



The potential estimation and cost analysis of wind energy production in Oman

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Abstract

Selecting the wrong turbine can result in a massive financial mistake. Hence, this paper investigated three research questions. First, which region in Oman has greater potential in wind energy generation? Which type of wind turbines is the most suitable for the south and north regions of Oman? Second, what makes this turbine the best option for the south and north regions of Oman? In this study, 36 different types of wind turbines were evaluated using the HOMER Pro software. The evaluated turbines had a production capacity starting from 500 kW and were assessed for their suitability for electricity production in two villages—one in the north and the other in the south of Oman which will represent the north and south regions of Oman. Each of these villages has an electric load demand of 10 MW. Each turbine was evaluated in terms of the percentage of unmet electric load and the cost of energy production. The results show that most of the turbines evaluated performed better in the south compared to the north which indicated that the south has a greater potential in wind energy application. The Leitwind 90 1000 kW turbine proved most suitable in both the northern and southern locations as it gave the lowest cost of energy which are US\$ 0.0606 per kW and US\$ 0.0453 per kW in the north and south, respectively, and the lowest unmet electric load which are 59.3% in the north and 45.6% in the south compared to the other types of wind turbines.

Keywords Wind speed · HOMER pro · Wind turbines · Unmet electric load percentage · Cost of energy

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1 Introduction

Technological developments and industrialization resulted in an increased demand for energy worldwide (Solangi et al., 2019). The production and consumption of energy are one of the main emitters of greenhouse gases (Ali et al., 2018). Many countries depend on fossil fuels for its energy generation. However, the quantity of fossil fuel reserves is different from one country to another. This situation has resulted in technological issues, serious political conflicts, unavoidable economic dependency, important social consequences, and major environmental concerns (Solangi et al., 2019). Also, the use of fossil fuels has resulted in some of the major problems in the globe which are climate change and global warming (Ali et al., 2017).

Lately, the development of the resources of renewable energy came in response to the rising environmental concerns (Ali et al., 2016; Saeidi et al., 2011). Renewable energy such as solar, geothermal wind, biomass, and hydro is available in abundance worldwide and can satisfy the energy demand of the entire world (Shah et al., 2019). Authorities around the world are all working toward reducing the emissions of greenhouse gases by adapting low-carbon and resource-efficient strategies such as renewable energy to achieve sustainability (Ali et al., 2019a). Renewable energy has numerous benefits because of its environmentally friendly nature, and it is very important in achieving sustainable economic growth, reducing the country's energy crisis, achieving energy security, and reducing carbon dioxide emissions (Wang and Solangi 2020). However, the utilization of renewable energy is a big challenge for both developed and developing countries (Ali et al., 2019b). A sustainable and reliable energy system is essential for increasing the standards of living all around the world (Ali et al., 2018).

Among the different renewable energy sources for energy production, wind energy is considered one of the most promising energy sources (Solangi et al., 2018). Wind generates as a result of the variation of temperature on the earth's surface. The direction and speed of wind are influenced by rotation and radiation of the earth. In addition, differential heating of the land and the sea also influence the flow of air. Hence, coastal areas have more wind energy. The availability of wind energy depends on the speed of the air (Farooq & Kumar, 2013). Wind power is mainly defined as the use of mechanical power generated from the flow of air through the wind turbines to turn on electric generators to produce electricity. The use of wind energy has many advantages over the use of fossil fuels as it is more environmentally friendly, consumes no water, and widely distributed.

Annually, the electrical power generated using wind energy continues to grow rapidly and it reached 10.8% of worldwide electricity usage. Wind energy is the most powerful and latest form of energy in today's world (Wang et al., 2018). The year 2007 has witnessed a record-breaking increase of about 20,000 MW of wind energy capacity, getting the world total to 94,100 MW which is enough to provide the residential electrical energy requirements of 150 million people. In 2008, the total installed capacity of wind power has reached 100,000 MW (Al-Badi et al., 2009).

It is very important that the project location for wind energy utilization is geographically feasible and such location is decided based on environmental, technical, economic, social, and political factors (Solangi et al., 2018). Many environmental issues must be considered before deciding on the location of wind power plants. These environmental concerns include the impact of wind turbines on wildlife and their habitats because wind turbines' motion can seriously threaten many species of birds and their breeding areas. Other concerns are noise and visual pollution because wind turbines can be over

100 m high and can produce sounds that exceed 100 dB. Although evaluating these factors is critical, they are beyond the scope of this study (Eltamaly, 2013; Fulzele & Dutt, 2011).

The current study is focused on the potential of wind energy in Oman. Oman's area is estimated at 212,469 km²; the country is surrounded in the south and east by the Arabian Sea and in the north by the Gulf of Oman. Oman has different landscapes, including a long coastal plain, deserts, valleys, and many mountains (Yousif et al., 2019). The climatic condition in Oman can be described as relatively hot throughout the year, but Oman's inland climate is dry, while the coastline tends to be humid. In the summer, temperatures often climb to 43 °C in coastal cities. Dhofar, in southern Oman, is affected by a summer monsoon which makes average temperatures cooler than in the north. In winter, temperatures in the country are lower, with an average of about 17 °C (Wind Europe, 2018). According to Al-Badi et al. (2009), the north and western parts of Oman have a low wind speed. However, areas in the south such as the Dhofar Mountain Chain in the north of Salalah have a high wind speed.

The topic of the utilization of wind energy in Oman is very important as the economy in Oman is strongly dependent on gas and oil revenues, which holds approximately 81% of the country's earnings from export in 2006 and 48.6% of its gross domestic product (GDP). Since 1967, the exportation of crude oil has been the main source of income in Oman. However, compared to the other Gulf Cooperation Council (GCC) countries, Oman's oil fields generally have lower production, more widely scattered, smaller, and have a greater production cost (Al-Badi et al., 2009). About 99% of the power generation in the country is based on natural gas. The largest consumer of electricity is the residential sector as it takes over half the total system energy (Al-Badi et al., 2009). The energy demand in Oman is expected to continue rising because of the faster population and industrial growth, and electricity shortage may occur soon if the current trend in electricity demand continued to increase. Therefore, it is strongly encouraged to find alternative energy sources such as wind, solar, geothermal, and hydro (Kazem, 2011).

