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Comprehensive Energy-Econo-Enviro (3E) Analysis of Grid-Connected Household Scale Wind Turbines in Qatar

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Abstract

Among various types of renewables, wind energy requires a less initial investment that is projected to decrease even more due to technology advancement, a higher number of turbines, and ease of restrictions. Unlike traditional power-plants, wind turbines have been developed in various dimensions, and minimal land is taken out of production, so they are recommended for small countries facing a lack of space. Given these facts, a potentio metric study of supplying the electricity of a residential house in 5 cities of Abu Samrah, Ar-Ruways, Doha, Duhan, and Musayid, Qatar, is performed using HOMER and meteorological 20-year-average data taken from the NASA website. The studied system is connected to the grid, and a techno-Econo-environmental study is conducted. The study results of the turbulence intensity (TI) parameter indicated the mechanical components of the wind turbine in the Doha station were under intermediate fatigue loads while these loads were lower in the remaining stations. According to the results, it is clear that Doha station, with a price per kWh of electricity generated, and a total net present cost (NPC) of $0.086 and $6349, respectively, produces the most cost-effective wind power electricity due to using BWC XL.1 horizontal axis wind turbine. The highest amount of CO2 emissions savings and most top production of CO2 are associated with Doha (-300 kg) and Abu Samrah (2844 kg) due to using EOLO and Turby wind turbines, respectively. Ar-Ruways generate the highest (8890 kWh/y) and lowest (658 kWh/y) amounts of wind power electricity and Abu Samrah stations which are due to utilizing Generic 10 kW and Turby wind turbines, respectively.

Keywords: Power curve; Hub height; Wind speed; National electricity grid; Weibull function.;

1. Introduction

For the first time in history, in 2015, the urban population has surpassed the rural one and future trends also reveal that, by 2020, around 70% of the world population will be living in cities. Among all continents, Asia and Africa will be more influenced by urbanization and, by 2050, their urban population will increase from 40% and 48% to 56% and 64%, respectively [1]. A dilemma involving this issue is the constantly increasing emission of carbon due to this rapid growth of world population and urbanization [2, 3].

Qatar also is experiencing rapid economic growth which is accompanied by a rapid escalation in population and urbanization and, therefore, higher demand for energy sources like fossil fuels, electricity, and water has resulted in an increased air and environmental pollution [4]. According to the IPCC (Intergovernmental Panel on Climate Change) reports, by producing 45 tons of CO_2 per capita per year, Qatar is ranked as the highest per capita carbon emitter globally [5, 6]. Air pollution is very alarming in Qatar because it often exceeds the local and international recommended standards [7]. According to WHO (World Health Organization), Duha is one of the most polluted cities in the world which ranks 12 in terms of air poor quality (annual average particulate matter formation) [8]. Although some international, national, and governmental policies are needed to solve these problems, people and regions can also be useful in reducing these issues [9]. For example, Qatar has large fossil fuel energy resources [10], but the country has also adopted a sustainability-oriented strategic solution for reducing energy consumption while producing more reliance on clean and renewable energy sources and that is raising public awareness about environmental damages due to overconsumption of energy [11] and the necessity of preserving fossil fuel as an inheritance for future generations, providing job security in

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this field and improving the lifestyle [12]. This roadmap will definitely enable Qatari citizens to give priority to saving energy and protecting the environment [13].

For human development to continue, renewable, i.e., infinite, energy sources have to be found. Due to its abundant benefits, wind energy application has grown rapidly [14, 15]. The most important advantage of wind turbines is that they are less environmentally harmful [16-18]. Wind turbines directly produce no air or environmental pollution [19,20]. This secures people residing around wind farms from serious health problems. Given the fact that wind is a renewable energy source and it is not dependent upon shipping or underground reverses, it also helps prevent indirect transportation-induced pollution. Furthermore, unlike the majority of methods, wind energy is capable of producing electricity without water. Thus, it prevents water pollution and shortages of energy caused by droughts [21].

In windy areas, wind turbines can produce electricity during all hours day and night. This is particularly true for coastal and mountainous regions. They can be installed at various places for residential or commercial applications. Wind equipment can be mounted in houses, farms, offshore platforms, and on top of high hills. This form of renewable energy is highly scalable. While traditional power-plants are built to provide electricity for huge populations, turbines are developed in various sizes. The energy produced by different models of wind turbines can supply the required power of a small farm, a house, or hundreds of houses [22,23].

Another advantage of wind turbines is that they occupy far less area than conventional power-plants or even solar farms and people can continue other activities around the wind farms. This is of high importance for small countries facing space problems — businesses, farmers, and landowners that install wind turbines on their lands and enjoy a significant saving and can keep their lands economically viable without using a considerable area of land. Wind turbines also cut the utility costs of residential houses. Wind energy is available in almost all parts of the earth, but there are discrepancies regarding wind compatibility and power. It is estimated that 1 million GW of wind energy is available all over the world and if the potential wind energy is extracted from 1% of these amounts, it could supply all the electricity demand of the world [24].

Belke and Palm (2009) studied the wind energy potential by collecting data at four various places in Ethiopia, i.e., Addis Ababa, Mekele, Nazret, and Debrezeit, and analyzing them using HOMER [25]. They determined monthly average wind energy potential, the probability density function of wind speed (PDF), wind cumulative density function (CDF) and wind duration curve (DC) for all four areas. According to the measurements at 10 m altitude, results indicated a reasonable wind energy potential with an average wind speed of 4 m/s for the studied sites, except for Debrezeit.

Rodrigues and Rossi (2016) compared to power generation of two small wind turbines (a 6 kW and a 5 kW) using HOMER [26]. They investigated the wind sources of three various cities: Campinas and Cubatãoin Brazil and Roscoe in Texas, US. A grid-connected and an off-grid system (using batteries) were evaluated. Results showed that for the 5 kW and 6 kW turbines, the cost of electricity (COE) of the off-grid system were up to 9.95 and 19.8 times higher than that of the grid-connected system, respectively.

Ayodele and Ogunjuyigbe(2016) studied the wind energy potential at Vesleskarvet, the Antarctic, to meet the energy demands of the South African SANAE IV Research Station located at Vesleskarvet [27]. Optimization results using HOMER showed that 15 wind turbines (PGE20/25 model) with the following specifications seemed capable of meeting the energy demands of SANAE IV research base: 25 kW rated power, 3.5 m/s cut-in wind speed, 25 m Hub height, 9 m/s rated wind speed and 25 m/s cut-out speed. These entailed $1,336,262 total NPC, operational cost of $976,500, and $0,102 COE.

Qolipouret al., (2016) used HOMER for a techno-economic evaluation of manufacturing small residential-scale wind turbines in six districts of Ardebil Province, Iran, given the wind speed data in the period of 2008 to 2014 [28]. Using an integrated ranking method and considering the power generation capacity of turbines, their manufacturing costs, profits, the sum of net and depreciation costs, and emissions per plant were calculated separately for each district. Results indicated that Ardebil, BilaSavar, Kowsar, Firozabad, Nir, Namin, and Airport sites ranked as sixth to first.

Becerra et al., (2017) studied the financial feasibility of installing wind farms in small-scale for Chile by evaluating real-world scenarios in high potential areas to be used for the residential sector [29]. They used HOMER for their evaluations. The selected places were Laguna Verde in the central parts and Porvenirin the southern parts of Chile. Given the 90 kW rated capacity, a small-scale wind farm was studied. Results obtained after 240 simulations indicated that direct connection to the wind farm consisting of FD16-30 wind turbines, by producing the lowest total NPC, was among the most optimal scenarios chosen.

Qolipouret al., (2018) applied mathematical modeling for facilitating the simultaneous optimization of construction of new wind power-plants and renewable electricity prices at various areas of Kermanshah Province, Iran [30]. Their case study included the development of one, two, or three wind power-plants in three regions of Taze Abad, Samer, and Gilan-e-Qarb (in the order of their potential wind power). First, ten-year wind speed data (2006-2016) of these three areas were simulated for techno-economic feasibility evaluation of wind power-plants using HOMER. Then, the software outputs were used to solve the related mathematical model in MATLAB. Results showed that by constructing one, two, or three wind power-plants, the optimal price would be $0.159, $0.151, and $0.140 per kW of electricity generated.

