TECHNO-ECONOMIC ASSESSMENT OF ESTABLISHMENT OF WIND FARMS IN DIFFERENT PROVINCES OF SAUDI ARABIA TO MITIGATE FUTURE ENERGY CHALLENGES

by

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Original scientific paper
https://doi.org/10.2298/TSCI171025109S

In the present study, the techno-economic feasibility of development of 15 MW wind power plants (wind farms) in the Kingdom of Saudi Arabia has been investigated by analyzing long-term wind speed data. To achieve this aim, two geographically distinct sites covering different non-coastal locations of the Kingdom of Saudi Arabia have been selected. Long-term data indicates that the yearly average wind speed of Kingdom of Saudi Arabia varies from 3.0-4.5 m/s at 10 m height. The wind farms simulated consist of different combinations of 600 kW commercial wind machines (50 m hub-height). The NREL's (HOMER Energy's) HOMER software has been employed to perform the analysis. The study presents the monthly variations of wind speed, cumulative frequency distribution profiles of wind speed, monthly and yearly amount of energy generated from the proposed 15 MW wind farms (50 m hub-height) at different non-coastal locations of Kingdom of Saudi Arabia, cost of generating energy ($/kWh), capacity factor (%), etc. The cumulative frequency distribution indicates that the wind speeds are less than 3 m/s for 48% and 59% of the time during the year at Badanah (Northern province) and Khamis-Mashayt (Southern province), respectively. This implies that wind electric conversion systems or wind farms will not produce energy for 48% of the time during the year at Badanah and for 59% at Khamis-Mashayt. The annual energy produced by 15 MW wind farms (50 m hub-height) has been found to be 18778 and 11314 MWh at Northern and Southern provinces, respectively. The cost of wind-based electricity by using 600 kW (50 m hub-height) commercial wind electric conversion systems has been found to be 0.0612 and 0.1016 US$/kWh for Badanah and Khamis-Mushayt, respectively. Also, the capacity factor of the wind-based power plant has been found to vary from 9 to 15% for the considered locations.

Key words: *wind speeds, commercial wind machines, wind farms, hub-heights, cost of energy*

Introduction

In this century, environmental concerns (Kyoto Protocol), volatile fuel prices and impending exhaustion of fossil fuels are important issues in the world. The world is heavily depending on abundant and uninterrupted supply of energy for living and working. Attempts are being world-wide to create a global sustainable energy infrastructure. In this regard, renewable energy, such as wind or solar, is the driver to future prosperity/challenges and a healthy global

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environment. Renewable energy is considered world-wide as a long-term and nature-friendly solution for power production. The prospects of renewable wind/solar based power systems need to be exploited to mitigate increasing demand of energy and to overcome harmful effects of pollution. Wind is developing into a sustainable power source in several countries, and is playing an important role in meeting the energy challenges that the world is facing today. Literature reports that wind energy (being freely accessible, in-exhaustible, site-dependent, environment-friendly, non-polluting) is being vigorously pursued by a number of developed and developing countries with average wind speeds in the range of 4-10 m/s, in an effort to reduce their dependence on fossil-based non-renewable fuels [1-6]. Cumulative global wind energy capacity reached about 486749 MW as of end of 2016 [7]**.** The price of generating energy using commercial wind electric conversion system (WECS) has dropped dramatically over the last decade and currently it is in the range of 4-5% per kWh. The technology of the wind machines has improved remarkably over the last five years**.** The WECS in the range of 5 MW are commercially available. The previous factors have stimulated the rate of increase in installed capacity during the last ten years and is in the range of 25-30% per annum [8]. Typical wind power applications include (but not limited to): lighting, military installations, communication/gas stations, electricity for remote settlements (to meet vital neds of remote locations which are far from utility grid), water pumping for irrigation, cathodic protection of oil pipe-lines*, etc.*

Stand-alone WECS or wind farms require large storage capacity (to meet the load demand) because of their intermittent nature. The strengths and weaknesses of wind farms are highlighted [7]. More often, wind farms are deployed in grid-connected mode (grid-friendly). Many countries are harnessing wind resource with different scales ranging from demonstration projects to commercial size wind farms. Literature clearly highlights that efforts are being made world-wide in development and establishment of wind farms [9-21].