Oman has never had industrially extracted wind power. While some wind turbine projects have been established, most have been for experimental studies even though Oman has ideal mean wind speed and land availability. Oman has other low-cost power sources available like natural gas and diesel which is most likely the main reason for the lack of effort in establishing wind power usage in Oman. Nevertheless, in recent years the interest in wind power in Oman has noticeably increased, and studies have been done related to wind power, including wind energy resource assessment.

Furthermore, this study will investigate the potential of wind energy in Oman and discuss the costs of the utilization of such type of energy using HOMER Pro (HOMER Energy LLC, Boulder, Colorado, USA). The software is used to assess technical and financial feasibility for power systems whether on- or off-grid (Soe & Zheng, 2014). Also, this program helps designers determine an optimal system combination leading to a system model with the lowest cost of energy (COE).

The software will help in achieving the purpose of this paper which is to investigate the wind energy in Oman by focusing on three research questions: Which region in Oman has greater potential in wind energy generation? Which type of wind turbines is the most suitable for the south and north regions of Oman? What makes this turbine the best option for the south and north regions of Oman?

This study can form a preliminary reference for future wind power applications of renewable energy systems at similar locations in Oman.

2 Literature reviews

Many recent researches have ensured greater emphasis on diversity in power production and sustainable energy. Several studies used HOMER software to analyze the potential of renewable energy, including Sharma et al. (2013), where they did a study to find an alternative to the conventional diesel generator energy system for a site in village Imaliya (Bhanpur). The study used HOMER software to obtain the most feasible configuration of a hybrid renewable energy system which includes PV-solar and wind energy system for the village.

Hassan et al. (2016) carried out a study to design a hybrid energy system model for the rural area in Muqdadiah district of Diyala state, Iraq. The study used a combination of solar photovoltaic and wind turbine. The results of the study revealed that the hybrid energy system will be a good replacement for the conventional energy systems and will be a better solution to produce electricity in remote areas with a reasonable cost.

Navita et al. (2015) performed a study to evaluate a stand-alone solar-wind hybrid energy system using HOMER software for Indore region, India. The study showed that the hybrid solar wind system is more effective than the stand-alone solar and the stand-alone wind systems.

Razmjoo et al. (2019) used HOMER software to investigate renewable energy potential in two cities, namely Zabol and Zahak in the southeast of Iran until the year 2030. The software was used to analyze the technical and economic matters related to the use of a hybrid energy system consisting of PV, wind, and diesel energy systems for the two cities with the help of data collected from Iran's meteorological organization. The results of the simulation showed that the amount of electrical energy produced by PV array for Zahak and Zabol was 1669 kWh/yr and 1700 kWh/yr, respectively, and the amount of electrical energy produced by wind turbine for Zahak and Zabol was 7263 kWh/yr and 9036 kWh/yr, respectively.

Aziz et al. (2019) used HOMER software to analyze the electricity supply by different hybrid energy systems in a typical rural community in Iraq. HOMER software was employed for the optimization of the systems using the multi-year module. Five design cases were assessed and proposed which consist of a different combinations of diesel generator, hydro, PV, and battery energy storage. The results of the simulation showed that the hybrid energy system which consists of diesel, hydro, PV, and battery energy systems was the most economical choice due to its low net present cost (NPC), which is US\$ 113,201, and due to its acceptable environmental and technical performance levels.

Li (2019) conducted a study using HOMER software to analyze the economic and technical feasibility of hybrid stand-alone energy systems which consist of photovoltaic/battery and PV /fuel cell/battery energy systems for a center of community containing 100 residential buildings in Kunming, China. The software used meteorological and geographical data from the study area to describe the techno-economic feasibility and the optimum sizing of the proposed systems. The levelized cost of energy and the total net present cost were used in identifying the optimal energy systems. The result of the simulation showed that the optimal hybrid PV and battery system has a total net present cost of US\$ 7,727,992, and a levelized cost of energy of US\$ 1.536/kWh. In addition, the optimal fuel cell, PV, and battery system has a total net present cost of US\$ 7,815,223, and a levelized cost of energy of US\$ 1.553/kWh.

Gebrehiwot et al. (2019) conducted a study using HOMER software to assess the potential of a hybrid energy combinations for the electrification of an Ethiopian rural remote

village. The software was used to develop a load profile, assess primary data, and identify the optimal least cost system choice for the village. The results of the simulation indicated that the hybrid energy system which consists of diesel generator, wind turbine, photovoltaic, and battery was economically the best option in satisfying the daily peak demand of 19.6 kW of the village with an energy cost of US\$ 0.207/kWh and a net present cost of US\$ 82,734. This optimal configuration contributes to a reduction of 37.3 tons of carbon dioxide emissions per year compared to the diesel-only-based energy system.

Mamaghani et al. (2016) used HOMER software to conduct a systematic evaluation of different off-grid configurations in three small rural communities located in Colombia. The energy combinations consisted of solar panels, wind turbine units, and diesel generators. The initial capital cost, cost of energy, and net present cost were used as an economic indicator. The analysis of the cost indicated that the diesel, solar PVs, and wind energy mix were the optimal option in Puerto Estrella. In the other two communities, namely Jerico and Unguia, the solar and diesel energy combination was the optimal option.

Al Saadi and Krarti (2011) used HOMER software to estimate the optimal energy sources for the extra energy requirement raised due to the presence of new 500 residential buildings located in Masirah Island using HOMER software. It was observed that the extra load was 16 MW which cannot be satisfied by the current power generation of the diesel-based plant of 8.4 MW. A number of sensitivity and optimization analyses were performed to estimate the best hybrid energy combination for the settlement. The results of the simulation indicated that the presence of storage batteries is particularly important option to be kept in mind during the implementation of any hybrid energy system. In addition, it was revealed that the implementation of wind turbines was found to be a cost-effective option which can contribute to a reduction in the overall cost of energy by more than 48% compared to using diesel generators only. However, the use of PV energy system was found to be not a cost-effective option for the settlement.

