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# Energy, exergy, economic and advanced and extended exergy analyses of a wind turbine

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ABSTRACT

Energy, exergy, economic, advanced exergy, and extended exergy analyses are reported of a Bergey Excel-S wind turbine with nominal power of 10 kW in two cities: Tehran (medium wind potential) and Manjil (high wind potential). The results show that the energy efficiency of the wind turbine is higher in Manjil (3.33%) than Tehran (1.08%). The exergy efficiency in these areas is lower. This means that the exergy efficiency in Manjil is 10.8% but in Tehran is 6.43%. The cost of electricity generated by the wind turbine in Tehran is 0.23 $\frac{US\$}{kWh}$. This cost is reduced to 0.73 $\frac{US\$}{kWh}$ in Manjil. The advanced exergy analysis demonstrates that the avoidable exergy destruction percentage of the wind turbine increases with wind speed. The extended exergy analysis shows that, in windy areas, the highest exergy percentage is exhibited by the system's input and output exergy flows and power production (88.7%), while, in areas with medium wind speed potential, the exergy is equal to is the equivalent extended exergy content of the influx of capital cost (58.9%).

## 1. Introduction

Distributed generation is a method that generates electricity at or near the place of consumption, by the use of small-scale technology. The traditional pattern of power generation is based on utilization of a limited number of large-scale electrical power plants and then transmitting and distributing the electrical energy to consumers, who may be thousands of kilometers away from the generation site [1–8]. But, this method leads to the loss of a considerable amount of energy through the transfer and distribution networks [1].

Large fossil fuel power plants, through the emission of greenhouse gases, cause significant to the environment, and, due to the need for an extensive and complex transmission and distribution network, are prone to damage from natural disasters or security threats [1–8].

Distributed generation is a different type of electrical generation, based on its type, nominal capacity, and cost. Small gas turbines, with capacities of around 500 kW to 20 MW and energy efficiencies of around 25 to 40% is being increasingly used in distribution networks, and industrial and commercial applications [1,3,5,8–11]. Other prime movers for distributed generation, such as micro-turbines, wind turbines, water turbines, photovoltaics, solar thermal energy systems, biomass generators, geothermal generators, are also finding expanded uses. These power generation technologies can be divided into two categories: non-renewable ones, such as micro-turbines, fuel cells, gas turbines, and renewable ones, such as wind turbines and solar PV cells [12–21].

Drastic improvements have been made in the area of wind turbines for power generation, since 1975. In 1980, the first wind electricity generator connected to the electrical grid was installed. After a short time, the first multi-megawatt wind farm in the United States was installed and put into operation. By the end of 1990, the capacity of the wind turbines connected to the electrical grid reached 200 MW, worldwide, which could generate 3200 GWh, almost all of which is in the state of California, United States and Denmark. Today, other countries such as the Netherlands, Germany, Britain, Italy, and India have initiated particular and national programs for expansion and commercial distribution of the wind energy. During the last decade, the cost of power generation has been significantly decreased by the help of wind turbines. Nowadays, the wind turbines have higher efficiency and credibility compared to 15 years ago. Yet, wind energy is not extensively use at present. The emphasis of most wind turbines is on electricity generation for the electrical grid, since this kind of wind energy application can have an important role in the world's power consumption. Based on current policies and programs, it is estimated

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**Nomenclature**

| | |
|---|---|
| A | swept area ($m^2$) |
| c | coefficient, electricity cost ($\frac{US\$}{kWh}$) |
| $C_P$ | specific heat at constant pressure ($\frac{kJ}{kg\,K}$) |
| E | specific exergy ($\frac{kJ}{kg}$) |
| EE | extended exergy ($\frac{MJ}{Year}$) |
| HDI | human development index |
| i | interest rate Eq. (23) |
| I | salvage factor Eq. (22) |
| k | coefficient |
| L | year or number of annual working hours |
| $m_i$ | observation |
| P | power (kW) |
| R | characteristic gas constant ($\frac{kJ}{kg\,K}$) |
| T | temperature (K) |
| u | wind speed (m/s) |
| $\bar{u}$ | mean wind speed (m/s) |

*Greek symbols*

| | |
|---|---|
| ω | humidity ratio |

*Subscripts*

| | |
|---|---|
| A | air |
| AV | avoidable |
| UV | unavoidable |
| c | cut-in or capital |
| ch | chemical |
| f | furling |
| e | electrical |
| e | electricity |
| EN | endogenous |
| EX | exogenous |
| F | furling |
| gen | generation of electrical power by wind |
| h | inhabitants |
| I | initial |
| ins | insurance |
| L | labor |
| O | operation |
| P | potential |
| Ph | physical |
| R | rated |
| Surv | survival |
| wh | working hours |

that by 2020 wind energy contribution to the global energy supply will be approximately 375 TWh annually [22,23]. This amount of energy would be generated by the use of wind turbines having a capacity of 180 GW [22,23]. Generally, wind energy as a long-term energy source has the potential to provide as much as double the current electrical energy consumption of the world [22,23].

Much research has been reported on energy, exergy and economic investigations of wind turbines. Ahmadi and Ehyaei [15] in 2009 assessed with exergy analysis a Bergey Excel-S wind turbine of 10 kW capacity for two cities in Iran: Tehran with medium wind potential, and Manjil City with high wind potential. The results indicated that, by choosing optimal values of rated, furling and cut-in speeds, which are among the characteristics of wind turbines, the annual power generation of the wind turbine can be increased by 20%, while reducing its entropy production by 76.9%. But economic aspects are not considered in this research, and only one target function is considered: entropy generation.

Numerous similar assessments have been reported, before 2011, in terms of energy, exergy and economic analyses of wind turbines. Similar research has been conducted by Koreneos et al. in 2003 [24], Jia et al. in 2004 [25], Dincer and Rosen in 2005 [26], Sahin et al. in 2006 [27], Pope et al. in 2010 [28], Hepbasli and Alsuhailbani in 2011 [29], Redha et al. in 2011 [30], Ozturk in 2011 [31], Baksut et al. in 2011 [32], and Xydis in 2012 [33].

In all of the above articles, aspects of exergy and the potential of using wind turbines in different areas have been investigated. Most of the past research has been on wind potential or other renewable energy sources and their comparison with conventional electricity generation methods.

Asgari and Ehyaei in 2015 [16] performed exergy and economic analyses of a wind turbine and its optimization by the use of Search and Genetic Algorithm methods. They considered the weather conditions of Tehran for these analyses. The optimization raised the output power, the energy efficiency and the exergy efficiency increased by 61, 56.5 and 62.2%, respectively. In this article, only one target function has been considered.

Lamas in 2017 [34] carried out an exergy-economic analysis of a wind turbine. This analysis considered every component of the system, such as the wind turbine, the gearbox, the inverter, etc. A relation was proposed for return on capital for the wind turbine. The return on capital for the wind turbine was found to be 3.5–5 years.

Sayad in 2002 [35] evaluated the wind power potential in the Za'afarana district in Egypt considering several kinds of wind turbines. He concluded that the installation of wind turbines is cost-effective. A similar study by Al-Sultan et al. in 2010 [36] examined the region with the highest wind potential in Oman, considering various large-scale wind turbines. Kayhani et al. in 2010 [37] investigated wind power in Tehran, by analyzing small and medium-sized wind turbines in two independent and parallel-to-network modes. They showed that wind turbines are suitable for the network-independent mode. Amal et al. in 2013 [38] evaluated the use of small wind turbines for supplying the electricity needs of residential areas in Karachi City, Pakistan. They showed that the use of the considered system for half of residential consumers would lead to a reduction in electricity use of 678 MWh. Sheridan et al. in 2012 [39] evaluated the wind energy potential for the Atlantic coast of the United States, and showed that up to 70% of the electricity consumption of the coast of Maryland can be supplied by wind turbines. Mostafaeipoor et al. in 2013 [40] investigated the wind turbine potential in terms of wind speed, for various altitudes of Binalood City. By considering the costs of installation of the wind turbine pillar and the wind speed at higher altitudes, they showed that a wind turbine at a 40 m altitude is suitable and installation of the wind turbine would be economical. Fazelpoor et al. in 2015 [41] assessed the wind potential in Tabriz and Ardabil, cities in northwest Iran. They showed that power generation by wind turbines is economically justifiable in these cities. Dabbaghiyan et al. in 2016 [42] investigated the wind potential in Bushehr province, in southern Iran, and showed that the best location for wind turbines is Bordkhun City. Fazelpour et al. in 2017 [43] evaluated the wind energy potential of four areas of Sistan and Baluchestan Province in Iran, using Windographer Software to show prevailing wind direction. The results showed that Zahedan and Zabol cities are suitable for large-scale wind turbines, while Mirjaveh City is suitable for small scale wind turbines.