Shaahidet al., (2018) conducted the economic feasibility of developing a 30 MW wind power-plant in Turaif, Saudi Arabia [31]. In this study, the choice of commercial wind equipment, energy simulations, and the size of wind farms were performed using HOMER. The annual energy produced by this 30 MW wind farm (hub height of 50 m) reached 39752 MWh. By developing this 30 MW wind farm around 1598 tons of CO_2 emissions could be saved annually.

Mendez and Bicer (2019) studied wind energy potential in Qatar and its environmental and financial effects on the natural gas industry [32]. They selected a commercial wind turbine according to the wind speed and direction data.

Results indicated that, with an average wind speed of 5.06 m/s, a 17 MW wind power plant annually reduces 6.8 tons of CO_2 emissions as well as having an annual economic impact of $3.32 million on Qatar's economy.

Given the facts mentioned above and since no research has been conducted so far on vertical and horizontal axis wind turbines in Qatar to find the lowest cost of wind-powered electricity, this study is the first one to use 20-year average data taken from the NASA website and HOMER software for techno-Econo-environmentalresearch in this regard. The studied system was connected to the national grid, and such parameters as COE, total NPC, and the emissions produced were investigated. Eventually, the most suitable wind turbine among eight commercially available wind turbines (4 horizontal axis and four vertical axis) were identified for each station. Since the results of the present work can be used as a guide to help decision-makers and policymakers in the field of energy in Qatar, the authors of the present study have tried to accurately study the wind potential in different stations, determine various costs of wind power, and perform environmental analyses.

The HOMER software performs the most accurate technical, economic, and environmental calculations for renewable energies, and the reason for choosing it is its simplicity of use and one-year analysis. The present work used HOMER software whose database only contains the information on horizontal-axis wind turbines (HAWTs). The authors have been able to upgrade the software's features by inputting experimental data on the power curve of vertical-axis wind turbine (VAWTs) in a .txt file format which is the first attempt in this respect.

Furthermore, using realistic and updated data for the price of grid electricity, equipment, annual interest rate, etc. makes the results beneficial for policymakers in the energy sector to make sound decisions about wind-powered electricity in Qatar.

2. The Studied Area

Qatar is a country located in Southwestern Asia, occupying the small Qatar Peninsula on the northeastern coast of the Arabian Peninsula. Doha is its capital city, and its sole land border is with neighboring Saudi Arabia to the south, with the rest of its territory surrounded by Persian Gulf boundaries with Iran, Kuwait, Iraq, Saudi Arabia, Bahrain, and United Arab Emirates. The country covers an area of 11493 m^2 [33]. In 2018, Qatar's total population was 2.7 million [34]. Figure 1 shows Qatar's geographical location in the world.

Slightly tropical weather dominates throughout the year. Summer is the hottest time of the year that lasts very long from May to September with highs up to 50˚ C. Winter season (from November to May) is also rather mild with temperatures between 21˚ to 27˚ C [35]. Due to the growth in population and urbanization, Qatar is facing increasing energy demands [36]. Therefore, the first important step is to design and implement initiatives for reducing energy use by households [37].

Qatar is the second-largest consumer of electricity among the Gulf Cooperation Council (GCC) countries [38]. Qatar Electricity & Water Company (QEWC) has announced that in the last decade, Qatar has enjoyed rapid economic and infrastructural developments and this has led to a 6% to 7% increase in annual electricity demand [39]. In 2014, annual energy consumption in this country reached 17 million MW per capita [40]. Under the Kyoto Protocol and through ratification of the COP21 agreement by April 22, 2016, Qatar has shown its tendency to follow a GHGs reducing strategy [41]. Besides, preserving the environment for future generations, there is another critical goal which Qatar seeks for in the coming years [42]. Nowadays, Qatar's economy is considerably dependent upon oil and gas industry. Because of the precarious prices of the oil and hydrocarbons, however, a sustainable and clean energy-producing alternative seems necessary [43]. Qatar has estimated to generate 1800 MW of its required power by renewables by 2030 [44]. Qatar, along with other GCC countries, by an annual wind potential of more than 1400 hours, has the potential capacity for using wind energy [45]. Figure 2 shows the renewable energy deployment target of GCC countries by 2020 among which Kuwait and Qatar hit the highest potential by 10 and 6 percent, respectively [16]. Figure 3 depicts the wind potential at various areas of this country at 50 m height [46].

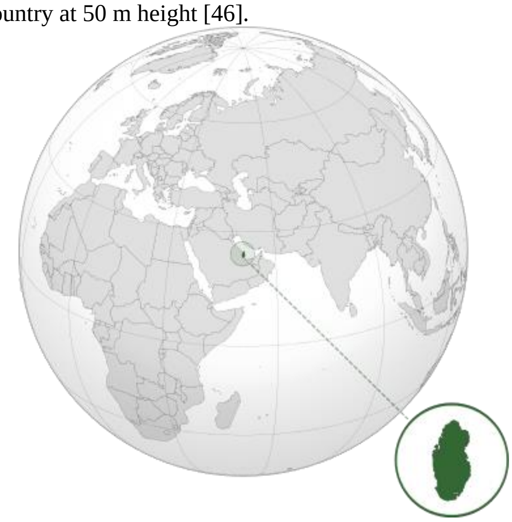

Figure 1. The location of Qatar in the world.

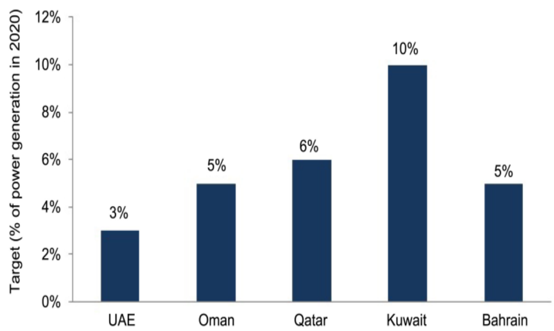

Figure 2. Target of Renewable energy in Gulf Cooperation Council countries by the year 2020.

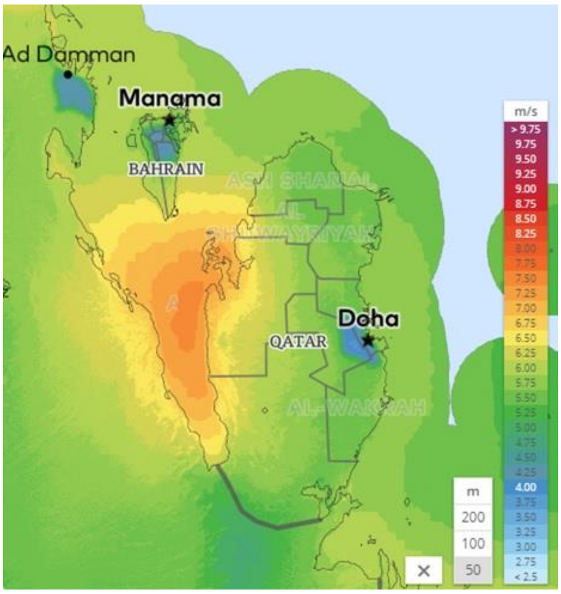

Figure 3. Wind atlas of Qatar in the height of 50m [46].

3. Methodology

HOMER was used to design and evaluate an optimal micropower in both off-grid and grid-connected states to achieve the applied program's purposes. When planning a power generation system, many decisions have to be made about the due configuration of the system: what components such as panel, wind turbine, diesel generator, etc., are required to build a power system? What is the appropriate number and size of each component?