Odou et al. (2020) carried out a study using HOMER software to estimate the techno-economic feasibility of hybrid renewable energy systems in Fouay, Benin Republic. The results of the simulation indicated that PV, diesel generator, and battery energy combination was the optimal option obtained from the different cases applied to electrify the area in a sustainable approach. It was founded that the best hybrid system economically depends mainly on the distance of the source from the load point and the potential of the different energy sources available.

Okonkwo et al. (2021) used HOMER software to study two different hybridized energy systems for application in Salalah region in the south of Oman. The results of the study showed that the wind, PV, and battery energy system is more cost-effective in terms of initial cost, consumption of energy, and renewal price.

Barhouni et al. (2021) used HOMER software to compare between different combinations of energy systems and to identify the system with the lowest cost of energy in the Dhofar region in the south of Oman. The results of the study revealed that the simulated renewable energy systems have a lower cost of energy compared to the cost of energy purchased from the power grid. In addition, it was discovered that the lowest cost of energy was obtained from the PV–wind grid-connected system and the renewable energy fraction obtained when using this configuration was as high as 83.3%.

Moreover, in the topic of exploring the potential of wind energy in Oman Hereher and El Kenawy (2020) conducted a study to analyze the potential of different renewable energy sources including wind energy in Oman. The study adopted a novel approach to analyze the potential of renewable energy where data from different climatic indicators are joined with socioeconomic drivers of energy development. The study was based on a daily dataset

of the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR), and three climate indicators were used to describe the intensity, duration, and frequency of wind speed and solar radiation. The results of the study showed that wind energy has a great potential and can be used as an alternative to fossil fuel resources in Oman with about 4.4% of the land in Oman able to provide a sustainable wind energy source. In addition, the study specified some sites in which wind energy can be used effectively in these sites including Al-Jazir and Duqum coasts of southeastern Oman.

Majority of the above-mentioned studies related to HOMER software used the concept of hybrid energy system with the inclusion of an unconventional energy sources and studied its feasibility for the selected study area. However, this study will be focused on wind energy and its potential in replacing the fossil fuel-based energy system entirely in the areas in which wind energy has the highest potential. In addition, a limited number of studies were done in Oman to explore the potential of wind energy and the economic costs associated with it. In this study, we went beyond the specification of the wind energy potential of the country and the most suitable locations for the use of wind turbine, as we discussed the costs and the best types of wind turbine which will help in making use of this potential.

3 Materials and methods

The following section provides a description of HOMER software in terms of use, the input data required in order to simulate the electricity costs for the specified study area, and the output data obtained after the simulation is done.

3.1 Description of input data

Before using the HOMER Pro software, all needed metrological data and appropriate configurations for the study, including electric load, wind speed, and project lifetime, must be gathered and identified. When starting HOMER Pro, input data such as the primary load, wind turbine type, wind resources, and project configurations should be entered so that the software builds a model plan.

3.1.1 Electric load

The primary load is the electric load that the system should satisfy directly to prevent unmet load. In every time step, the power-producing components are dispatched from the system by the HOMER software to provide the total primary load (HOMER Pro 3.11 n.d.).

In the primary load section, the monthly profile for both south and north villages was set to 10 MW for each hour with 10% day-to-day random variability and 20% time-to-time step of random variability. HOMER Pro automatically calculated the load factor as 0.55.

3.1.2 Components

Bloomberg New Energy Finance (BNEF) states that the cost of wind turbines has dropped enormously in recent years. The BNEF's Wind Turbine Price Index shows that recent turbine contract prices are just over 1,000,000 US\$/MW, while in 2009 it was around 2,000,000 US\$/

MW (BNEF, 2018). The literature shows that wind energy's COE differs between countries because it is, to some extent, location-dependent. Therefore, the initial cost in this study was set at 2,000 US\$/kW, the replacement cost was set at US\$/2,000 per kW, and the O&M cost was determined to be 20 US\$/kW.

In the components section, 36 wind turbine types were tested for the same wind resources. The wind turbines were assumed to last 20 years.

3.1.3 Resources

In the resources section, the wind was the resource for the wind turbines. The wind speed at the hub height of each turbine was entered in this section.

In this study, the monthly wind speed average was obtained at a 50 m height for the northern and southern parts of Oman from the National Aeronautics and Space Administration (NASA) through HOMER Pro resources. Table 1 shows the wind speed at 50 m for both the north and south of Oman. These wind speeds were then projected to different heights because each type of wind turbine has its specifications, including hub height, which is the turbine's tower height; power curve; and wind speed working range.

Wind speed was extrapolated using a log law calculation that requires a known velocity to be extrapolated, the height at which the velocity is calculated (i.e., hub height), reference height where the velocity is known (e.g., at 10 m), and a roughness length in wind direction (i.e., power-law exponent). In this study, the hub height for each turbine is shown in Tables 2 and 3. The power-law exponent used to extrapolate the wind speed to different hub heights was 0.03. The reason for using 0.03 as an exponent is that it symbolizes the landscape of the study area in Oman, which is a fallow field (Katabatic Power, 2019). The wind speed at each hub height for each turbine was calculated by HOMER software with the help of log law (Katabatic Power, 2019) as shown in Eq. (1):

$$v_2 = v_1 \frac{\ln\left(\frac{z_2}{z_0}\right)}{\ln\left(\frac{z_1}{z_0}\right)} \quad (1)$$

Table 1 Reference wind speed at 50 m

Months	North average wind speed (m/s)	South average wind speed (m/s)
January	4.26	5.69
February	4.62	5.33
March	4.46	4.8
April	4.47	4.91
May	5.74	6.62
June	6.45	9.19
July	7.33	10.6
August	6.79	9.78
September	6.04	7.08
October	4.08	4.83
November	3.58	4.98
December	4.17	5.72