In Refs. [35–43], which consider recent advances in wind turbine technology, studies have been reported on the economic evaluation of various kinds of wind turbines (vertical and horizontal axis; large, medium and small scales; etc.).

Aghbashlo et al. in 2017 [44] applied the extended exergy approach in northern regions of Iran. In this approach, the exergy of labor, maintenance, initial installation and environmental impact are considered. The results showed, that compared to the exergy method, this method is more suitable for decision-making about the fitness of regions for wind turbines. Despite the extensive work done to date, no studies have been reported to date of advanced exergy analyses of wind turbines. In this article, a formulation of extended exergy analysis for wind turbines was proposed. But the application and review of this method is very limited.

Ishaq et al. [45] proposed in 2018 a trigeneration system consisting of a solar heliostat, a wind turbine and a copper-chlorine cycle for hydrogen production. They investigated this system with energy and exergy approaches, and found the system energy and exergy efficiencies to be 49% and 48.2%, respectively.

Lombardi et al. [46] in 2018 performed a life cycle analysis for a micro wind turbine with a vertical axis, considering raw material extraction, manufacturing, distribution, and disposal stages. They concluded that a 3 kW wind turbine has less environment impact than a 1 kW unit.

Usón et al. [47] carried out a feasibility study of a trigeneration system. This system included a solar collector, a photovoltaic cell and a wind turbine, and produced electricity and hot and fresh water for a single family. Based on the investigation, the system exergy efficiency was 7.76%.

Stanek et al. [48] reported a thermo-ecological cost analysis of wind turbines in Poland and Italy. They concluded that the environment impact of a wind turbine is 47 to 65 times lower than that for a coal fired power plant. Similar research for other wind turbine capacities was recently done by Mendecka et al. [49].

Saffari and Dincer [50] investigated a power to gas system which included a wind turbine, an electrolyzer and a methanation unit. The system energy and exergy efficiencies were found to be 44% and 45%, respectively.

Based on the literature for wind turbines, it is observed that no comprehensive study that includes energy, exergy, economic, advanced exergy and extended exergy has been reported, for a specific location. A majority of the studies have considered only one aspect of analysis, for example exergy or economics, solely. Also, an advanced exergy analysis formulation for a wind turbine has not been reported before. Regarding the extended exergy analysis of a wind turbine, only one article is found in the literature [44]. The formulas utilized in the present analysis are presented in that article. But a case study analysis has not been done for different regions.

In the current study, all these analyses are used to investigate the use of a Bergey Excel-S wind turbine with a nominal capacity of 10 kW for satisfying residential power demands, for two Iranian cities: Tehran with medium wind power potential, and Manjil with high wind potential. The monthly and annual average energy and exergy efficiencies, as well as the cost of electricity generated, by the wind turbine, are determined for the residential applications. Based on the advanced exergy analysis, the avoidable and unavoidable exergy destructions of the wind turbines are calculated. Based on the extended exergy approach, a new definition of efficiency, which includes installation, maintenance, labor, etc., is proposed and calculated for weather conditions of the two mentioned cities. The main innovative aspects of the current study are as follows:

- Energy, exergy, economic, advanced exergy and extended exergy methods are applied to assess comprehensively wind turbines
- A wind turbine is evaluated with the advanced exergy approach based on conditions of Tehran and Manjil
- A wind turbine is evaluated with the extended exergy approach based on conditions of Tehran and Manjil

## 2. Mathematical modeling

### 2.1. Energy analysis

Fig. 1 shows a schematic of a horizontal axis wind turbine.

The electrical power generated by a wind turbine can be expressed as follows [51,52]:

$$\begin{aligned} &P_e = 0 && (u < u_c) \\ &P_e = a + bu^k && (u_c \leqslant u \leqslant u_r) \\ &P_e = P_{er} && (u_r \leqslant u \leqslant u_f) \\ &P_e = 0 && (u > u_f) \end{aligned} \tag{1}$$

where pe is the rated power (in kW), uf, ur and uc are the furling, rated and cut-in speeds (in m/s), and k is the Weibull shape index. Also, a and b are coefficients, expressible as follows [51,52]:

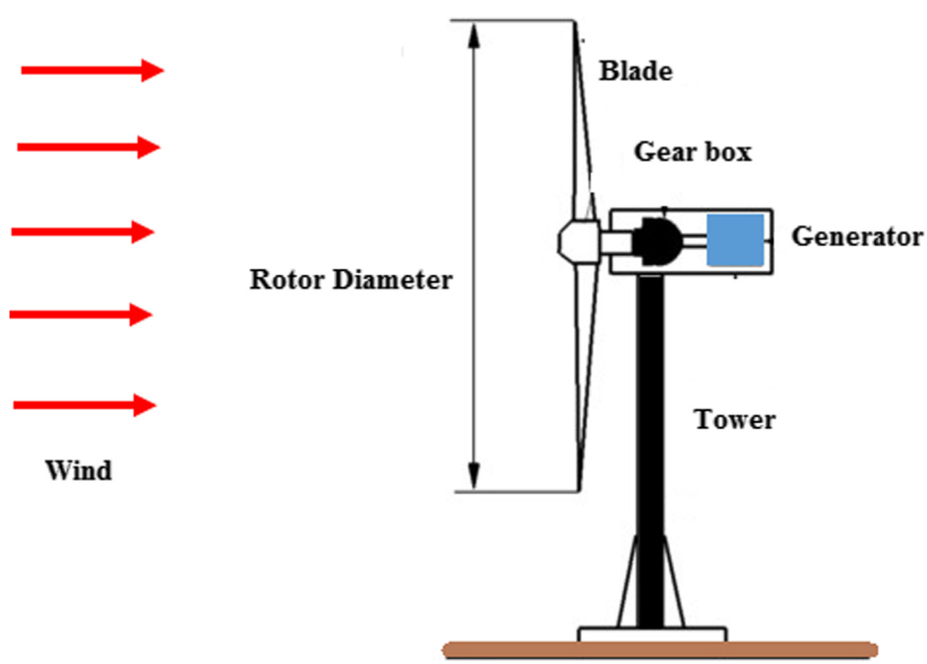


**Fig. 1.** The schematic of horizontal axis wind turbine.

**Table 1**
Specifications of Bergey Excel-S 10 kW wind turbine.

| Specification | Value |
|---|---|
| Cut-in wind speed (m/s) | 3.1 |
| Rated wind speed (m/s) | 13.8 |
| Rated power (kW) | 10 |
| Furling wind speed | 15.6 |
| Type | 3 blade up wind |
| Swept area ($m^2$) | 38.47 |
| Gear box | None – direct drive |
| Temperature range (°C) | −40 to 60 |
| Generator | Permanent magnet alternator |
| Tower height (m) | 24 |

$$a = \frac{p_{er} u_c^k}{u_c^k - u_r^k}$$
$$b = \frac{p_{er}}{u_r^k - u_c^k} \tag{2}$$

The coefficients k and c can be written as follows [51,52]:

$$k = \left(\frac{\sigma}{\bar{u}}\right)^{-1.086} \tag{3}$$

$$c = \frac{\bar{u}}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{4}$$

where σ is the standard derivation, Γ is the Gamma function, and $\bar{u}$ is the average wind speed (m/s).

The indices $\sigma$ and average speed $\bar{u}$ can be written as follows [51,52]:

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

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{n} m_i u_i \tag{6}$$

Here, $m_i$ is the number of wind flows at a certain speed, n is the total number of wind flows at a certain speed, and $u_i$ is the wind speed (m/s) measured at an altitude of 10 m.

We can calculate the wind speed at other altitudes as follows [51,52]:

$$u(z_2) = u(z_1)\left(\frac{z_2}{z_1}\right)^{\beta} \tag{7}$$

$$\beta = a - b\,\log_{10} u(z_1) \tag{8}$$

Here, $z_1$ and $z_2$ are wind turbine and standard altitudes (m) respectively, $u(z_1)$ and $u(z_2)$ are the wind speeds at altitudes $z_1$ and $z_2$ respectively, while a and b are constant coefficients having respective values of 0.11 and 0.061 in the day, and 0.38 and 0.209 at night.