Various technologies used, changes in the costs of these technologies and the availability of energy sources render it more difficult to make reasonable decisions. Optimization algorithms and sensitivity analysis of HOMER facilitate the evaluation of many feasible systems. HOMER outputs the simulation results in the form of tables and diagrams which makes it easy to compare various configurations. Then it compares them according to their economic and technical rankings and provides for the derivation of charts and graphs in reports and presentations. When one wants to assess the effect of changing such factors as access to resources and economic conditions on efficiency and cost-effectiveness of various systems configuration, HOMER's sensitivity analysis might be helpful. Results of this analysis can be used for the determination and identification of the factors most influential on the system design and operation. Also, HOMER's sensitivity analysis results might be useful for solving general equations of technology alternatives utilized for planning and decision-making. HOMER software simulates the operation of a system by doing the calculations of energy balance in 8769 hours of the year. For each time step, HOMER compares the thermal and electrical demand in that time step to the energy that the system can supply in that time step, and calculate the flows of energy to and from each part of the system. For systems that include fuel-powered generators or batteries, HOMER also decides in each time step how to operate the generators and whether to discharge or charge the batteries. Energy balance calculations are performed by HOMER for each system configuration, which can then determines whether an arrangement is feasible, i.e., or whether it can meet the electric demand under the situations that you specify, which can also estimate the installing and operating cost of the system over the project lifetime. The system cost calculations account for expenses, such as capital, operation and maintenance, replacement, interest and fuel [47].

The validation of data in the present work has been conducted using wind speed data from Lutak station in Teimourian et al. (2019) [48] work and the Weibull function calculated by them has been compared with that calculated by HOMER. Data used in the study by Teimourian et al. are obtained by an analytical method and from curve-fitting on the wind power data where C=7.22 and K=1.6. However, in the present work, using the HOMER software, C and K obtained from curve-fitting are 7.36 and 1.97, respectively. The reason for choosing the Weibull distribution function for validation is the fact that its uses for measuring potential and fitting the actual probability of wind occurrence. As the comparison in Figure 4 shows, there is a good agreement between the HOMER-plotted Weibull function and that obtained by Teimourian et al.

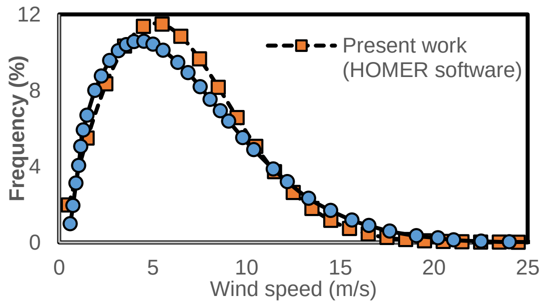

Figure 4. Validation of HOMER results against results of other works using Weibull function

The components used in the present work are explained below [49].

3.1. Wind Turbine

Based on the power curve and hub-height wind speed, HOMER calculates the wind turbines' power output. It should be noted that the power curves typically specify wind turbine performance under conditions of standard temperature and pressure. HOMER multiplies the air density ratio by the power value predicted by the power curve to regulate actual conditions, according to the following equation:

$$P_{WTG} = \frac{\rho}{\rho_0} \times P_{WTG,STP} \quad (1)$$

Where ρ is the actual air density (kg/m^3), ρ_0 is the air density at standard pressure and temperature equal to 1.225, $P_{WTG,STP}$ is the power output of wind turbine at standard pressure and temperature.

The HOMER database contains only technical information and data about the power of horizontal axis wind turbines. In the present work, the experimental diagrams of power and technical specifications of four vertical axis wind turbines (WRE, Turby, Spiral, and WOLO) are converted into .txt files and added to HOMER software as inputs.

3.2. Converter

An inverter's efficiency is the efficiency with which it converts DC electricity to AC electricity (in %). The inverter can operate at the same time as one or more AC generators. Inverters that are not able to perform this way are sometimes called switched inverters. The rectifier's efficiency is the efficiency with which it converts AC electricity to DC electricity (in %). It is noteworthy that HOMER assumes the rectifier and inverter efficiencies are constant. Most solid-state converters are less efficient at a very low load because of standing losses.

3.3. Battery

HOMER calculates in each time step the maximum value of power that can absorb by the storage bank. The maximum charge power changes from a one-timestep to the next is pursuant to its state of charge and its recent discharge and charge history. Three separate limitations impose by HOMER on the maximum charge power of storage banks.

The Kinetic storage model is the first limitation which is given by the following equation [50, 51]:

$$P_{batt,cmax,kbm} = \frac{kQ_1 e^{-k\Delta t} + Qkc(1-e^{-k\Delta t})}{1-e^{-k\Delta t}+c(k\Delta t-1+e^{-k\Delta t})} \quad (2)$$

where Q_1 is the available energy [kWh] in the storage bank at the beginning of the time step, Q is the total amount of energy [kWh] stored in the storage bank at any time, c is the storage bank capacity ratio [unitless], k is the storage bank rate constant [h^{-1}], $\Delta t$is the time step length [h].

The maximum charge rate of the storage component is the second limitation which is given by the following relation[50, 51]:

$$P_{batt,cmax,mcr} = \frac{(1 - e^{-\alpha_c \Delta t})(Q_{max} - Q)}{\Delta t} \quad (3)$$

whereα_c is the storage's maximum charge rate [A/Ah], and $Q_{max}$is the total capacity of the storage bank [kWh].

The storage component's maximum charge current is the third limitation which is given by the following equation[50, 51]:

$$P_{batt,cmax,mcc} = \frac{N_{batt} I_{max} V_{nom}}{1000} \quad (4)$$

whereN_{batt} is the number of batteries in the storage bank, I_{max} is the storage maximum charge current [A], $V_{nom}$is the storage's nominal voltage [V].

HOMER sets the utmost storage charge power equal to the minimum of these three values according to the following equation[50, 51]:

$$P_{batt,cmax} = \frac{Min\ (P_{batt.cmax.kbm}\cdot\ P_{batt.cmax.mcr}\cdot\ P_{batt.cmax.mcc})}{\eta_{batt.c}} \quad (5)$$

where$\eta_{batt,c}$is the efficiency of storage charge.

3.4. Generator

By recording fuel curve inputs, HOMER plots the corresponding efficiency curve. The fuel curve shows the quantity of fuel that the generator consumes to produce electricity. The fuel curve is assumed as a straight line by HOMER. The following equation gives the fuel consumption of the generator in units/hr as a subordinate of its electrical output:

$$\dot{m}_{fuel} = F_0 Y_{gen} + F_1 P_{gen} \quad (6)$$

whereF_0 is the fuel curve intercept coefficient [units/hr.kW],F_1 is the fuel curve slope [units/hr.kW], $Y_{gen}$is the generator rated capacity [kW], $P_{gen}$is the generator electrical output [kW].

HOMER defines the electrical efficiency of the generator as the electrical energy coming out divided by the chemical energy of the fuel going in. The following equation gives this relationship:

$$\eta_{gen} = \frac{3.6\ P_{gen}}{\dot{m}_{fuel} LHV_{fuel}} \quad (7)$$

whereLHV_{fuel} is the lower heating value of the fuel [MJ/kg].

3.5. Cost Calculations

The real rate of discount is used to convert between annualized costs and one-time costs. HOMER uses the real interest rate to calculate annualized costs and discount factors from NPCs. HOMER calculates the annual real interest rate (i) from the nominal interest rate (i') by the following equation:

$$i = \frac{i' - f}{1 + f} \quad (8)$$

where*f* is the expected inflation rate, the inflation rate is assumed the same for all costs.

The total NPCis obtained by dividing the total annual cost by the capital recovery factor. The following equations used by HOMER to calculate the capital recovery factor:

$$CRF = \frac{i\ (1 + i)^N}{(1 + i)^N - 1} \quad (9)$$

Moreover, the cost per kWh of electricity generated is gained by dividing the total annual price by the price of the real electricity load generated.

4. Data Required for Simulation

HOMER requires wind speed data for simulating wind turbine systems. For the studied stations, these were 20-year-average data [52] taken from the NASA website which are presented in Table 1. It can be observed that the highest average wind speed (4.1 m/s) is associated with the Doha station.