Table 2 Northern area turbine results

North						
No	Type	Hub height (m)	Quantity	COE (US\$/kWh)	NPC (US\$)	Unmet electric load (%)
1	Enercon E-101 E2 [3.5 MW]	74	3	0.129	23.1 M	79.9
2	Enercon E-115 [3 MW]	122	4	0.0802	26.4 M	63.1
3	Enercon E-126 [7.5 MW]	135	2	0.128	33.4 M	70.7
4	Enercon E-126 EP4 [4.2 MW]	135	3	0.0875	27.8 M	64.4
5	Enercon E-44 [900 kW]	55	12	0.19	23.8 M	85.9
6	Enercon E-48 [800 kW]	65	13	0.135	22.9 M	81
7	Enercon E-53 [800 kW]	73	13	0.108	22.9 M	76.2
8	Enercon E-70 [2.3 MW]	85	5	0.143	25.3 M	80.2
9	Enercon E-82 E2 [2 MW]	85	5	0.103	22 M	76
10	Enercon E-82 E4 [3 MW]	84	4	0.149	26.4 M	80.1
11	EWT DW 52 [900 kW]	40	12	0.189	23.8 M	85.9
12	EWT DW 54 [900 kW]	50	12	0.149	23.8 M	82.1
13	EWT DW 61 [900 kW]	75	12	0.102	23.8 M	73.7
14	Generic 1.5 MW	80	7	0.109	23.1 M	76.2
15	Leitwind 101 2000 kW	80	5	0.0837	22 M	70.5
16	Leitwind 101 2500 kW	94	4	0.0905	22 M	72.7
17	Leitwind 101 3000 kW	143	4	0.0884	26.4 M	66.5
18	Leitwind 77 1000 kW	80	10	0.0797	22 M	69.1
19	Leitwind 77 1500 kW	65	7	0.12	23.1 M	78.4
20	Leitwind 77 800 kW	62	13	0.079	22.9 M	67.5
21	Leitwind 77 850 kW	65	12	0.0796	22.5 M	68.4
22	Leitwind 80 1000 kW	80	10	0.0767	22 M	67.8
23	Leitwind 80 1500 kW	60	7	0.116	23.1 M	77.6
24	Leitwind 80 1650 kW	65	7	0.121	25.5 M	76.5
25	Leitwind 80 1800 kW	80	6	0.116	23.8 M	77.1
26	Leitwind 80 800 kW	65	13	0.0748	22.9 M	65.7
27	Leitwind 80 850 kW	80	12	0.0707	22.5 M	64.4
28	Leitwind 86 1000 kW	80	10	0.0726	22 M	66
29	Leitwind 86 1500 kW	100	7	0.0849	23.1 M	69.5
30	Leitwind 90 1000 kW	98	10	0.0606	22 M	59.3
31	Leitwind 90 1500 kW	80	7	0.0828	23.1 M	68.7
32	Leitwind 90 2000 kW	98	5	0.0896	22 M	72.5
33	Vestas V47 [660 kW]	50	16	0.159	23.3 M	83.6
34	Vestas V82 [1.65 MW]	70	7	0.119	25.5 M	76.1
35	Windflow 33 [500 kW]	30	20	0.473	22 M	94.8
36	Windflow 45 [500 kW]	38	20	0.198	22 M	87.5

COE cost of energy; NPC net present cost

Table 3 Southern area turbine results

South						
No	Type	Hub height (m)	Quantity	COE (US\$/kWh)	NPC (US\$)	Unmet electric load (%)
1	Enercon E-101 E2 [3.5 MW]	74	3	0.0854	23.1 M	69.7
2	Enercon E-115 [3 MW]	122	4	0.0577	26.4 M	48.6
3	Enercon E-126 [7.5 MW]	135	2	0.0864	33.4 M	56.7
4	Enercon E-126 EP4 [4.2 MW]	135	3	0.0623	27.8 M	50.1
5	Enercon E-44 [900 kW]	55	12	0.109	23.8 M	75.5
6	Enercon E-48 [800 kW]	65	13	0.0829	22.9 M	69
7	Enercon E-53 [800 kW]	73	13	0.07	22.9 M	63.3
8	Enercon E-70 [2.3 MW]	85	5	0.0884	25.3 M	67.9
9	Enercon E-82 E2 [2 MW]	85	5	0.0672	22 M	63.3
10	Enercon E-82 E4 [3 MW]	84	4	0.0925	26.4 M	68
11	EWT DW 52 [900 kW]	40	12	0.108	23.8 M	75.3
12	EWT DW 54 [900 kW]	50	12	0.0906	23.8 M	70.6
13	EWT DW 61 [900 kW]	75	12	0.0674	23.8 M	60.5
14	Generic 1.5 MW	80	7	0.0705	23.1 M	63.3
15	Leitwind 101 2000 kW	80	5	0.0574	22 M	57
16	Leitwind 101 2500 kW	94	4	0.0611	22 M	59.6
17	Leitwind 101 3000 kW	143	4	0.0621	26.4 M	52.3
18	Leitwind 77 1000 kW	80	10	0.0555	22 M	55.6
19	Leitwind 77 1500 kW	65	7	0.0765	23.1 M	66.1
20	Leitwind 77 800 kW	62	13	0.0553	22.9 M	53.6
21	Leitwind 77 850 kW	65	12	0.0555	22.5 M	54.6
22	Leitwind 80 1000 kW	80	10	0.0538	22 M	54.2
23	Leitwind 80 1500 kW	60	7	0.0737	23.1 M	64.9
24	Leitwind 80 1650 kW	65	7	0.0774	25.5 M	63.2
25	Leitwind 80 1800 kW	80	6	0.0744	23.8 M	64.2
26	Leitwind 80 800 kW	65	13	0.053	22.9 M	51.5
27	Leitwind 80 850 kW	80	12	0.0508	22.5 M	50.4
28	Leitwind 86 1000 kW	80	10	0.0516	22 M	52.2
29	Leitwind 86 1500 kW	100	7	0.0587	23.1 M	55.8
30	Leitwind 90 1000 kW	98	10	0.0453	22 M	45.6
31	Leitwind 90 1500 kW	80	7	0.0575	23.1 M	54.9
32	Leitwind 90 2000 kW	98	5	0.0609	22 M	59.5
33	Vestas V47 [660 kW]	50	16	0.093	23.3 M	72
34	Vestas V82 [1.65 MW]	70	7	0.0763	25.5 M	62.6
35	Windflow 33 [500 kW]	30	20	0.204	22 M	87.9
36	Windflow 45 [500 kW]	38	20	0.107	22 M	76.9

COE cost of energy; NPC net present cost

where:

- v_2 is the wind speed (m/s) to be calculated.
- v_1 is the wind speed (m/s) at the height of the anemometer.
- z_2 is the hub height.
- z_1 is the reference height (i.e., the height of the anemometer).
- z_0 is the roughness length ($z_0 = 0.03$) for the fallow field.