The demand for electrical power in Saudi Arabia is increasing at an unprecedented rate. This demand is driven by high population growth and a large number of mega industrial projects. The demand for electricity is expected to reach about 55000 MW by 2020 [22]. Also, the previous significant increases can be attributed to rapid growth in residential, commercial, and industrial sectors. Since, Saudi Arabia's has reasonable wind regime, an appreciable fraction of its energy needs may be harnessed from wind energy. Also, use of alternative sources of energy reduces (GHG) CO_2 emission which is the principal cause of global warming. Utilization of renewable energy avoids tons of CO_2 and other pollutants which are emitted by burning oil [12]. Literature indicates that addition of 1.5 MW WECS, capable of producing about 4 million kWh of energy per year, would eliminate 5.6 million tonnes of CO_2 (which is the biggest contributor to global warming) [23, 24]. Utilization of renewable sources of energy is a step forward to overcome/address the problems of global warming and environmental degradation.

Work related to renewable energy in Saudi Arabia has been subject matter of several earlier studies [25-32]. In the present study, long-term wind speed data (of the period 1970-1982) of two geographically distinct non-coastal locations/provinces of Kindom of Saudi Arabia (K.S.A.) has been analyzed to assess the techno-economic feasibility of development of wind power plants (wind farms) in K.S.A. The provinces/locations considered in the study include: Northern (Badanah) and Southern (Khamis-Mushayt). In general, long-term data indicates that the yearly average wind speeds of K.S.A. vary from 3.0-4.5 m/s at 10 m height. Attention has been focused on the feasibility of development of 15 MW wind farms. The wind farms simulated consist of different combinations of 600 kW (50 m hub-height) commercial wind machines (CWM). National Renewable Energy Laboratory (NREL's) and HOMER Energy's HOMER (hybrid optimization model for electric renewables) software has been utilized to carry out the techno-economic analysis of wind farms. The HOMER is a sophisticated tool or computer-model that facilitates design of electric power systems [33]. The study presents the monthly variations of wind speed, frequency distribution/profiles of wind speed (*i. e.* availability of wind in different wind speed bins), *etc.* Emphasis has been placed on estimation of monthly and yearly amount of energy that can be generated from the proposed 15 MW wind farms (50 m hub-height) at various locations considered in the study. Furthermore, the study estimates the cost of wind-based electricity (COE, US$/kWh) and capacity factor of wind power plants for different locations by using 600 kW (50m hub-height) commercial WECS.

Saudi Arabia has approximately one-fifth of the world's oil reserves, and is the largest oil producer and exporter of total petroleum liquids in the world. Natural gas and oil had 44% and 56% share in conventional power generation. Figure 1 shows the contribution of different energy sources in the total conventional power generation in the country [34].

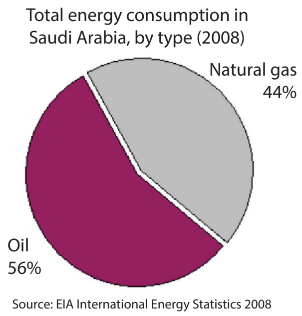

Figure 1. Conventional power generation sources in Saudi Arabia

Background information

The Kingdom of K.S.A. is basically an arid/desert land with long hot summers, and short cool winters. The topographic features of the K.S.A. are characterized by mountains in the west bordering the Red Sea that act as wind deflectors, large desert areas in the interior where high temperatures create low pressure cells, and the Arabian Gulf and Red sea which are narrow sea areas in the east and west, respectively. The K.S.A. is located within the latitudes 16° N and 32° N. The month of March marks the beginning of spring and the transition from winter to summer climate. Climatic conditions dictate the availability of wind energy at a site. Wind farms or WECS systems are characterized by availability of wind speed/regime/resource. The long-term wind speed data of different locations used in the present study covers the period 1970-1982. The information of the locations considered in the present study is indicated in tab. 1. [35].