The average power generation by the wind turbine can be expressed as follows [52]:

$$P_{e,ave} = \int_0^{\infty} P_e f(u) du \tag{9}$$

where f(u) is the Weibull distribution density function of wind speed [52]. By calculation of the integral and according to Eq. (1), the average power generated by a wind turbine can be written as follows [52]:

$$P_{e,ave} = P_{er}\left\{\frac{\exp(-(\frac{u_c}{c}))^k - \exp(-(\frac{u_r}{c}))^k}{(\frac{u_r}{c})^k - (\frac{u_c}{c})^k} - \exp(-(\frac{u_f}{c}))^k\right\} \tag{10}$$

The energy efficiency for the wind turbine can be calculated as follows:

$$Energy\ Efficiency = \frac{P_{e,ave}}{P_{e,r}} \tag{11}$$

### 2.2. Exergy analysis

Generally, exergy can be divided into four categories: physical, chemical, kinetic and potential [53]. In a wind turbine, due to a lack of height difference between the inlet and outlet, the potential exergy difference can be neglected. The physical exergy indicates the maximum theoretical work which can be obtained from a system as comes to equilibrium with a specified reference environment. In the exergy analysis of a wind turbine, the chilling effect and the pressure are not negligible due to the temperature difference between the turbine's inlet and outlet. Chemical exergy is associated with the change in the chemical composition of a system or flow. In the current study due to changes in air humidity on the turbine's inlet and outlet (chilling effect). Based on the speed changes in the turbine's inlet and outlet, the most important exergy difference on between the wind turbine's inlet and outlet is the kinetic exergy.

The overall specific exergy of a system et is defined as follows [53]:

$$e_t = e_K + e_P + e_{Ph} + e_{Ch} \tag{12}$$

Here, e is the specific exergy (kJ/kg), and the subscripts p, Ph, Ch and K denote potential, physical, chemical and kinetic specific exergies, respectively.

The wind Turbine's input and output kinetic specific exergies can be written as follows [14,15]:

$$e_K = \frac{1}{2}u_i^2 \tag{13}$$

$$e_K = \frac{1}{18}u_i^2 \tag{14}$$

The change in physical specific exergy across the wind turbine can be expressed as follows [53]:

$$e_{Ph} = (c_{Pa} + \omega c_{Pv})T_0\left[\frac{T}{T_0} - 1 - \ln\left(\frac{T}{T_0}\right)\right] + (1 + 1.6078\omega)RT_0 \ln\frac{P}{P_0} \tag{15}$$

Here, cPa is the specific heat at constant pressure of air (kJ/kg K), cPv is the specific heat at constant pressure of water vapor (kJ/kg K), T is the temperature (K), ω is the humidity ratio, R is the characteristic gas constant (kJ/kg K), and T0 and P0 are the standard temperature and pressure which are equal to 288.15 K and 1 atm.

The wind turbine inlet or outlet pressures can be calculated as follows:

$$P = P_0 + \frac{u_i^2}{2} \tag{16}$$

The chemical specific exergy at the wind Turbine's inlet or outlet can be calculated as follows [14,15]:

**Table 2**
Number of air flows at a certain speed for Tehran broken down by month.

| $u_i$ (m/s) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $1 < u_i < 3$ | 59 | 62 | 82 | 79 | 71 | 76 | 98 | 106 | 119 | 96 | 64 | 60 |
| $4 < u_i < 6$ | 25 | 36 | 65 | 61 | 53 | 67 | 73 | 51 | 43 | 37 | 31 | 8 |
| $7 < u_i < 10$ | 15 | 22 | 20 | 32 | 27 | 27 | 7 | 5 | 6 | 10 | 14 | 2 |
| $11 < u_i < 16$ | 0 | 2 | 2 | 7 | 12 | 3 | 2 | 1 | 0 | 2 | 2 | 2 |
| $u_i > 16$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 3**
Number of air flows at a certain speed for Manjil broken down by month.

| $u_i$(m/s) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $1 < u_i < 3$ | 53 | 58 | 85 | 29 | 22 | 22 | 14 | 18 | 12 | 12 | 32 |
| $4 < u_i < 6$ | 16 | 24 | 30 | 29 | 21 | 13 | 14 | 13 | 11 | 23 | 25 |
| $7 < u_i < 11$ | 27 | 25 | 46 | 41 | 47 | 27 | 39 | 31 | 26 | 27 | 19 |
| $11 < u_i < 16$ | 31 | 26 | 54 | 49 | 40 | 66 | 78 | 53 | 56 | 48 | 32 |
| $17 < u_i < 21$ | 4 | 6 | 12 | 16 | 43 | 46 | 51 | 54 | 50 | 14 | 10 |
| $22 < u_i < 27$ | 0 | 2 | 3 | 9 | 20 | 22 | 16 | 12 | 13 | 8 | 0 |

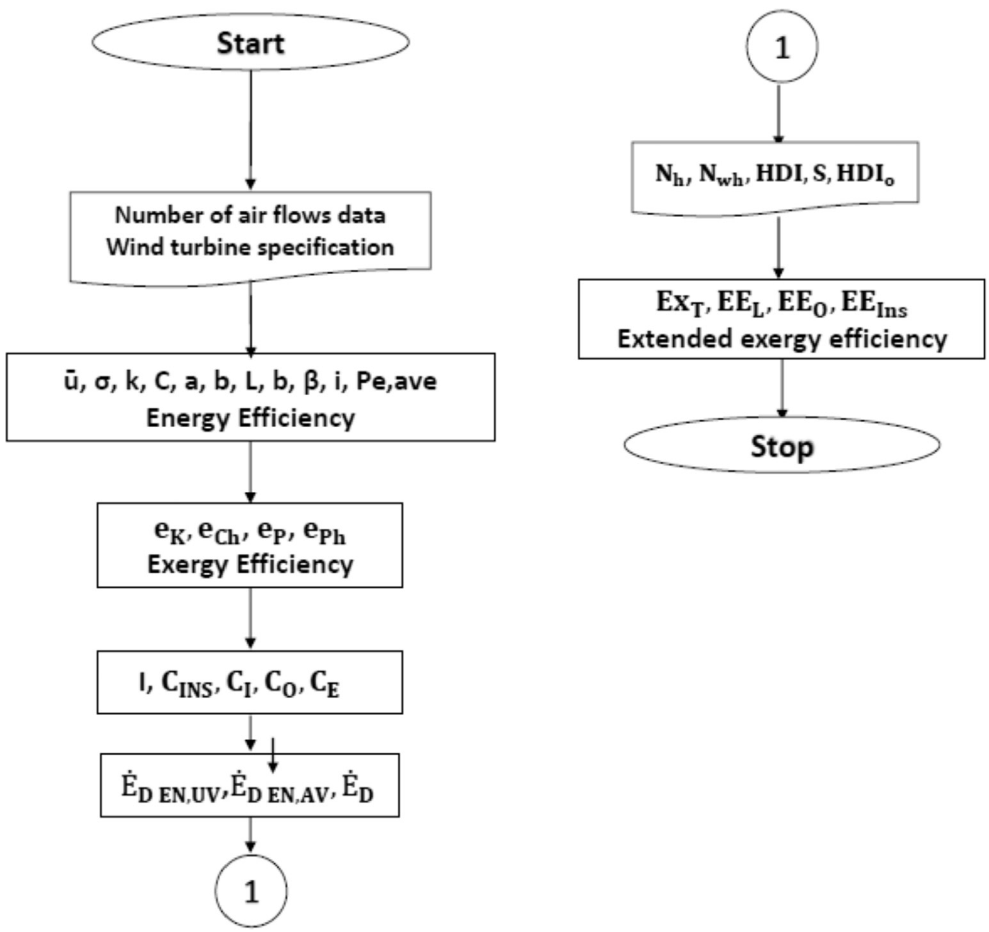


**Fig. 2.** Flow chart of mathematical modeling.

$$e_{ch} = RT_0\left\{(1+1.6078\omega)ln\left[\frac{1+1.6078\omega_0}{1+1.6078\omega}\right]+1+1.6078\omega\ln\left(\frac{\omega}{\omega_0}\right)\right\} \quad (17)$$

The exergy destruction rate in the wind turbine can be calculated as follows [15,16]:

$$\dot{E}_D = \dot{m}_a[(e_{K,in}-e_{K,out})+(e_{Ph,in}-e_{Ph,out})+(e_{Ch,in}-e_{Ch,out})]-P_{e,ave} \quad (18)$$

The mass discharge rate of the air flow through the swept area of wind turbine can be calculated as follows:

$$\dot{m} = \frac{2}{3}\rho_a A_2 u_1 \quad (19)$$

where ρa is the air density (kg/m$^3$), A2 is the swept area (m$^2$), and u1 is the wind speed (m/s).

The exergy efficiency of the wind turbine can be written as follows [15,16]:

$$Exergy\ Efficiency = \frac{P_{e,ave}}{\frac{8}{27}\rho A_2 u_1^3} \quad (20)$$

### 2.3. Economic analysis

The cost of the electricity generated by the wind turbine can be written as follows [54]:

$$C_E = C_I + C_O + C_{Ins} \quad (21)$$

Here, $C_E$ is the unit cost of generated electricity ($\frac{US\$}{kWh}$), $C_I$ is the initial investment cost ($\frac{US\$}{kWh}$), $C_O$ is the maintenance and operation cost ($\frac{US\$}{kWh}$) and $C_{Ins}$ is the insurance cost ($\frac{US\$}{kWh}$).