3.1.4 Project configurations

In the project section, the economics, constraints, and emissions were entered. For this study, the annual interest rate was set at 7.5%, and no penalties were considered. In the constraint's subsection, a maximum annual capacity shortage of 100% was allowed and the renewable power output was set at 100% wind power output. Because wind energy has no emissions, all the emissions were set to zero. In the HOMER Pro software, optimization configurations should be entered. In the current study, the time step was set to 60 min and a generator control was established to allow systems with a generator capacity that operates at less than peak load. The cost of the wind turbine was based on the number of kW each turbine can produce and was assumed to include the cost of a converter. After all the inputs were entered and all configurations were set, the model was run. HOMER Pro software lists results in order according to the optimal system design. However, because this study tested only one type of wind turbine at a time, there was only one result for each turbine.

3.2 Description of output data

After entering all the input data as mentioned previously, HOMER Pro software will generate the output data in the form of tables and graphs. The output data includes: wind speed, unmet electric load, cost of energy, net present cost, number of required wind turbines. These output data will help in finding the potential and cost of wind energy in Oman. The following points provide a description of these output data.

3.2.1 Wind speed

Table 3 shows that the wind in the south is stronger than in the north. Oman is known to have higher wind speeds in the south throughout the year compared to the north as has been reported by Dorvlo and Ampratwum (2002) and Al-Yahyai and Charabi (2015). Dorvlo and Ampratwum's showed that the Thumrait, Sur, Masirah, and Marmul wind stations, all in the south of Oman, have noticeably higher wind speeds compared to the national average. These studies concluded that there is great potential for wind power at the four stations.

Due to these findings, it was expected that wind turbines would perform better in the south compared to the north. This expectation was based on the fact that each type of wind turbine has its wind power curve to calculate the power output on standard conditions (Abul'Wafa et al., 2011). In the wind power curve, the wind should reach a speed in the range of 9–12 m/s to get the maximum power output from the wind turbine.

Furthermore, if the wind speed at the hub height is above a specific cutoff value, the turbine does not produce power. This cutoff value is different from turbine to the turbine; for example, the Leitwind 80 1000 kW wind turbine cuts off when the wind speed is above 25 m/s.

3.2.2 Unmet electric load

The unmet electrical load is the load which is the power system cannot serve because the supply of energy is less than the consumer demand. For every system, HOMER software calculates over the year the total unmet load (HOMER Pro 3.11 n.d.). The appearance of a lower unmet electrical load in the results increases the feasibility of the designed power system.

3.2.3 Cost of energy

The cost of energy is defined by the software as the average cost per kWh of valuable electrical energy created by the system (HOMER Pro 3.11 n.d.). Furthermore, the COE measured in this study was calculated in US dollars per kW and was calculated by dividing the yearly payment of the total cost estimated for each turbine with the yearly energy output (Grieser et al., 2015; Hosseinalizadeh et al., 2017). For example, Hosseinalizadeh et al. (2017) found that if the average wind speed increased, it would cause the COE to decrease. Moreover, they found that the change in electric load demands affects the COE but does not have a weighty effect on the cost-effectiveness of wind turbines. Their study also indicated that an increase in the average wind speed decreases the minimum capacity of a wind turbine, thus decreasing the capital cost of the system.

3.2.4 Net present cost

The NPC of each wind turbine in the north and south villages was the same. Moreover, for the south and north villages the NPC varies slightly between 33.4 million and 22 million between the different types of wind turbines.

3.2.5 Number of required wind turbines

One of the major concerns in the utilization of large-scale wind energy is the significant land requirement (Denholm et al., 2009). Each wind turbine produces turbulence in the areas around it, so each turbine needs to be placed well and far away from the other turbines. The general rule of thumb of the space between each wind turbine is around 7 rotor diameters from one to another. In other words, an 80 m rotor must be 560 m away from the adjacent turbines (Sciencing, 2018). Hence, the greater the number of wind turbines, the greater the area required for the installation of wind farms. Such a factor should be considered before selecting the best type of wind turbine. The best type of wind turbines should give the highest amount of wind energy with the lowest number of turbines to minimize land use as much as possible.

4 Case study

The following section describes HOMER software in general in terms of operation and how it is used in this study. Also, the areas in which the study is carried out are described in terms of locations in the country and electric load requirements.

4.1 Description of HOMER software

Hybrid Optimization Model for Electric Renewable (HOMER) is a widely used software for the design and evaluation of grid and off-grid energy systems for a variety of applications. The software was developed in 1993 by Mistaya Engineering for the National Renewable Energy Laboratory (Abdul-Wahab et al., 2019). HOMER software can simulate different system configurations with the help of some inputs such as meteorological data, component costs, manufacturer's data, resource availability, modeler constraints. Moreover, the software will use the input data to perform different calculations, namely initial capital cost, NPC, COE, and operations and maintenance (O&M) costs. The results of the simulation will be ranked according to their NPC, which is the life cycle cost of a system and contains the initial construction cost, penalties from pollutants, costs of maintenance, fuel, and other anticipated costs. Finally, the simulation results in HOMER will be represented in the form of tables and graphs. These tables and graphs will help the researchers to evaluate and compare the different configurations in economical and technical terms (Abdul-Wahab et al., 2020).

In this study, HOMER Pro software was used to analyze the technical and economic feasibility of 36 different turbines for two villages in the northern and southern parts of Oman. The models, produced in different countries by different companies, were selected from the available wind turbine models in HOMER Pro software. Each turbine model's information includes production capacity, wind power curve, and several turbines used to generate the required power in the area. Figure 1 shows a flow diagram of the methodology followed in the operation of the software.

4.2 Study area

To study the wind energy in Oman, the current study will be conducted on a village in Salalah in the south of Oman and a village in Al Batinah Governorate in the north of Oman. Figure 2 shows the locations under study. Both the northern and southern villages under study are assumed to have a power load of 10 MW and are comprised of domestic consumers; therefore, turbines generating less than 500 kW of power were not considered as the typical wind turbines are rated between 500 and 2 MW (Castellano, 2012; Elavarasan, 2018).