Given the availability of the national electricity grid in the studied region, the studied hybrid renewable energy system (Figure5) is connected to the national electricity grid, and it is possible to sell/ buy electricity to/ from the national grid. An equal price of $0.022 per kWh is assumed for buying or selling power from/to the national grid [53]. Besides, given the fact that $CO_2$is regarded as the primary pollutant emitted, 632 g of CO_2 is considered per kWh of electricity produced by the national electricity grid. The buying/selling capacity of 1000 kW from/to the national grid is also assumed. The amount of electricity required for a residential house is 14 kWh/d on an annual-average basis (Figure5).

As can be observed in Figure 6, the peak load required is 2.12 kW which happens in June and the mean electricity needed is 0.579 kW. The daily random variability of 15% for the necessary power was also taken into account.

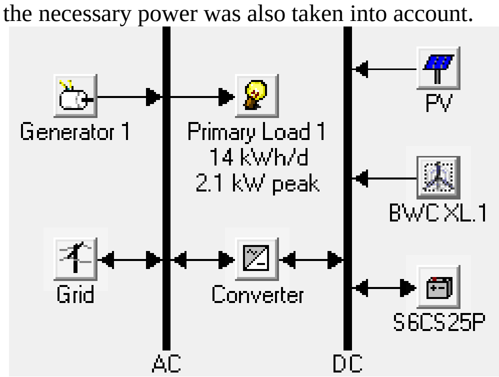

Figure 5. Schematic of the studied hybrid renewable energy system.

4.1. Wind Speed in the Studied Area

The wind speed will play an essential role in the designed system. Therefore, it is required to study the wind speed in the area of interest. To this end, wind data corresponding to the geographical location of the studied areas was taken from the NASA website. Figure 7 shows the daily-average wind speed for a year in the studied stations. From the results in Figure 7, it is evident that for Abu Samrah station, Ar-Ruways, Doha, Duhan, and Musayid stations the maximum and minimum daily-average wind speeds are respectively as follows: 4.4 m/s in June and 3.2 m/s in November, 4.6 m/s in June and 3.4 m/s in October, 4.9 m/s in June and 3.3 m/s in October, 4.4 m/s in June and 3.2 m/s in November, 4.3 m/s in June and 3.1 m/s in November.

Given the fact that the cut-in speed for many small wind turbines (power less than 10 kW [54]) is 3-3.5 m/s, we decided that small-scale wind-power generation is possible for all months of the year [55]. The wind energy potential for installing wind turbines is regarded as poor (<4 m/s), marginal (< 4-4.5 m/s), good to very good (5.5-6.7), and excellent (> 6.7 m/s) [56]. This is according to the wind speed available. In the stations studied in Qatar, it is clear that the wind speed can be categorized as good and very good or excellent for many hours of the day. According to Figure 7, wind speed is higher in hot seasons. Thus, in the summer month, when demand for electricity is the highest, the area can enjoy the maximum generation in case of installing wind turbines which is one of the advantages of using residential-scale wind turbines.

Table 1. Monthly averaged wind speed in the stations under study

Station	Z(m)	Long.	Lat.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
AbuSamrah	114	50.8	24.8	3.6	4.1	3.9	3.6	3.9	4.4	4.1	4.0	3.6	3.3	3.2	3.6
Ar-Ruways	0	51.2	26.1	4.0	4.5	4.3	4.0	4.5	4.6	4.2	4.1	3.7	3.4	3.5	3.9
Doha	10	51.6	25.3	3.9	4.5	4.6	4.4	4.7	4.9	4.2	3.8	3.5	3.3	3.6	3.8
Duhan	30	50.8	25.4	3.7	4.2	4.0	3.7	4.1	4.4	4.1	4.0	3.6	3.3	3.2	3.6
Musayid	17	51.6	25.0	3.6	4.2	3.9	3.7	4.0	4.3	4.0	3.9	3.5	3.3	3.1	3.6

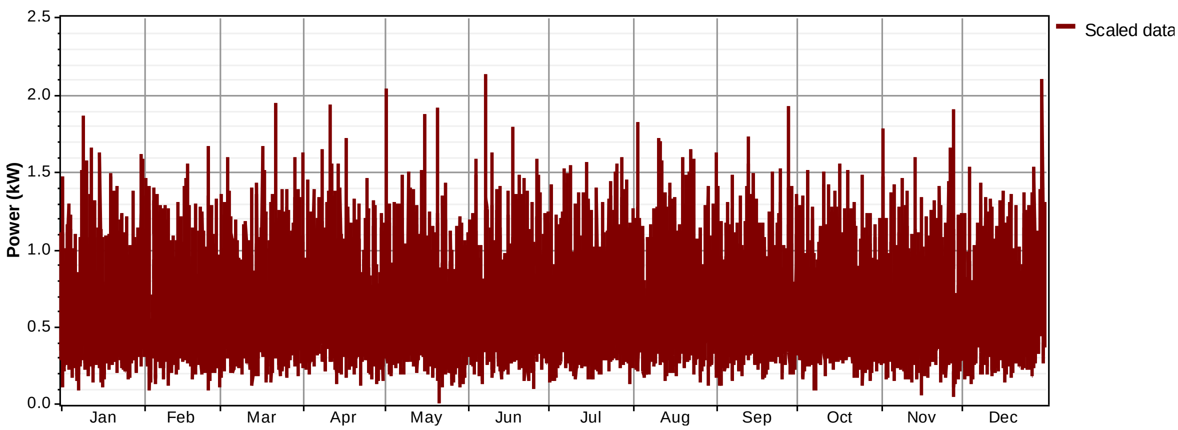

Figure 6. Annual required electricity amount.