Note that$C_I$ can be calculated as follows [54]:

$$C_I = \frac{CI}{8760P_{e,ave}} \quad (22)$$

where C is the total cost of installation ($\frac{US\$}{kWh}$), and I is an index, which can be calculated as follows [55]:

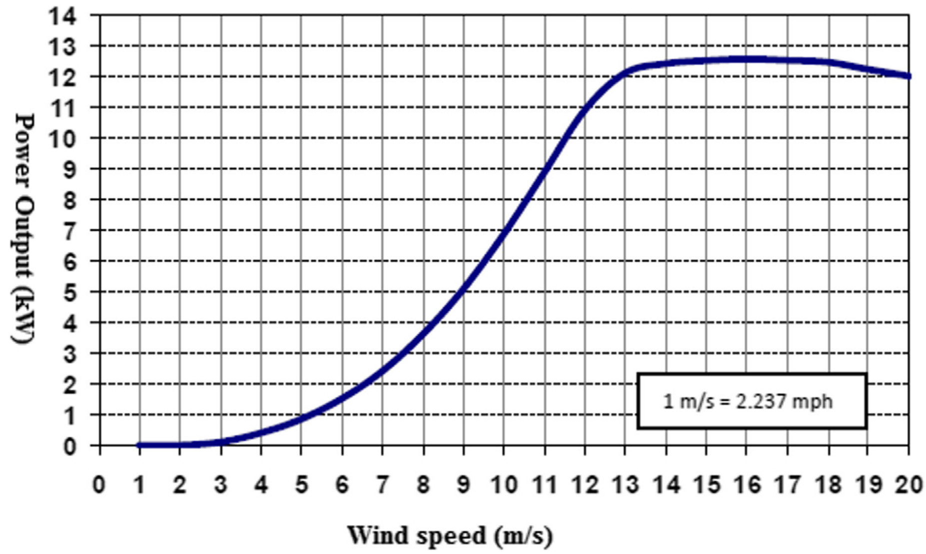


**Fig. 3.** Bergey Excel S 10 kW power curve.

**Table 4**
Comparison the results for $P_{e,ave}$ (in kW) of Bergey Excel S 10 kW manufacture catalogue and mathematical modeling.

| Location | Power curve | Mathematical model | Error (%) |
|---|---|---|---|
| Tehran | 1.03 | 0.97 | 4.8 |
| Manjil | 3.27 | 3.14 | 3.9 |

$$I = \frac{i(i+1)^L}{(1+i)^L - 1} \tag{23}$$

Here, L is the lifetime of the wind turbine (yr), and i is the interest rate, which is considered to be 2% in the current study [54,55]. The lifetime of the wind turbine is considered to be 20 years. The total cost of maintenance and insurance ($C_O + C_{Ins}$) is considered to be 6% of the initial installation cost ($C_I$) [54,55].

### 2.4. Advanced exergy analysis

An important aim of conventional exergy analysis is calculation of the exergy destruction by each component of the system, and the determination of the system's exergy efficiency. Using conventional exergy analysis, the system can be optimized. This information also helps with categorization of the components of a system according to the highest exergy destruction. Moreover, using exergy data and its economic value, the system can be optimized. In advanced exergy analysis, the exergy destruction of each component is divided into two parts. One part of the exergy destruction is due to the irreversibility of the component itself, and is called the endogenous exergy destruction. Another part is due to the effects of the system's components, which are transferred to a given component. This part of the exergy destruction is the exogenous exergy destruction [56]. A part of exergy destruction is irreducible and unavoidable, due to industrial constraints and the