5 Results and discussion

Wind profile patterns vary, and different wind turbine types are suitable for those different patterns. Wind farm performance is controlled by the wind resource (i.e. wind speed) at a given location. The literature agrees on the fact that the energy production

capacity of a wind turbine at a specific location hinges on the expected wind speed conditions at that location. Wind turbines can be classified based on their suitability at a given location by an annual average wind speed rating. As a result, manufacturers normally issue the average wind speed rating for a turbine as component-specific. Therefore, the relationship between a wind turbine's power generation capability and wind speed rating is straightforward for a commercial wind turbine array that forms a wind farm.

The results in this paper are for two village-level simulations, one in the northern and the other in the southern part of Oman. Tables 2 and 3 show the results of HOMER's simulation. These simulations were done to fulfill electricity supply for rural residents by building a wind power system using HOMER Pro modeling.

5.1 Factors influencing the selection of the most suitable wind turbine

A few factors influenced the selection of suitable wind turbines in the north and south for constructing wind power plants, including the COE, the NPC, the unmet electric

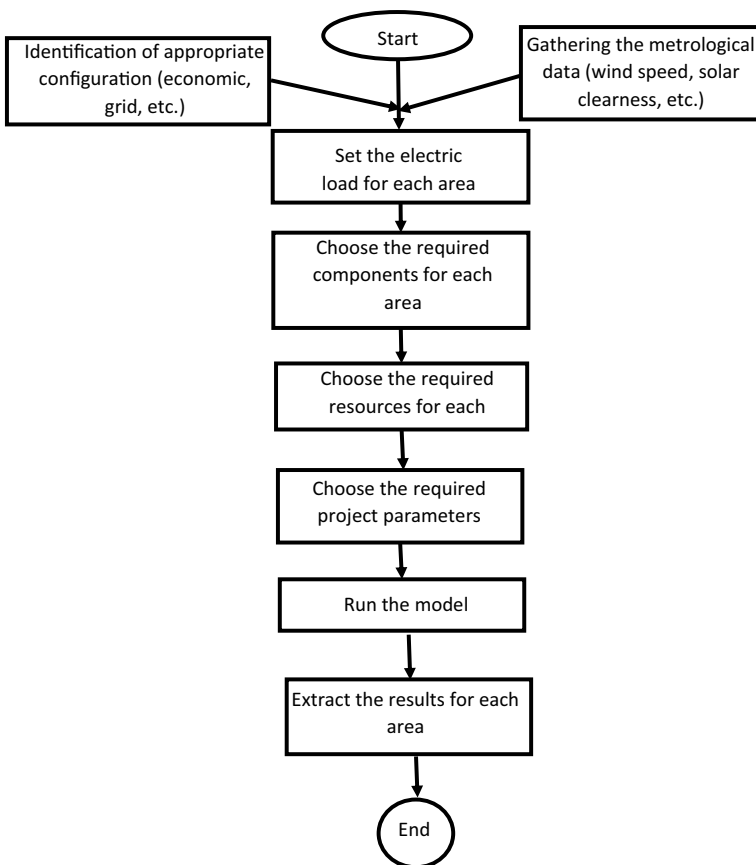


Fig. 1 Methodology flowchart

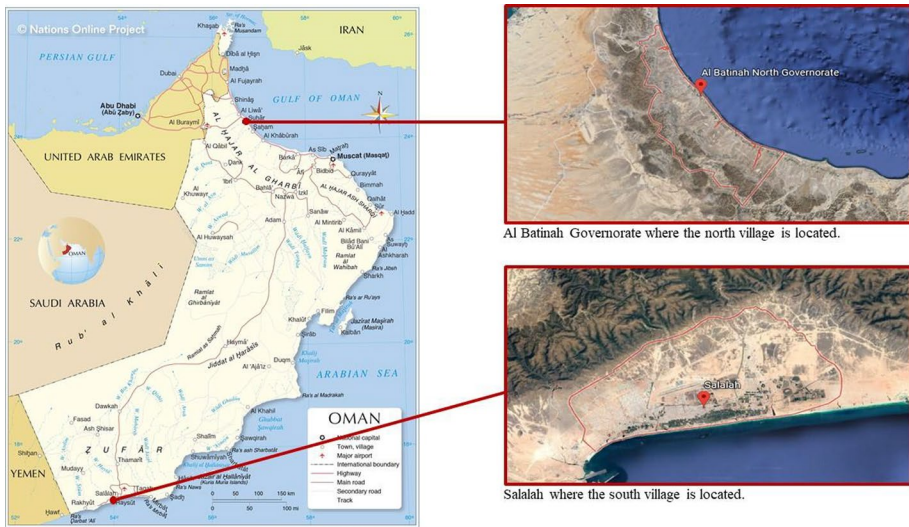


Fig. 2 The locations under study in north and south of Oman (<https://www.nationsonline.org/oneworld/map/oman-map.htm>; Google Earth)

load, and the number of turbines required to generate 10 MW of electricity for the villages.

5.1.1 Unmet electric load

For this study and as expected, the unmet electric load in the north is higher than in the south due to the higher wind speeds in the south. Figure 3 shows a comparison between the unmet electric load for each turbine in the north and south villages. The unmet electric load from the 36 tested wind turbine types ranged between 59.3 and 94.8% in the north and 45.6 and 87.9% in the south.

5.1.2 Cost of energy

In this study, the COE was higher in the north compared to the south. Figure 4 shows a comparison between the COE for each turbine in the north and south. The COE in the north ranged from US\$ 0.0606–0.473 per kW, while in the south it ranged from US\$ 0.0453–0.204 per kW. Figures 5 and 6 show the 36 types of turbines studied starting from the lowest COE to the highest COE for the north and south, respectively. The 36 tested turbines have different power capacity ranges starting from 500 kW, and each type has a name with a unique ending that indicates the turbine's power rating. The norm was that the energy output increased as the turbine's power rating increased (Table 4).