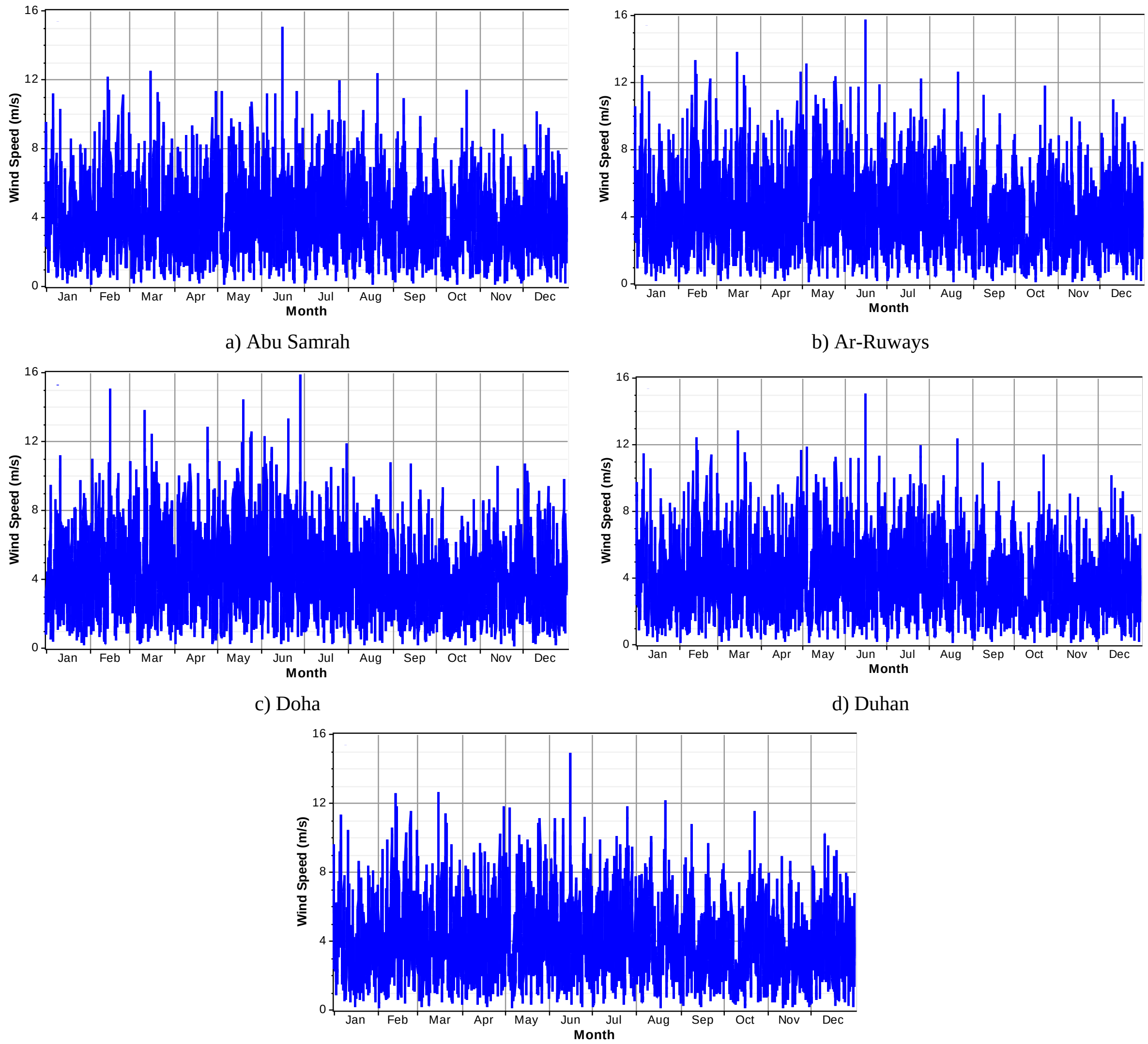

Figure 7. The annual amount of wind speed for understudy stations.

Statistical methods were used to determine the wind energy potential in one of the areas of interest and to estimate the energy output of this site. A function that has proved accurate based on the measurements in various points of the world is the Weibull probability density distribution that requires k (shape factor) and c (scale factor) parameters and is in the following form [57]:

$$p(U)=\left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1}\exp\left[-\left(\frac{U}{c}\right)^{k}\right] \qquad (10)$$

where the scale parameter, *c*, indicates how strong the wind in a place is, while the shape parameter, *k*, means how peaked the wind distribution is, i.e. if the wind speeds tend to be very close to an absolute value, the distribution will have a high *k*-value and be very peaked. The empirical relations are used to determine *k* and *c*.

Wind turbines can convert 59.3% of the existing wind energy into electricity [58]. The turbine's power output (P) is given by the following relation [59]:

$$P=\frac{1}{2}\rho A V^3 C_p \qquad (11)$$

where ρ is the air density [kg/m^3], A is the swept area [m^2], V is the wind speed [m/s], and C_p is the turbine's power factor for the corresponding wind speed.

The tall tower base of horizontal-axis wind turbines (HAWTs) allows access to the stronger wind in sites with wind shear which maximizes the power output of the turbine. Also, since the blades always move perpendicular to the wind, receiving power through the whole rotation, they are more efficient. The main advantage of vertical axis wind turbines (VAWTs) is that the wind turbine does not need to be pointed into the wind. This is an advantage on sites where the direction of the wind is very variable, such as on rooftops of residential buildings. Furthermore, with a vertical axis, the generator and other preliminary components can be placed nearby the ground, so the tower does not need to support it, which also makes maintenance easier. In the present work, 4 VAWTs and 4 HAWTs (commercially available) are used,and their specifications are presented in Table 2.

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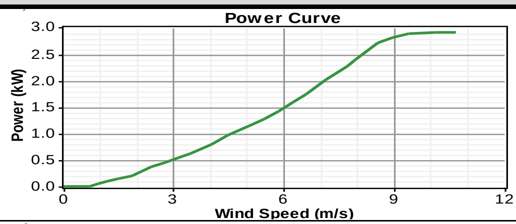
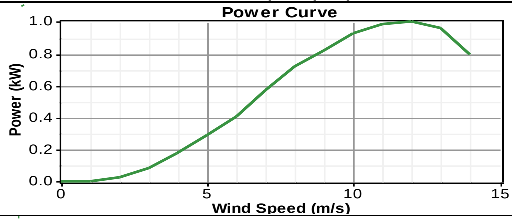
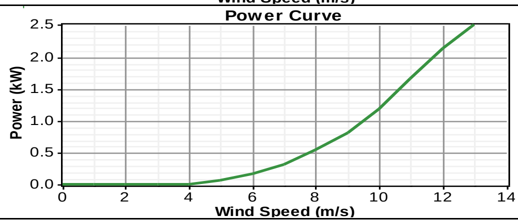
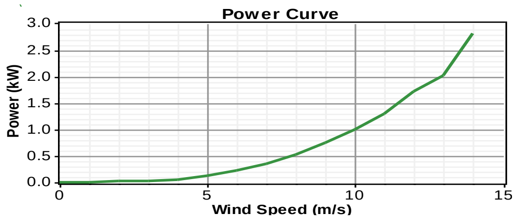
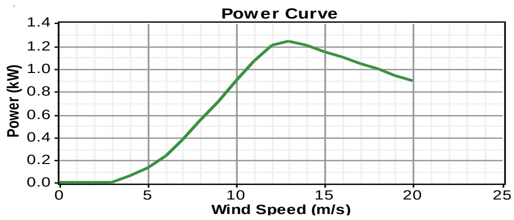
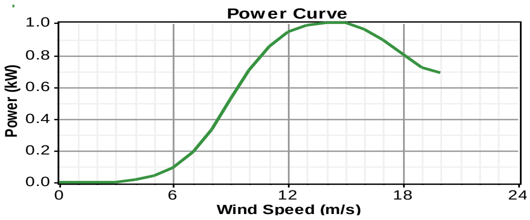
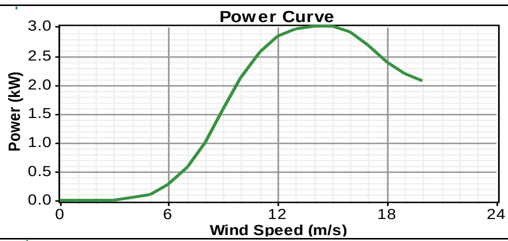
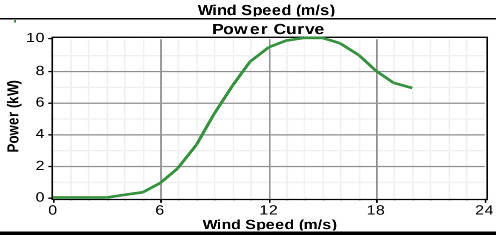
Table 2. Information of used wind turbines.

Power curve	Figure	Type
		EOLO 3kW
		Spiral 1kW
		Turby 2.5 kW
		WRE 3kW
		BWC XL.1
		Generic 1 kW
		Generic 3 kW
		Generic 10 kW

Since Qatar is both lands- and sea-locked country, wind turbulence analysis in its stations is of high importance since the wind turbines are designed based on the wind speed and wind turbulence specifications [59]. Also, turbulence remarkably affects the applied fatigue loads on wind turbines, and a high level of turbulence reduces power generation and accelerates the fatigue of mechanical components [60, 61]. The following relation gives TI:

$$TI = \frac{\sigma}{V_{ave}} \quad (12)$$

where σ is the standard deviation, V_{ave} is the average wind speed.The intensity of turbulence is ranked as low, mid, and high if it is ≤ 0.1, 0.1-0.25, and ≥ 0.25 [60], respectively.

4.2. The Price of Equipment

Since a diesel generator is used in the studied hybrid system, 0.56 $/l was entered into the software as the price of diesel [62]. Also, 5% was considered as the annual real interest rate [63]. The project lifetime of 25 years and zero pollution penalty were also taken into account. Table 3 summarizes the price, size, and type of equipment for the wind turbines selected for this study and shown in Table 2.