Table 1. Information of selected provinces / locations

Site/Location//Region	Latitude [°N]	Longitude [°E]	Altitude [m]
Badanah (Northern region)	30° 54′	41° 08′	542
Khamis-Mushayt (Southern region)	18° 18′	42° 48′	2060

Wind speed data analysis and frequency distribution profiles

The long-term (1970-1982) daily average wind speeds of different locations considered in the study are demonstrated in figs. 2 and 3. In general, the monthly average wind speed (of the Saudi Arabia) ranges from 3.0-4.5 m/s at 10 m height [34]. It can be depicted from figs. 2 and 3. that wind speed is generally higher during the summer months (May to August) as compared to other months *(this is due to topography, this is a welcome/favorable characteristic because the load is high in summer in this part of the world.).* This implies that WECS or wind farms (if installed) would produce appreciably more energy during summer time. The data also indicates that there is noticeable variation in wind speed. These variations indicate that the energy output from WECS or wind farms would be subjected to considerable differences.

Wind is faster, less turbulent and yields more energy at 30 m or more heights above the ground (therefore, wind turbines are mounted tall towers).

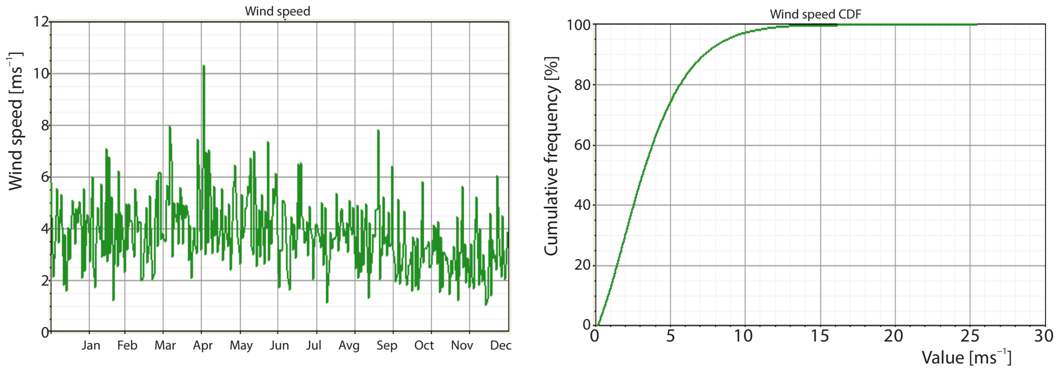

Figure 2. Daily wind speed data and frequency distribution of Northern Province (Badanah)

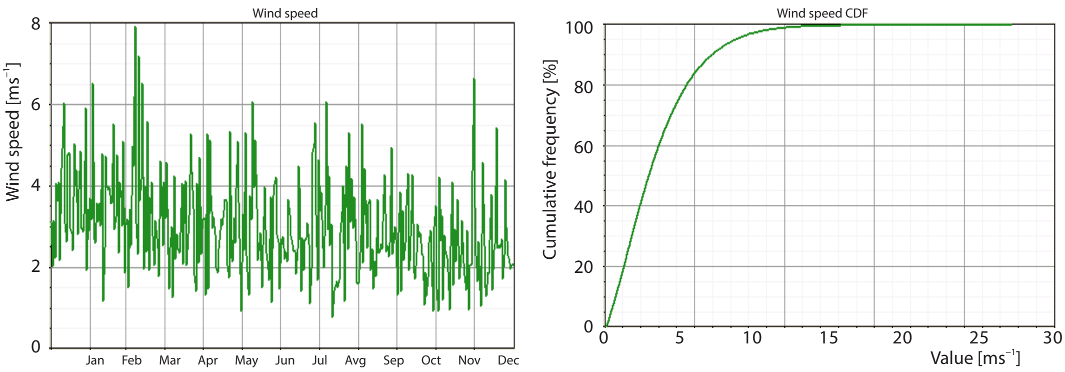

Figure 3. Daily wind speed data and frequency distribution of Southern Province (Khamis Mushayt)