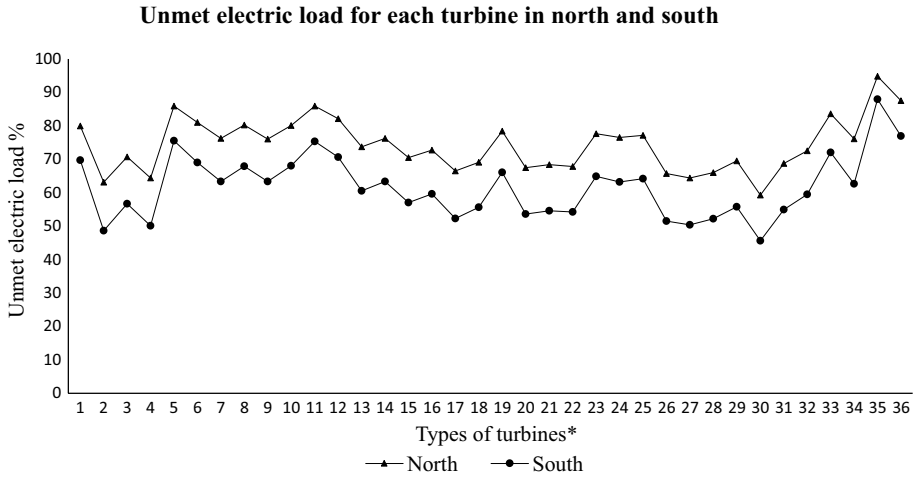


Fig. 3 Unmet electric load for each turbine in the north and south

5.1.3 Net present cost

The NPC of each wind turbine in the north and south villages was the same. Moreover, for the south and north villages, the NPC varies slightly between 33.4 million and 22 million.

5.1.4 Number of required wind turbines

The lowest number of the required wind turbine was 2 and was given by the type Enercon E-101 E2 [7.5 MW]. However, this type of wind turbines has a high COE, NPC, and unmet

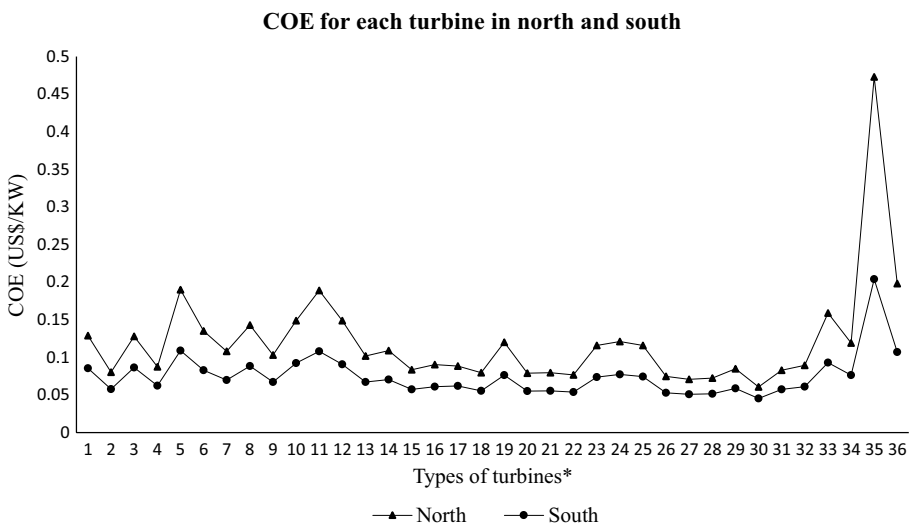


Fig. 4 COE for each turbine in two northern and southern villages in Oman

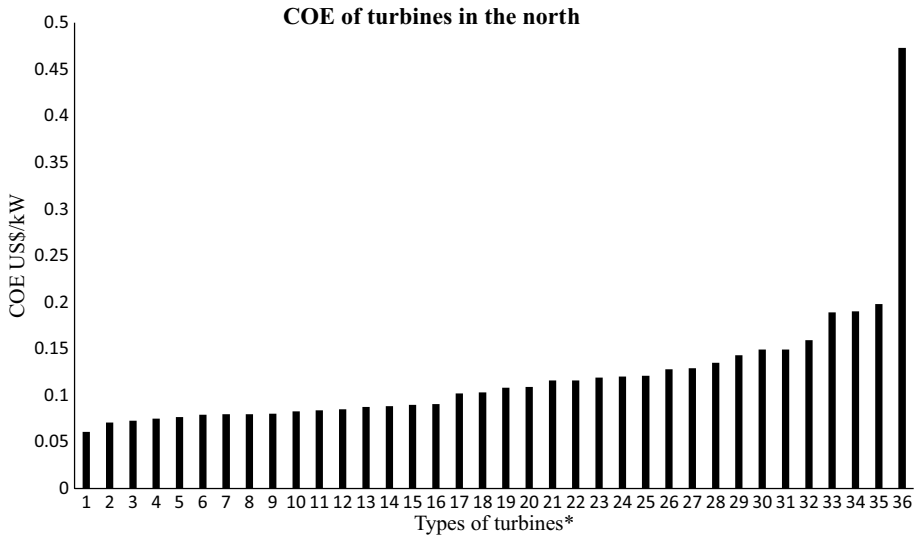


Fig. 5 COE for wind turbines in Oman’s north

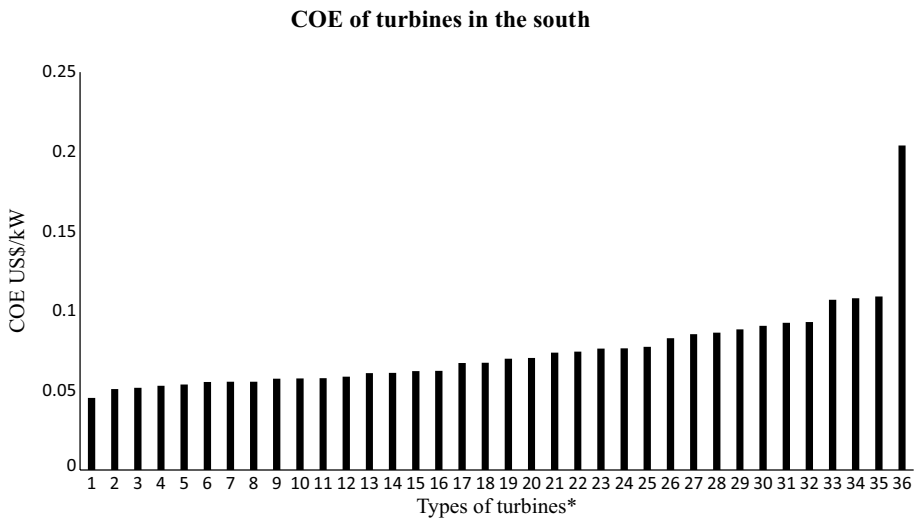


Fig. 6 COE of wind turbines in Oman’s south

electric load. The presence of a high unmet electric load suggests that this type of wind turbine does not produce a good amount of wind energy. On the other hand, the Leitwind 90 1000 kW requires only 10 wind turbines to achieve a low percentage of unmet electrical load in both the south and north villages which is still low compared to the other types with the lower unmet electrical load.