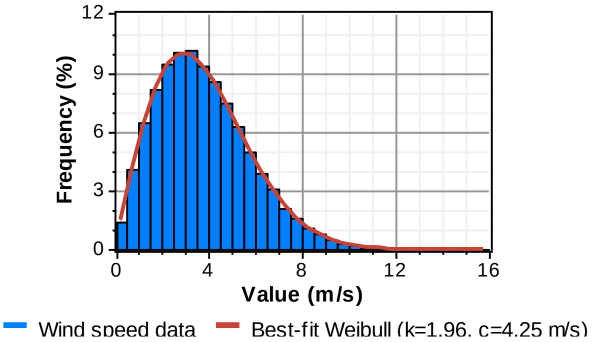
5. Results

Figure 8 shows the corresponding cumulative distribution function for the studied stations. The Weibull plot shows a good agreement with the measured speed shown in normalized form by a bar graph. As it could be seen from Figure 8, Abu Samrah (wind speed: 2-3.5 m/s; 38.7%), Ar-Ruways (2.5-3.5 m/s; 27.7%), Doha (2.5-3.5 m/s; 28.2%), Duhan (2-3 m/s; 28.8%), and Musayid (2-3.5 m/s; 38.5%) have the highest percentage of wind frequency, respectively. Also, c and k parameters determined based on the red line in Figure 8 and obtained by fitting to the experimental data of wind speed, are 4.25 m/s and 1.96, 4.58 m/s and 1.96, 4.63 m/s and 2.02, 4.31 m/s and 1.96, and 4.29 m/s and 1.96 for AbuSamrah, Ar-Ruways, Doha, Duhan, and Musayid stations, respectively.

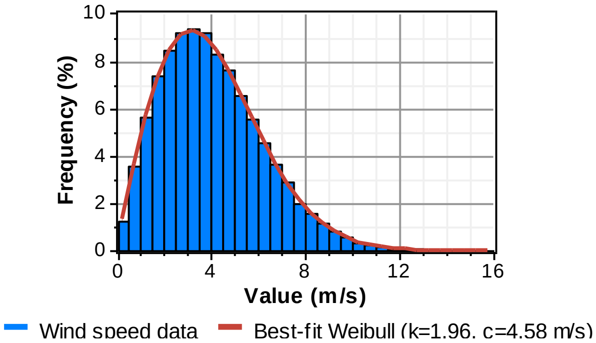
As it could be observed in Figures 9 and 10, in Abu Samrah, Ar-Ruways, Doha, Duhan, and Musayid stations, the wind speed is higher than 4 m/s for 58.9, 53.9, 53, 58.1, and 58.5 percent of windy hours. Also, windy hours between the cut-in and cut-out speeds of most wind turbines, are 3598, 4043, 4119, 3675, 3633 hours/year(y), respectively. Windheim suggests 4000 running hours and a useful lifetime of 20 years for a wind turbine to be economically viable [74]. According to Windheim's criterion, therefore, using wind energy will be cost-effective for Ar-Ruways and Doha stations.

Table 3. Price, type and size of equipment.

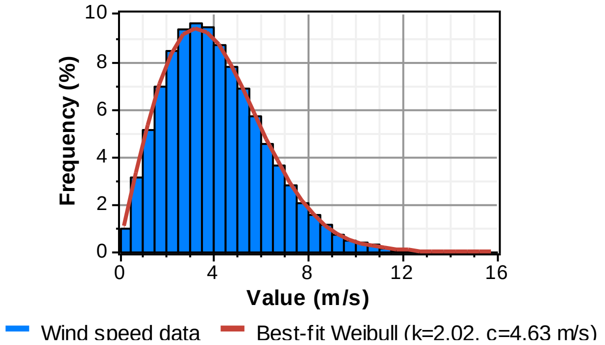
Equipment	Price			Type
	Initial	Replacement	Operating & Maintenance	
Wind turbine BWC XL.1 [64]	2307	1845	10	Lifetime: 20 year Hub height: 25 m
Wind turbine Generic 1 kW [65]	2000	2000	20	Lifetime: 20 year Hub height: 25 m
Wind turbine Generic 3 kW [66]	9000	8000	15	Lifetime: 20 year Hub height: 25 m
Wind turbine Generic 10 kW [67]	6118	6118	35	Lifetime: 19 year Hub height: 25 m
Wind turbine EOLO [68]	5269	5269	130	Lifetime: 20 year Hub height: 10 m
Wind turbine Spiral [69]	1900	1900	48	Lifetime: 20 year Hub height: 10 m
Wind turbine Turby [70]	19243	19243	480	Lifetime: 20 year Hub height: 25 m
Wind turbine WRE [71]	13635	13635	340	Lifetime: 20 year Hub height: 25 m
Diesel generator [72]	3500	3000	0.023	Life time: 10000 h
Converter [72]	800	700	100	Life time: 15 year Efficiency: 90%
Battery Surrette 6CS25P [73]	1200	1100	50	Life time: 9645 kWh