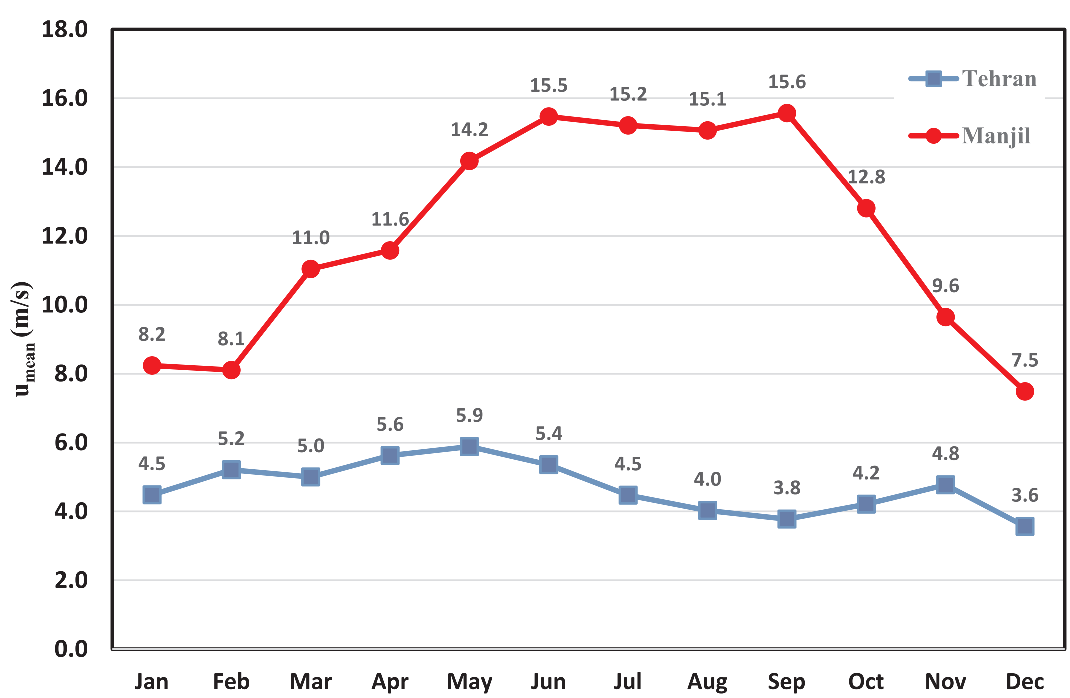


**Fig. 4.** Average monthly wind speed in Tehran and Manjil.

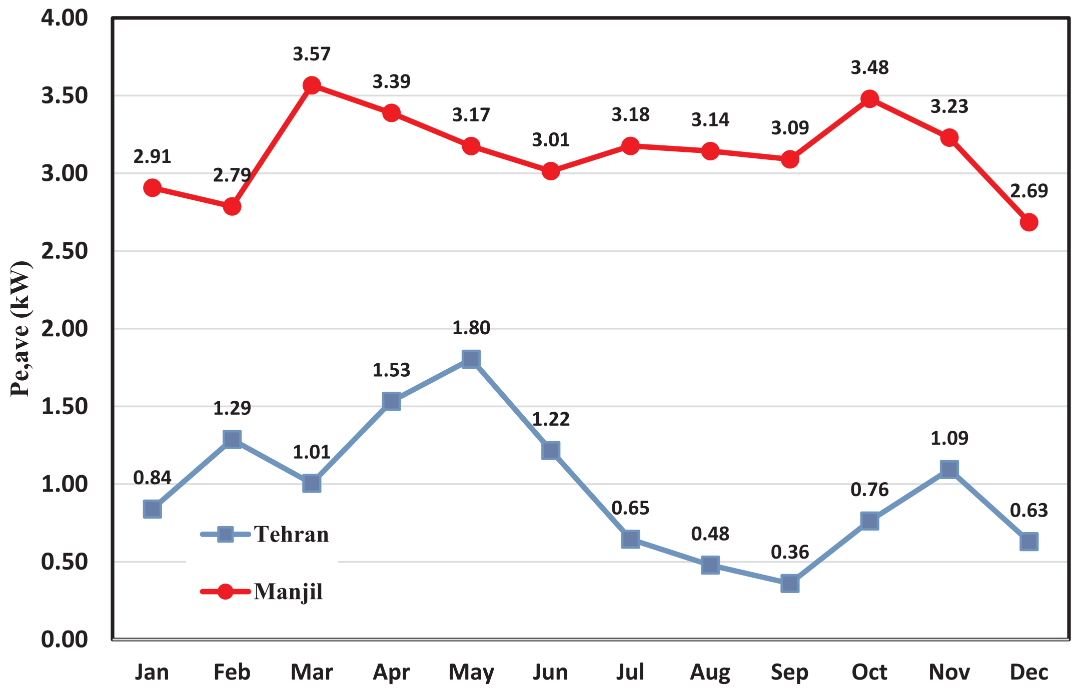


**Fig. 5.** Average monthly power generation by wind turbine in Tehran and Manjil.

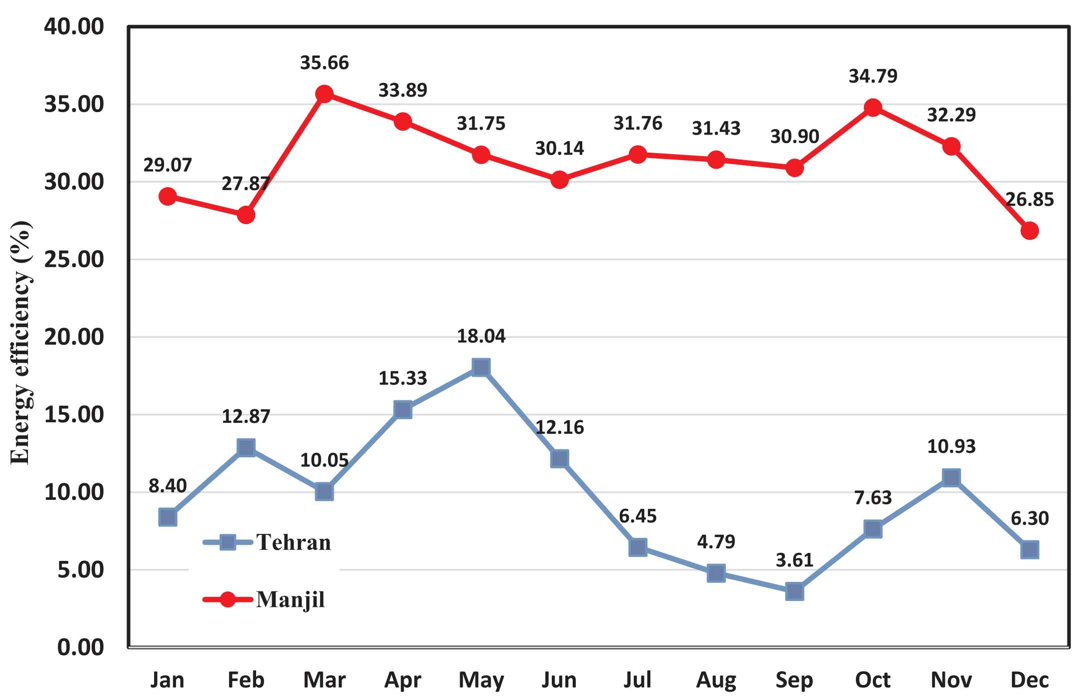


**Fig. 6.** Changes in average monthly efficiency of wind turbine with month of year for Tehran and Manjil.

production methods. The remaining part is avoidable. A portion of the avoidable exergy destruction can be eliminated or reduced, and advanced exergy analysis divides the exergy destruction in each component into avoidable and unavoidable parts. This information specifies the potential for upgrading the components of a cycle, and determines to what extent the exergy destruction is due to technological constraints. Thus, in advanced exergy analysis, in addition to the division of the exergy destruction into endogenous and exogenous parts, each of these categories is also divided into avoidable and unavoidable parts. So, the exergy destruction in a component is divided into endogens unavoidable, endogenous avoidable, exogenous unavoidable and exogenous avoidable parts, and these can be summed as follows [56]:

$$\dot{E}_D = \dot{E}_{D_{EN,UV}} + \dot{E}_{D_{EN,AV}} + \dot{E}_{D_{EX,UV}} + \dot{E}_{D\ EX,AV} \tag{24}$$

Here, the subscripts EX, EN, AV, and UV denote exogenous, endogenous, avoidable and unavoidable, respectively. Since wind turbine is an independent device, other equipment have no effect on it. So the exogenous exergy terms $\dot{E}_{D_{EX,UV}}$, $\dot{E}_{D_{EX,AV}}$ are equal to zero. The exergy destruction of wind turbines can be broken down as follows:

$$\dot{E}_D = \dot{E}_{D_{EN,UN}} + \dot{E}_{D_{EN,AV}} \tag{25}$$

For calculation of $\dot{E}_{D_{EN,AV}}$, it is assumed that a wind turbine has been

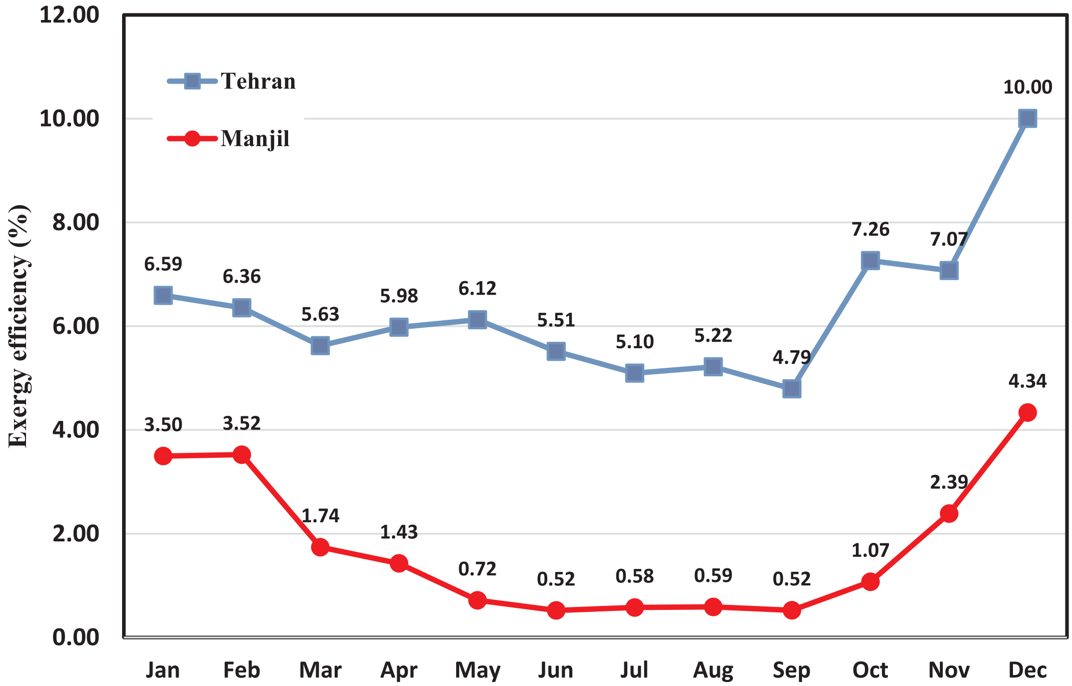


**Fig. 7.** Changes in average monthly exergy efficiency of wind turbine with month of year for Tehran and Manjil.

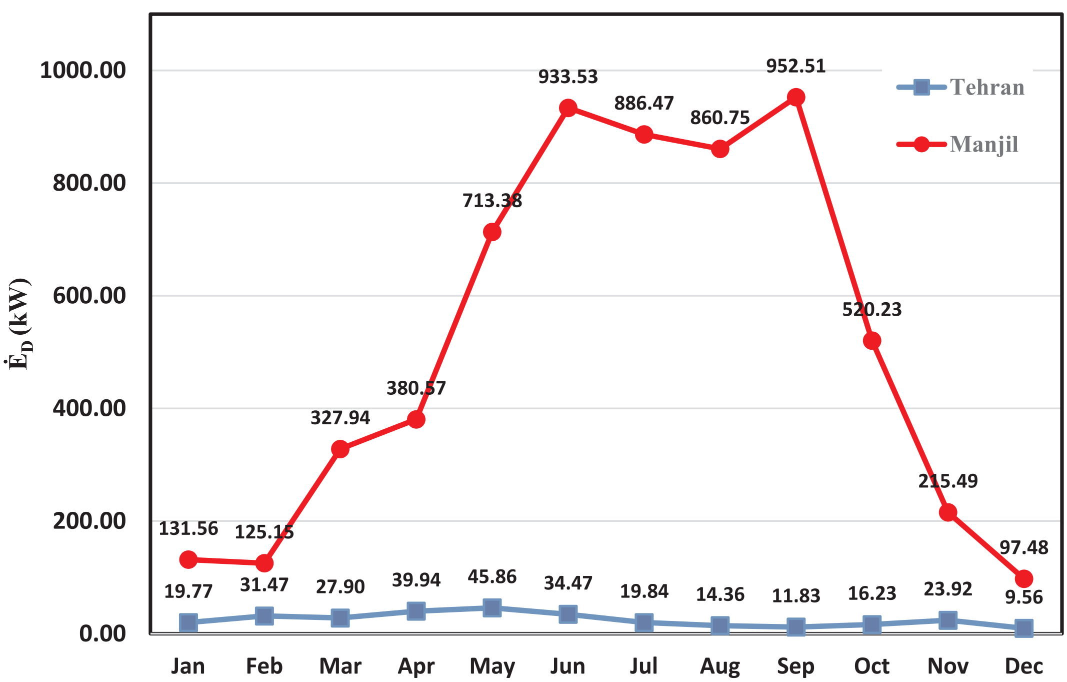


**Fig. 8.** Energy destruction for different months of the year for Tehran and Manjil.

designed that generates electricity at the rated power ($P_{er}$). Thus, we can write:

$$\dot{E}_{DEN,AV} = \dot{m}_a[(e_{K,in} - e_{K,out}) + (e_{Ph,in} - e_{Ph,out}) + (e_{Ch,in} - e_{Ch,out})] - P_{e,r} \quad (26)$$

For calculation of $\dot{E}_{DEN,UV}$, the value of $\dot{E}_{DEN,AV}$ is subtracted from $\dot{E}_D$.