Table 4 The names of the different types of turbines

Number	Turbine name	Number	Turbine name
1	Enercon E-101 E2 [3.5 MW]	2	Enercon E-115 [3 MW]
3	Enercon E-126 [7.5 MW]	4	Enercon E-126 EP4 [4.2 MW]
5	Enercon E-44 [900 kW]	6	Enercon E-48 [800 kW]
7	Enercon E-53 [800 kW]	8	Enercon E-70 [2.3 MW]
9	Enercon E-82 E2 [2 MW]	10	Enercon E-82 E4 [3 MW]
11	EWT DW 52 [900 kW]	12	EWT DW 54 [900 kW]
13	EWT DW 61 [900 kW]	14	Generic 1.5 MW
15	Leitwind 101 2000 kW	16	Leitwind 101 2500 kW
17	Leitwind 101 3000 kW	18	Leitwind 77 1000 kW
19	Leitwind 77 1500 kW	20	Leitwind 77 800 kW
21	Leitwind 77 850 kW	22	Leitwind 80 1000 kW
23	Leitwind 80 1500 kW	24	Leitwind 80 1650 kW
25	Leitwind 80 1800 kW	26	Leitwind 80 800 kW
27	Leitwind 80 850 kW	28	Leitwind 86 1000 kW
29	Leitwind 86 1500 kW	30	Leitwind 90 1000 kW
31	Leitwind 90 1500 kW	32	Leitwind 90 2000 kW
33	Vestas V47 [660 kW]	34	Vestas V82 [1.65 MW]
35	Windflow 33 [500 kW]	36	Windflow 45 [500 kW]

5.2 Analysis of the best wind turbine

Figures 3, 4, 5, and 6 show that the Leitwind 90 1000 kW turbine was the best option for both the northern and southern areas, where it proved to have the lowest COE in both areas as US\$ 0.0606 per kW in the north and US\$ 0.0453 per kW in the south. Also, the lowest unmet electric load percentages in both areas are 59.3% in the north and 45.6% in the south. The next best wind turbine in terms of lowest COE was the Leitwind 80 850 kW. It cost US\$ 0.0707 per kW in the north and US\$ 0.0508 per kW in the south. However, in terms of unmet electric load percentage, the Leitwind 80 850 kW turbine did not perform as well due to its unmet electric load in the north of 64.4% and its unmet electric load in the south of 50.4%. The next best turbine in terms of unmet electric load percentage was the Enercon E-115 3 MW with an unmet electric load in the north of 63.1% and an unmet electric load in the south of 48.6%. The Enercon E-115 3 MW was found to be relatively expensive in terms of COE (US\$ 0.0802 per kW in the north and US\$ 0.0577 per kW in the south). Eight wind turbines performed better than the Enercon E-115 3 MW in the north in terms of COE, while 10 wind turbines performed better than the Enercon E-115 3 MW in the south. This finding shows that the performance and suitability of a renewable energy component depend mainly on the location. Hence, the results of the study showed that the wind turbines performed better in the south compared to the north villages which indicates that the potential of wind energy application is better in the south of Oman. However, the wind turbine of the type Leitwind 90 1000 kW is the best wind turbine among the 36 tested turbines to be used in the north and south of Oman because it gave the lowest values of COE and unmet electrical load.

5.3 Policy and managerial implications

Oman is heavily dependent on fossil fuels in its economy and energy generation. The diversification in the energy mix is very important to ensure sustainable development in the country. The government should invest in renewable energy projects to support the energy system in Oman. Also, the government must introduce some policies to encourage investment in renewable energy projects. The introduction of renewable energy in the country's energy mix will provide significant advantages such as providing job opportunities for the locals and reducing air pollution.

6 Conclusion

The study has answered the three research questions raised at the start of this study regarding the potential of wind energy in Oman, the selection of the most suitable wind turbine for the south and north regions of Oman, and the factors on which this selection was made. It was concluded that the results of the simulation in HOMER indicated that southern part of Oman can produce a relatively large quantity of wind power; the unmet electric load in the south ranged between 45.6 and 87.9% which shows that the potential of wind energy in the south is more compared to the north with an unmet electric load ranging between 59.3 and 94.8%. This study also showed that the Leitwind 90 1000 kW wind turbine was the most cost-effective and suitable turbine for Oman based on the factors of the COE and unmet electric load percentage which was the lowest among the 36 analyzed wind turbines in both villages. It can also be concluded that the higher the power capacity of the turbine, the higher the met electric load percentage it produced. Simultaneously, the energy produced was more expensive. On the other hand, if the wind turbine had a smaller power capacity, the COE was relatively cheap, but the unmet electric load percentage was higher.

6.1 Limitation and future research suggestions

This study has been done comprehensively. However, there are still some limitations that should be addressed in future work. The study compared the potential of wind energy in the south and north of Oman, in which it was assumed that the villages in the north and south of the country have the same electrical load which is 10 MW for every month of the year. However, the electric load data change each month depending on some factors such as the climatic conditions. Hence, this study can be improved by using an actual load profile that changes every month to give more accurate results which will help in getting more precise results for the selection of the best wind turbine. Also, this study can be improved by further testing the performance of the best wind turbine in different locations or villages and compare the results of the simulation of each location to test its potential in the application of wind energy.

Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this article.

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