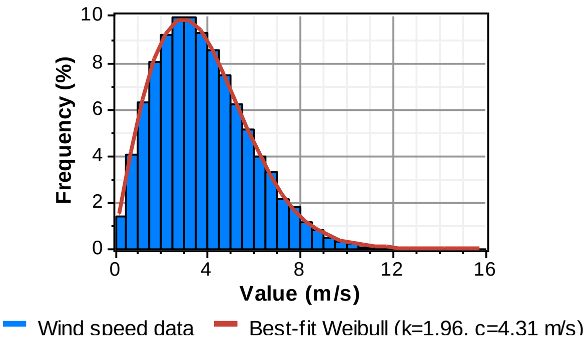
a) Abu Samrah



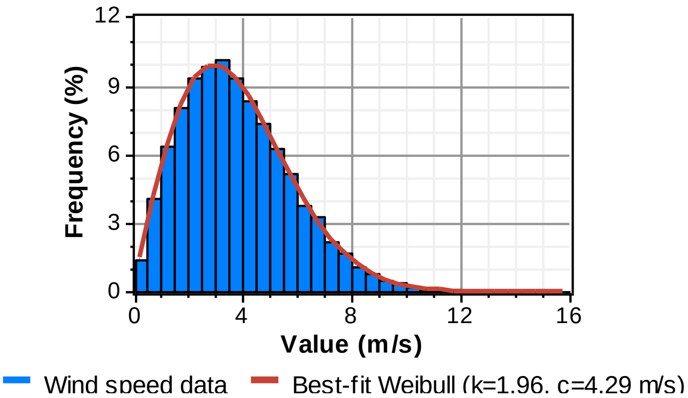
b) Ar-Ruways



c) Doha

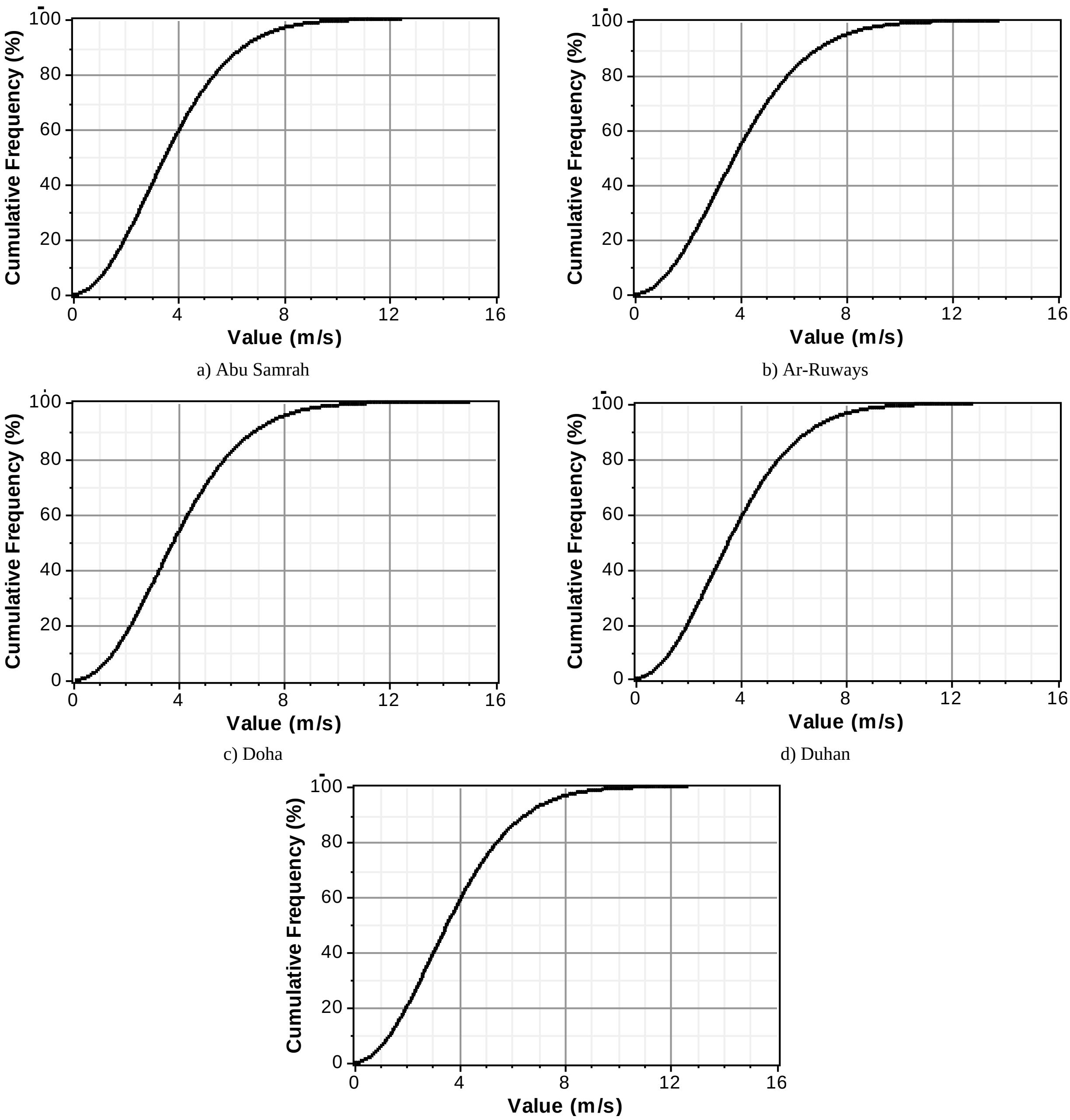


d) Duhan



e) Musayid

Figure 8. Wind speed Weibull function.



a) Abu Samrah
b) Ar-Ruways
c) Doha
d) Duhan
e) Musayid

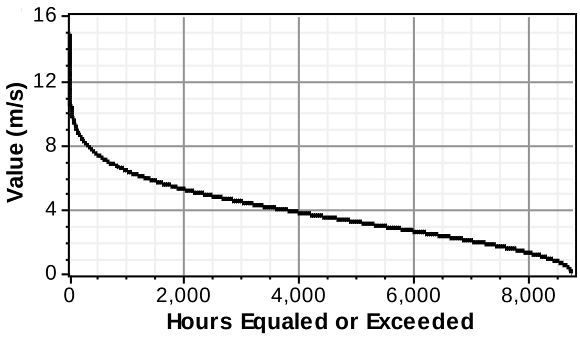
Figure 9. Annual wind speed cumulative distribution function.

a) Abu Samrah

b) Ar-Ruways

c) Doha

d) Duhan



e) Musayid

Figure 10. Wind continuity-wind speed curve

In Table 4 the results of TIparameter are presented.

Table 4. Turbulence Intensity for studied stations

Station	TI
Abu Samrah	0.093
Ar-Ruways	0.096
Doha	0.127
Duhan	0.096
Musayid	0.095

From the results, it is evident that Abu Samrah, Ar-Ruways, Duhan, and Musayid stations have a low level of turbulence (< 0.1) and Doha has an intermediate level of turbulence (0.1-0.25) which means the mechanical components of wind turbines in 4 stations of Abu Samrah, Ar-Ruways, Duhan, and Musayid are under low fatigue loadings while in Duhan, these loadings are intermediate. The lowest and highest amounts of TI parameter are related to Abu Samrah (0.093) and Doha (0.127) stations, respectively. The average value of TI for all stations is equal to 0.101.

Table 5 summarizes the study results of 8 types of residential-scale wind turbines (4 HAWTs and 4 VAWTs) simulated by HOMER for the five target cities in Qatar. In this table, for Abu Samrah station, the most reasonable cost of generation per kWh of wind electricity and the total net present cost is obtained by the horizontal axis wind turbine (BWC XL.1) which is $0.088 and $6433, respectively. It should be noted, however, that the vertical axis wind turbine (Spiral), also occupies the second position regarding cost-effectiveness by $0.088 for the production cost per kWh of wind electricity and $6448 for the total net present cost. According to the results, the worst wind turbine to be used on a residential-scale in this station is TurbyVAWT with a cost production of $0.454 and a total NPC of $32870. Immediately following Turby, WRE VAWT ranks as the second-worst turbine to be used in Abu Samrah station by a production cost and total NPC of $0.337 and $24333, respectively. CO_2 is the most important, dangerous, and sizeable pollutant produced by diesel generators as a backup system. Given the results in Table 5, the most and least suitable wind turbines regarding contaminants are EOLO (-23.5 kg/y) and Turby (2844 kg/y) wind turbines. The highest amount of wind electricity (6908 kWh/y) is generated by EOLO VAWT producing 82% of total electricity generated by wind energy. The average values for production cost per kWh of wind electricity, totalNPC and electricity generated for Abu Samrah station are $0.1853, $ 13917.63, and 2622.5 kWh/y, respectively. For this station, EOLO VAWT is recommended for the residential-scale since it has a reasonable production cost per kWh of wind energy and the highest amount of electricity generated compared with other studied wind turbines. It not only produces no emissions, but also brings about harmful emissions due to selling a considerable amount of power to the national grid.

For Duha station, the most cost-effective electricity generation alternatives are BWC XL.1 HAWT and Spiral VAWT. The production cost per kWh of wind electricity and total NPC are $0.088 and $6417 for BWC XL.1 and $0.088 and $6432 for Spiral, respectively. Regarding CO_2 production, by emitting 2820 kg/y of CO_2, Turby ranks as the first least environmentally friendly wind turbine due to producing the lowest amount of wind electricity (704 kWh/y) and having the most significant dependence on a diesel generator. EOLO is the most environmentally friendly wind turbine since, due to producing a high level of wind electricity (7090 kWh/y), it sells more power to the national grid than it needs for the diesel generator and saves 72.3 kg CO_2 annually. In this station, the highest rate of wind electricity generation (7184 kWh/y) is associated with Generic 10 kW HAWT. The average values for production cost per kWh of wind electricity, total NPC, and electricity produced for Duhan station are $0.1846, $13967.63, and 2741 kWh/y, respectively.

Having a production cost of 0.086 $/kWh of wind electricity, BWC XL.1 HAWT is the most cost-effective turbine type for Ar-Ruways station followed by Spiral and Generic 1 kW turbines ($0.086 and $0.088, respectively). By a total NPC of $6350, BWC XL.1 turbine is the cheapest option for this station with Turby producing the most expensive wind electricity in this station by a COE of 0.45 $/kWh. Regarding CO_2 emissions, Turby and Generic 1kW turbines are the least suitable options by the annual production of 2716 and 2699 kg CO_2, respectively, while EOLO VAWT is the most environmentally friendly turbine by saving 245 kg/y CO_2. The lowest amount of wind electricity generation in this station (893 kWh/y) is related to Generic 1kW turbine, while Generic 10 kW wind turbine, by producing 8890 kWh/y, generates the highest amount of wind electricity. It is noteworthy, however, that the EOLO wind turbine makes the highest contribution to the total wind power generated by producing 85.1% of the total 9117 kWh/y. The average values for production cost per kWh of wind electricity, wholeNPC, and electricity generated for Ar-Ruways station are $0.1816, $13896.75, and 3231.8 kWh/y, respectively.

