although Melbourne is the best choice in terms of energy and this leads to the lowest energy costs, but in terms of carbon emissions will have the highest emissions. In other words, the results show that more use of wind energy potential (higher energy efficiency – lower energy cost) does not mean an optimal choice, and environmental analysis is a very important indicator in choosing the final option. In conclusion, policymakers should make an optimal choice by weighing the above criteria based on each city's climatic conditions and constraints.
Summary and classification

**ENERGY ANALYSIS**

- SHIRAZ: 4.13%
- HARARE: 6.09%
- BUENOS AIRES: 8.38%
- WASHINGTON: 8.47%
- MADRID: 15.6%
- MELBOURNE: 17.1%

**EXERGY ANALYSIS**

- MADRID: 3.16%
- SHIRAZ: 3.68%
- MELBOURNE: 3.73%
- BUENOS AIRES: 4.04%
- WASHINGTON: 5.51%
- HARARE: 11.6%

**ECONOMIC ANALYSIS**

- SHIRAZ: 0.759 $/kWh
- HARARE: 0.436 $/kWh
- BUENOS AIRES: 0.312 $/kWh
- WASHINGTON: 0.306 $/kWh
- MADRID: 0.157 $/kWh
- MELBOURNE: 0.14 $/kWh

**ENVIRONMENTAL ANALYSIS**

- SHIRAZ: 627 kg/year
- HARARE: 465 kg/year
- BUENOS AIRES: 465 kg/year
- WASHINGTON: 414 kg/year
- MADRID: 376 kg/year
- MELBOURNE: 111 kg/year

- SHIRAZ: 9.09 $/year
- HARARE: 6.71 $/year
- BUENOS AIRES: 6.71 $/year
- WASHINGTON: 5.45 $/year
- MADRID: 1.61 $/year
- MELBOURNE: 0.46 $/year

*Figure 20* Summary and classification
In the present study, the behavior of a three-blade HAWT is expressed by considering the 4E characteristics with the effects of climate change. In this regard, a numerical model is developed based on Bergey Excel S 10 kW specifications to find the best policy for utilizing wind energy. The validation results of the presented mathematical model are verified with the information provided in the company's catalog. Hence, to find the most appropriate geographic conditions, the wind turbine and its corresponding characteristics are mathematically modeled in six cities from six different continents as case studies belonging to six distinct climates of class C (warm/mild temperate zone) more compatible with wind turbines. Therefore, the system's behavior is described in the energy field by energy efficiency and generated power of the wind turbine. The system's behavior is discussed in the field of exergy by the exergy efficiency and the calculation of total exergy. In economic studies, the cost of energy production by a wind turbine, including the cost of commissioning, repairs, and insurance, and the unit cost of energy produced by the wind turbine in each climate is achieved. Also, to study the system in the field of environment, four parameters are introduced and calculated based on the LCA method. These four parameters are as follows: ENEN, EXEN, ENENEC, and EXENEC. Consequently:

✓ From the energy analysis viewpoint, Melbourne, with Cfb climate (temperate oceanic climates), is declared the most optimal option for the wind turbine system, with an average energy efficiency of 17.1%.

✓ The best option is introduced by Harare's exergy analysis with Cwb climate (subtropical oceanic highland) and average exergy efficiency of 11.6%.

✓ From an economic point of view, the city of Melbourne, with its Cfb climate (temperate oceanic climates) and Levelized energy cost of 0.14 $/kWh, is declared the best choice.

✓ Environmental analysis with a focus on energy performance (ENEN and ENENEC parameters) announced Shiraz with Csc climate (cold-summer Mediterranean climate) and values of 111 kgCO₂/year and 1.61 $/year, which has the least damage to the environment as the most optimal option for the wind turbine system.

✓ Enviroeconomic analysis with a focus on exergy performance (EXEN and EXENEC parameters) also declared Shiraz as the most viable option for the wind turbine system, with Csc climate (cold-summer Mediterranean climate) and values of 224 kgCO₂/

Although this comprehensive study can provide information about choosing the best location and the best climate, as the first limitation, it should be noted that the results can be different by changing the weather conditions and the parameters. Another limitation is that performing an experimental evaluation for this study could be expensive and time-consuming. As the third limitation, there is no guarantee that the weather and wind conditions will stay similar to the states used in this study. Consequently, a relatively significant alteration in weather conditions could result in an alteration in the achieved results. However, it is valuable information for designing and constructing a wind turbine power plant based on the conditions and importance of each field.

The following are suggested for future research in this field:

1. Investigate the types of wind turbines in a particular climate to find the best type of turbine in different climates.
2. Provide a standard framework for determining energy policies for a country in specific climates (e.g., developing software that receives climate data as input and provides optimal policy as output).
3. 4E analysis of hybrid energy systems in different climates to increase sustainability.

NOMENCLATURE

\[ A \quad \text{area} \quad (\text{m}^2) \]
\[ C \quad \text{cost of electricity} \quad ($) / \text{kWh} \]
\[ C_p \quad \text{specific heat at constant pressure} \quad (\text{kJ/K. kg}) \]
\[ D \quad \text{diameter} \]
\[ E \quad \text{specific exergy} \quad (\text{kJ/kg}) \]
\[ I \quad \text{interest rate} \]
\[ K \quad \text{Weibull shape index} \]
\[ L \quad \text{life time} \quad (\text{Year}) \]
\[ N \quad \text{number} \]
\[ P \quad \text{power} \quad (\text{kW}) \]
\[ Q \quad \text{heat} \quad (\text{W}) \]
\[ R \quad \text{characteristic gas constant} \quad (\text{kJ/k.kg}) \]
\[ T \quad \text{working hours} \]
\[ U \quad \text{wind speed} \quad (\text{m/s}) \]
\[ m_i \quad \text{number of observations} \]
\[ \bar{u} \quad \text{average of wind speed} \quad (\text{m/s}) \]

GREEK SYMBOLS

\[ \omega \quad \text{moisture} \]
ρ  density
η  efficiency

SUBSCRIPTS
a  air
c  cut-in
Ch  chemical
f  furling
I  initial
in  inlet
Ins  insurance
K  kinetic
O  operation
out  outlet
P  potential
Ph  physical
r  rated
s  swept
ν  vapor

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