### 2.5. Extended exergy analysis

Exergy analysis is mainly focused on the exergy destruction in a process [57]. In 1970, exergy analysis with consideration for the life cycle was considered for all the material and energy consumed in processes, accounting for equipment production, setup and operation. A resulting method is Exergy Life Cycle Analysis (ELCA), which assesses Cumulative Exergy Consumption (CEXC). CEXC considers all consumed exergy flows, starting from natural resources and material extraction through to the final product [58–62]. Another combinational method is thermo-economic (TE). In this method, parameters other than energy (installation cost, profit, labor, repairs, insurance, etc.) are considered along with thermodynamic parameters (energy and exergy flows). In this analysis, all dynamic parameters of the system are considered [63,64]. In the Extended Exergy Approach (EEA), which includes ELCA and CEXC, one considers the point where the material is extracted from the initial resources through to the point where the product is processed

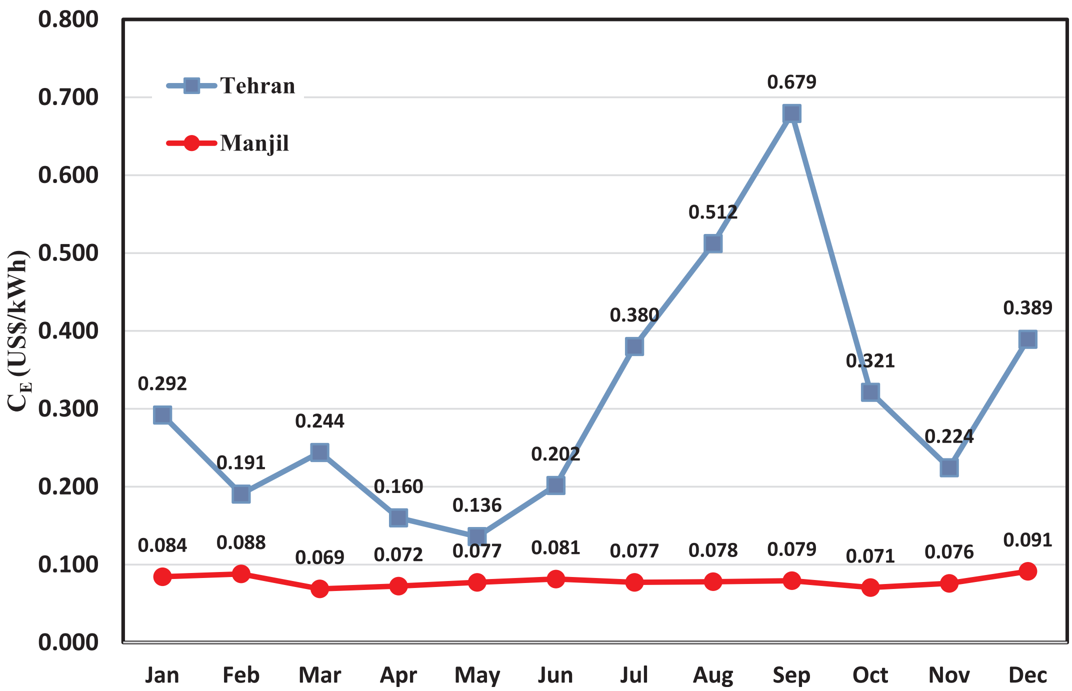


**Fig. 9.** Changes in average monthly cost of electricity generated by the wind turbine in Tehran and Manjil.

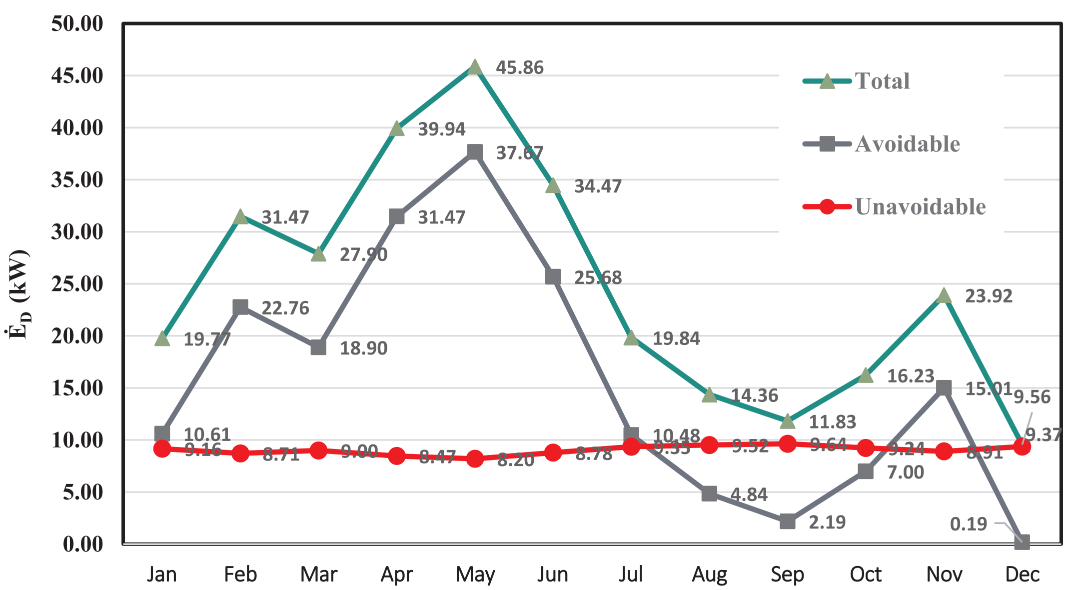


**Fig. 10.** Average monthly avoidable and unavoidable exergy destruction by the wind turbine broken down by month for Tehran.

or utilized. During system operation, all of the system's input and output exergy flows are considered. This TE method converts all costs to exergy flow [65–70]. An exergy balance based on the concept of EEA for a wind turbine follows [44]:

$$E_T + EE_L + EE_O + EE_{Ins} - Ex_{gen} - Ex_{des} = 0 \tag{27}$$

Here, $EE_L$, $EE_O$ and $EE_{Ins}$ denote the equivalent extended exergy values for initial cost, operation and maintenance, and insurance.

Also, $E_T$ is the total of the system's input and output exergy including physical, kinetic and chemical exergies $(\frac{MJ}{Year})$, $EE_L$ is the labor exergy $(\frac{MJ}{Year})$, and $Ex_{des}$ is the system's exergy destruction $(\frac{MJ}{Year})$, and $Ex_{gen}$ is the exergy generated power from the wind $(\frac{MJ}{Year})$. With the EEA method, the exergy destruction can be expressed as follows [44]:

$$Ex_{des} = Ex_T + EE_L + EE_O + EE_{Ins} - Ex_{gen} \tag{28}$$

The value of $EE_L$ can be calculated as follows [65–70]:

$$EE_L = Lee_L \tag{29}$$

where L is the number of annual working hours and $ee_L$ is the extended exergy cost of labor $(\frac{MJ}{Workhour})$. The latter term can be calculated as follows [44]:

$$ee_L = \frac{365 HDI ex_{surv} N_h}{HDI_o N_{wh}} \tag{30}$$

Here, $ex_{surv}$ is the exergy consumption for survival which is $1.05 \times 10^7 (\frac{J}{PersonDay})$, $N_h$ is the number of inhabitants which is 75 706 898 for Iran [44], $N_{wh}$ is the total annual working hours in Iran which is equal to 54539487345 $(\frac{Hour}{Year})$, HDI is the human development index, which is 0.774 [70,71], and HDI0 is the human development index for a primitive society, which is equal to 0.055 [70,71].