For Doha, the lowest and highest production costs per kWh of wind electricity generated are $0.086 and $0.45 associated with BWC XL.1 and Turby stations, respectively. The most cost-effective wind turbine, by a total NPC of $6349, is BWC XL.1. Also, the most and least suitable turbines regarding CO_2 emission are EOLO (-300 kg/y) and Turby (2720 kg/y). Considering the amount of electricity produced by wind energy, Generic 10 kW (8861 kWh/y) and Generic 1kW (890 kWh/y) have the highest and lowest values, respectively. It has to be mentioned, however, that the EOLO turbine takes the first place in producing the required electricity by supplying 86% of the total 9140 kWh of electricity annually. The average values for production costs per kWh of wind electricity, wholeNPC, and power generated for the Doha station are $0.1814, $13890.63, and 3238.1 kWh/y.

In Musayid station, BWC XL.1 and Spiral wind turbines are the most economical options having a price per kWh of electricity of $0.088 with BWC XL.1 (total NPC of $6422) slightly outperforming Spiral (entireNPC of $6436). From an economic point of view, Turby and WRE wind turbines, with production costs of $0.454 and $0.336 per kWh of electricity generated, are the least suitable ones. By producing -60.3 kg/y and 2828 kg/y CO_2, EOLO and Turby wind turbines are the most and least environmentally friendly options, respectively. The highest amount of wind electricity generated in this station is supplied by Generic 10 kW (7056 kWh/y, 70%) and EOLO (7045 kWh/y, 83%) wind turbines. The average values for production cost per kWh of wind electricity, total NPC, and power generated for Musayid station are $0.1849, $13973, and 2705.8 kWh/y, respectively. To sum up, it can be said that the Doha station with $0.086 per kWh of electricity generated which is due to using BWC XL.1 HAWT produces the most cost-effective wind electricity since it holds the lowest total NPC ($ 6349). The highest savings and production of CO_2 emissions are related to Doha (-300 kg/y) and Abu Samrah (2844 kg/y) stations, respectively. These pollutants are emitted by EOLO and Turby wind turbines, respectively. The highest (8890 kWh/y) and lowest (658 kWh/y) amounts of wind electricity generation are associated with Ar-Ruways and Abu Samrah stations using Generic 10 kW and Turby wind turbines, respectively. From the results, it is also evident that VAWTs are more costly than HAWTs. Furthermore, studies are indicative of the higher potential of wind energy for Ar-Ruways and Doha stations compared with other ones. The least suitable station for this purpose is Abu Samrah.

Table 6 compares theCOE of wind electricity in works performed in other parts of the world with the present work. Given that the present work uses 8 different types of wind turbines for different stations, the range of each kWh of generated wind power is between $ 0.086 to $ 0.454, which is in good agreement with countries close to Qatar such as Kuwait, Oman, and Saudi Arabia. The price of wind electricity in Qatar is also in the price range of the European Union, the United States, Japan, Taiwan, Turkey, Jordan, India, and the Eurasian region. This indicates that the Qatari wind energy potential is appropriate compared to other countries studied.

Table 5. Results of simulation.

Station	Turbine type	Total NPC ($)	COE ($/kWh)	CO_2 (kg)	Wind turbine production (kWh/y, % of total)
Abu Samrah	1	6451	0.089	2818	683, 13
	2	6433	0.088	2492	1259, 24
	3	14028	0.184	2235	2044, 35
	4	10392	0.131	1345	6787, 69
	5	10386	0.111	-23.5	6908, 82
	6	6448	0.088	2243	1694, 32
	7	32870	0.454	2844	658, 13
	8	24333	0.337	2672	947, 18
Duhan	1	6440	0.089	2796	722, 14
	2	6417	0.088	2459	1318, 25
	3	14006	0.183	2191	2164, 36
	4	10905	0.129	1289	7184, 71
	5	10362	0.110	-72.3	7090, 83
	6	6432	0.088	2209	1754, 33
	7	32858	0.454	2820	704, 13
	8	24321	0.336	2647	993, 19
Ar-Ruways	1	6393	0.088	2699	893, 17
	2	6350	0.086	2323	1560, 29
	3	13914	0.178	2003	2676, 42
	4	10793	0.125	1059	8890, 76
	5	10277	0.107	-245	7759, 85.1
	6	6369	0.086	2081	1979, 36
	7	32807	0.450	2716	912, 17
	8	24271	0.333	2545	1185, 22
Doha	1	6393	0.088	2700	890, 17
	2	6349	0.086	2319	1567, 29
	3	13911	0.178	1998	2667, 42
	4	10778	0.124	1029	8861, 77
	5	10250	0.106	-300	7845, 86
	6	6364	0.086	2072	1995, 37
	7	32809	0.450	2720	898, 17
	8	24271	0.333	2545	1182, 22
Musayid	1	6444	0.089	2803	710, 14
	2	6422	0.088	2469	1301, 24
	3	14013	0.183	2206	2125, 36
	4	10915	0.130	1308	7056, 70
	5	10368	0.111	-60.3	7045, 83
	6	6436	0.088	2218	1738, 32
	7	32862	0.454	2828	689, 13
	8	24324	0.336	2654	982, 19

1: Generic 1 kW 2: BWC XL 1 kW 3: Generic 3 kW 4: Generic 10 kW
5: EOLO 3 kW 6: Spiral1 kW 7: Turby 2.5 kW 8: WRE 3 kW

Table 6. Comparing the cost per kWh of wind power generation in different places with the present work

Ref.	Country	COE
[75]	China	0.021-0.023 EUR/kWh
[76]	European Union	0.2134 EUR/kWh
[77]	US	0.105-0.181 EUR/kWh
[77]	Japan	0.418 EUR/kWh
[78]	Taiwan	0.185 EUR/kWh
[77]	Canada	0.074 EUR/kWh
[79]	South Africa	0.363-1.601 $/kWh
[80]	Iran	0.674-2.847 $/kWh
[81]	Egypt	0.86 $/kWh
[82]	Saudi Arabia	0.0576 $/kWh
[83]	Oman	0.117 $/kWh
[84]	Kuwait	0.21-0.67 $/kWh
[85]	Turkey	0.348 $/kWh
[86]	Jordan	0.1108 $/kWh
[87]	Pakistan	0.0346 $/kWh
[88]	India	0.08 $/kWh
[88]	Eurasia	0.08 $/kWh
Present work	Qatar	0.086-0.454 $/kWh

6. Conclusion

Electricity demand in Middle Eastern countries is currently done mainly by traditional energy sources. Due to the negative impact of these resources and their depletion, as well as the increase in electricity demand, it seems that these countries should move towards renewable energy. Due to Qatar's relatively good potential in the field of wind energy, the use of wind energy at home scale is appropriate. According to studies, so far no comprehensive technical-economic-environmental potential measurement in the field of electricity supply at home scale using wind energy in Qatar has been done. Therefore, in the present work, using HOMER software, wind power generation is evaluated by 4 vertical axis turbines and 4 horizontal axis turbines in the on-grid mode for 5 stations located in Qatar. It should be noted that vertical axis wind turbines do not exist in the software database and have been added to the software by .txt files. Also, the use of up-to-date data on the price of equipment used, the real inflation rate, the up-to-date price of the national electricity grid, and the real price of diesel make the present work results usable with a very high percentage of confidence for energy decision-makers in Qatar. It should also be noted that the results of the present work can be used directly for regions with similar climates or the software and method of results analysis in the present work can be used for other regions of the world. The important results of the present work are:

- -By drawing Weibull functions and using the curve-fit method, parameters c and k were calculated for the studied stations.
- -By assessing the turbulence intensity parameter, it was observed that the wind turbines are only under relatively considerable fatigue loads at Doha station among the studied stations.
- - The minimum values of total NPC and COE parameters are $ 6349 and $ 0.086 per kWh, respectively, due to the use of BWC XL.1 horizontal axis wind turbine at Doha station.
- - The most environmentally friendly wind turbine that prevents the release of 300 kg of CO_2 emissions per year is EOLO 3kW, which is installed at the Doha station.
- - The highest wind power generation with at least 82% of the total electricity generated in all stations, is related to the EOLO 3kW vertical axis wind turbine.

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