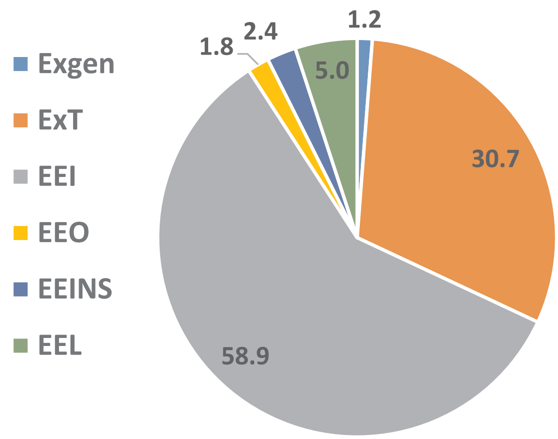


**Fig. 11.** Percentage contributions of components for the extended exergy analysis in Tehran.

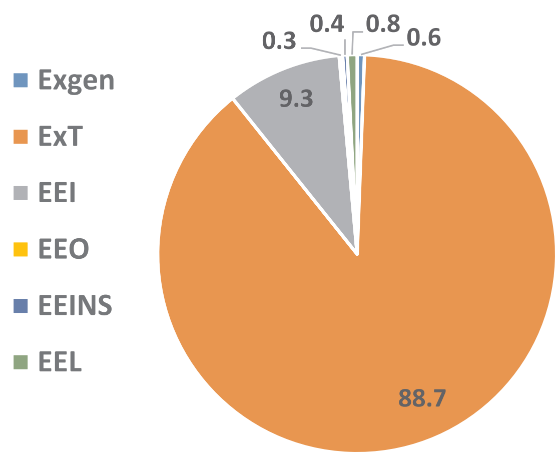


**Fig. 12.** Percentage contributions of components for the extended exergy analysis in Manjil.

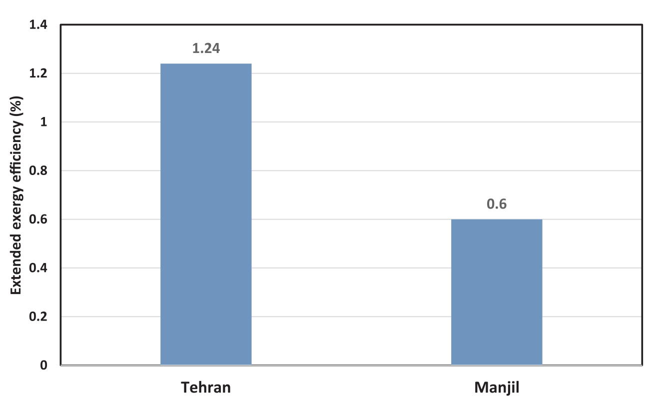


**Fig. 13.** Extended exergy analysis efficiencies for Tehran and Manjil.

The following equation relates $EE_I$, $EE_o$ and $EE_{Ins}$ [44]:

$$EE_{Ins} + EE_O + EE_I = (C_I + C_o + C_{Ins})ee_c \tag{31}$$

Here, $ee_c$ is the extended exergy of capital ($\frac{MJ}{\$}$), which can be calculated as follows [65–70]:

$$ee_c = \frac{365HDIex_{surv}N_h}{HDI_oS} \tag{32}$$

where S denotes the national monetary amount of wages and salaries ($\frac{\$}{year}$), which is reported as 43196401055 $\frac{\$}{year}$ in 2015 [44].

The extended exergy efficiency can be calculated as follows:

$$Extended\ exergy\ efficiency = \frac{Ex_{gen}}{EE_T + EE_I + EE_O + EE_{Ins} + EE_L} \tag{33}$$

### 2.6. Input data

The specifications of the 10 kW Bergey Excel-S considered in the current study are provided in Table 1 [72].

This wind turbine is considered for the cities of Tehran and Manjil. Tehran is located at a geographical latitude and longitude of 34o 51′N and 51o 19′E respectively, while Manjil is located at geographical latitude and longitude of 36o 44′N and 49o 24′E respectively [73]. The number of air flows for various wind speeds for Tehran and Manjil are provided in Tables 2 and 3 [73].

## 3. Results and discussion

Fig. 2 shows the flow chart for the mathematical modeling.

For validation of the results, the power curve of the manufacturer (see Fig. 3) is considered [72]. Based on annual average air flows at a certain speed and Fig. 3, the annual average power production is calculated with two methods. One method is based on Fig. 3 and the other is based on the mathematical model presented in this paper. Table 4 shows the comparison.

Fig. 4 shows the average monthly wind speed in Tehran and Manjil. In all seasons of the year, the average monthly wind speed in Manjil is higher than that of Tehran. Fig. 5 shows the average monthly power generation by the wind turbine in Tehran and Manjil. In all months of the year, the average monthly power generation by the wind turbine in Manjil is higher than that of Tehran. Fig. 6 shows the changes in average monthly efficiency of the wind turbine by month. The trend of energy efficiency in this figure is similar to that in Fig. 4. Fig. 7 shows the changes in average monthly exergy efficiency of the wind turbine broken down by month for Tehran and Manjil. Unlike Figs. 2 and 3, the exergy efficiency in Tehran is higher than that of Manjil, while the energy efficiency and average power generation in Manil are higher than the corresponding values for Tehran. It can be concluded that in places with higher wind potential, the exergy destruction is also greater, so the exergy efficiency in such places, is lower.

Fig. 8 shows the exergy destruction for the months of the year for Tehran and Manjil. As noted in the above paragraph, in places with higher average wind speed, the exergy destruction is greater.

Fig. 9 shows the changes in average monthly cost of electricity generated by the wind turbine for Tehran and Manjil. The electricity cost in Manjil is lower than that of Tehran. In places with higher wind potential, the cost of the generated electricity is lower.

**Table 5**
Number of air flows at a certain speed for Sabzevar broken down by month.

| $u_i$ (m/s) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $1 < u_i < 2$ | 78 | 62 | 91 | 82 | 61 | 65 | 43 | 58 | 101 | 104 | 138 | 95 |
| $3 < u_i < 5$ | 5 | 13 | 21 | 43 | 56 | 64 | 67 | 68 | 38 | 13 | 23 | 3 |
| $6 < u_i < 8$ | 6 | 7 | 12 | 7 | 8 | 26 | 10 | 7 | 16 | 0 | 0 | 0 |
| $u_i > 9$ | 0 | 0 | 0 | 2 | 1 | 2 | 6 | 3 | 3 | 0 | 0 | 0 |

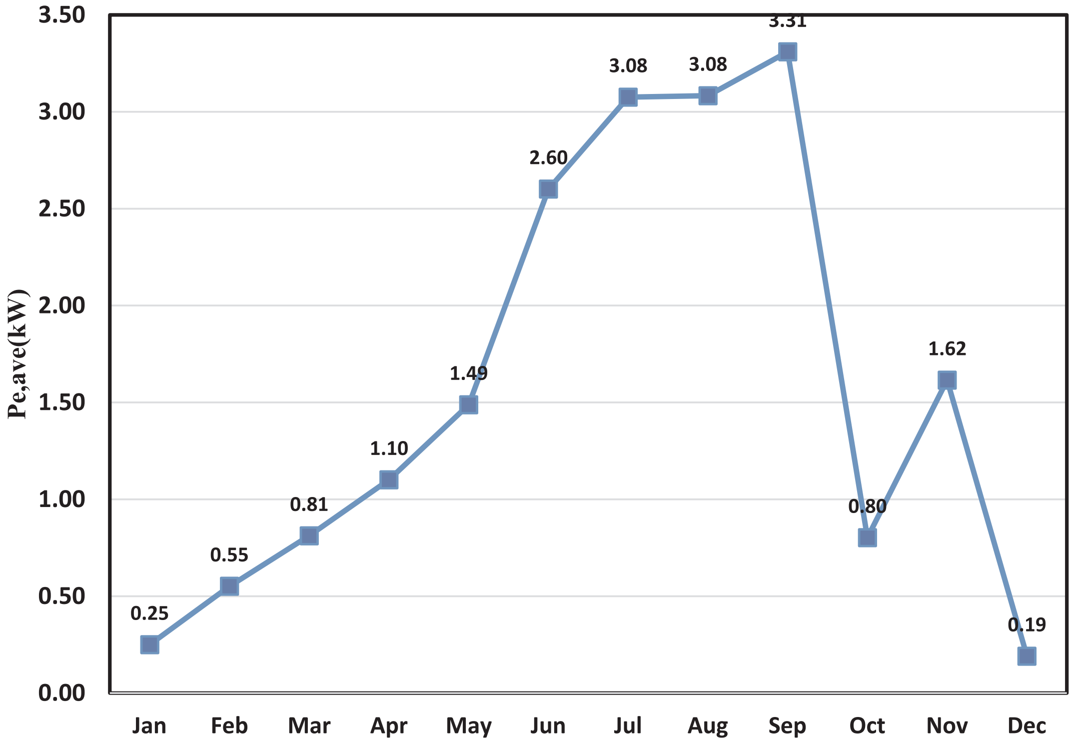


**Fig. 14.** Average monthly power generation by wind turbine in Sabzevar.

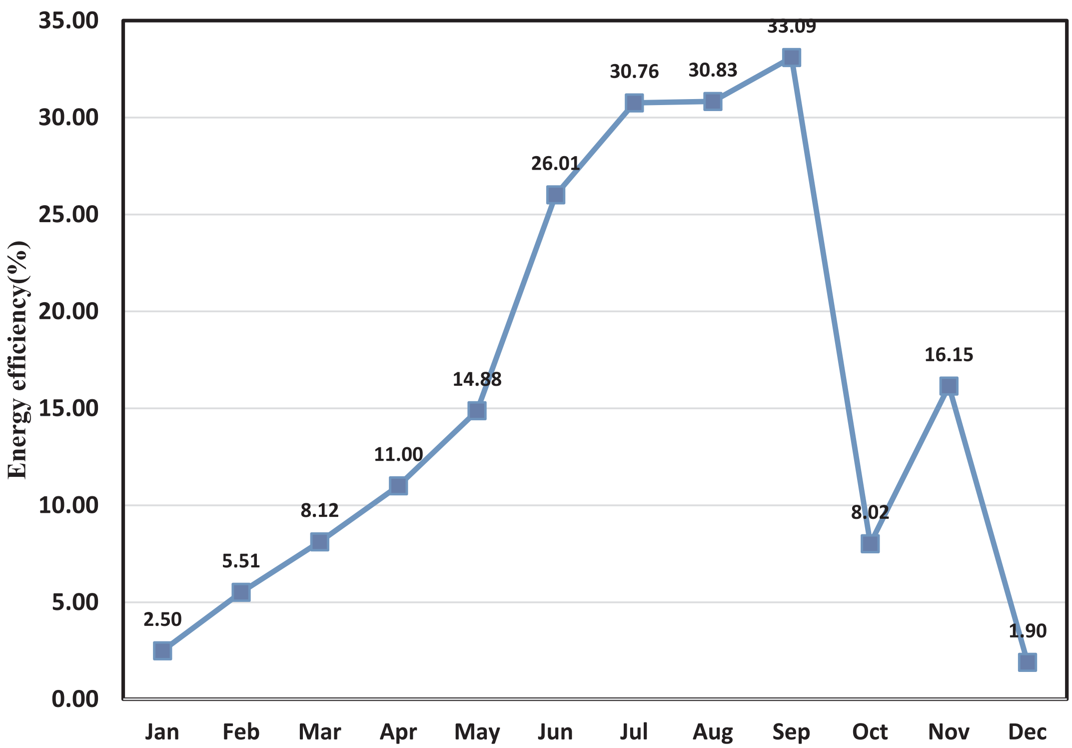


**Fig. 15.** Changes in average monthly efficiency of wind turbine with month of year in Sabzevar.

Fig. 10 shows the results of advanced exergy analysis for Tehran. It is seen in the figure that, from January to July, the amount of avoidable exergy destruction is higher than the unavoidable exergy destruction. This trend is reversed from August to October. In the November, the amount of avoidable exergy destruction is higher, while in December, it is lower. The trend of avoidable exergy destruction changes is similar to that of the average wind speed (Fig. 4). Whenever the average wind speed is increased, the avoidable exergy destruction also rises. It is evident, therefore, that avoidable exergy destruction (the exergy destruction that can be avoided) increases with wind speed.

Fig. 11 shows the percentage of the contribution of each component of the extended exergy analysis of the wind turbine in Tehran. It can be observed in this figure that the highest percentage share of the total exergy value of the system is related to the exergy equivalent of the

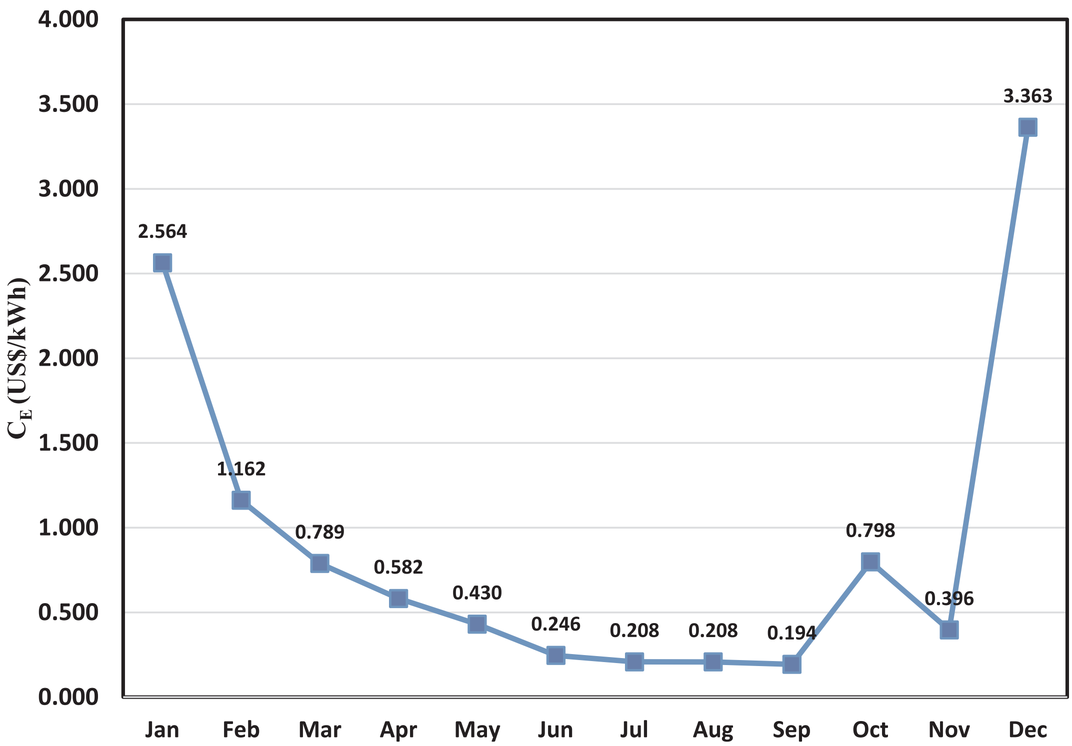


**Fig. 16.** Changes in average monthly cost of electricity generated by the wind turbine in Sabzevar.

initial installation costs (58.9%). The second highest percent of share exergy value is total the input and output of the system's annual exergies, including physical, kinetic and chemical exergies (30.7%). The lowest percentage share of the exergy is associated with the annual electrical power generation by wind (1.2%). In areas with moderate wind speeds (Tehran) and based on extended exergy analysis, the wind turbine is not economically viable. This is mainly because, according to this analysis, significant percentages are associated with the exergy equivalent to initial installation and labor costs.

Fig. 12 shows the percentage of the contribution of each component of the extended exergy analysis in Manjil. Unlike for Tehran, the highest percent share exergy value of the system total is related to total the input and output of the system's annual exergies (88.7%). The second highest percent share of exergy is related to the exergy equivalent of the initial installation costs (9.3%). The lowest percent share of exergy is related to the exergy equivalent of the operation and maintenance costs (0.3%).

Fig. 13 shows the extended exergy analysis efficiency for Tehran and Manjil. In this analysis, similar to the exergy analysis, the efficiency for Tehran is higher than that for Manjil.

### 3.1. *Extension of study to another city*

For further study, Sabzevar city is considered in the northeast of Iran. Sabzevar is located at a geographical latitude and longitude of 36° 12′N and 57° 43′E respectively [73]. The number of air flows for various wind speeds for Sabzevar is provided in Table 5 [73].

Figs. 14–16 show the average monthly power generation, energy efficiency and electricity cost of the wind turbine in Sabzevar.

## 4. Conclusion

Energy, exergy, economic, advanced exergy and extended energy analyses are successfully performed for a Bergey Excel-S wind turbine with nominal power of 10 kW for two cities in Iran: Tehran (medium wind potential) and Manjil (high wind potential). The results show that the energy efficiency of the wind turbine is higher in windy areas than in other areas, but that the exergy efficiency in these areas is lower. Also, the cost of electricity generated by the wind turbine in the windy areas is higher. The advanced exergy analysis demonstrates that the avoidable exergy destruction percentage of the wind turbine increases with wind speed. The extended exergy analysis shows that, in windy areas, the highest exergy percentage is exhibited by the system's input and output exergy flows and power production, while, in areas with medium wind speed potential, the exergy is equal to is the equivalent extended exergy content of the influx of capital cost.

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