The cumulative frequency distribution (CFD) of wind speed of different locations are illustrated figs. 2 and 3. The CFD (*i. e.* availability of wind in different wind speed bins) is considered as a tool to assess the potentiality of a given site. The calculations of wind energy (in HOMER) are made by matching the power-wind speed characteristics of CWM with the long-term hub-height wind speed data**.** The characteristics of the 600 kW CWM (and other study assumptions for simulations) are furnished in tab. 2. The power-curve of the 600 kW wind machine is shown in fig. 4. Today's best wind machines can achieve an overall efficiency of about 35% [36, 37]**.** However it may be mentioned that further technological milestones, may change the scenario

In general, the cut-in wind speed (speed at which wind machine starts producing useable energy) of most of the CWM is in the range of 3-4 m/s [25]. The CFD profiles of wind speed indicate that the wind speeds are less than 3 m/s for 48% of the time during the year, fig. 2, at Badanah and for 59% of the time during the year, fig. 3, at Khamis-Mashayt. This implies that WECS or wind farms (if installed in Northern and Southern Provinces of Saudi Arabia) will not produce energy for 48% and 59% of the time during the year. It can also be noticed that frequency distribution of wind speed of Northern province is than 3 m/s for 48% of the time and this is relatively better candidate for installation of WECS as compared to other province.

Table 2. Power-wind characteristics and details of 600 kW commercial wind machine

Wind machine model	Rated power [Kw] R_p	Rated speed [ms^{-1}] V_s	Cut-in speed [ms^{-1}] V_{ci}	Cut-out speed [ms^{-1}] V_{co}	Rotor diameter [m]	Hub heights [m]	Capital cost (US$)	O&M cost (US$ per year)	Turbine lifetime [years]
NORDEX 600	600	13.0	3	25	43	40, 50, 60	575000	13000	20

*R_p is the maximum power obtained from the WECS, V_{ci} is the speed at which WECS starts producing energy, V_s is the speed at which generated power reaches R_p, V_{co} is the speed at which WECS no longer produces power.

Results and discussions

The techno-economic feasibility of development of wind power plants (wind farms) has been carried out (by analyzing long-term wind speed data) for two geographically distinct sites representing different provinces/locations of the Kingdom. The key/driving parameters for assessing the feasibility of a given site for development of wind farm include**:** average wind speed, frequency distribution of wind speed, monthly wind energy generation, yearly wind energy generation, cost of energy (COE, $/kWh), capacity factor (%)*, etc.* The energy generation, COE, and capacity factor issues are discussed in the following subsections:

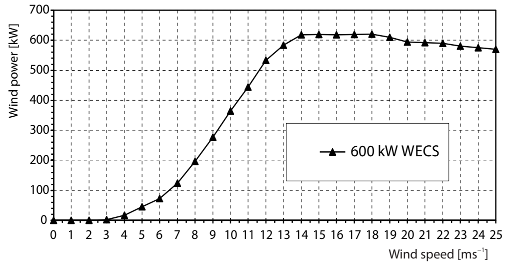

Figure 4. Power curve of commercial 600 kW wind machine

Energy generation from wind farms

In the present study, the selection of commercial wind machines, sizing of wind farms and energy simulations have been done using NREL's (HOMER Energy's) HOMER software**.** The HOMER is a system design software that facilitates design of electric power systems. Input information be provided to HOMER includes: renewable resources data (wind speed data), component technical details/costs*, etc.* The HOMER is an simplified optimization model/code, which performs hundreds or thousands of hourly simulations over and over in order to design the optimum systems. It uses life cycle cost to rank order these systems [33].

Figure 5 shows the monthly wind energy generation/yield from 15 MW wind farms (cluster of 600 kW wind machines, 50 m hub-height) at the two selected sites. It can be noticed that the power generated at Northern (Badanah) province during summer months (March to July) is greater as compared to other months. This is a welcome/favorable characteristic because the load is high during summer months in this part of the world. The energy generated at Southern (Khamis-Mushayt) province is less as compared to Northern province. This indicates that Northern province is relatively better candidate for installation of WECS or wind farms as compared to other province.

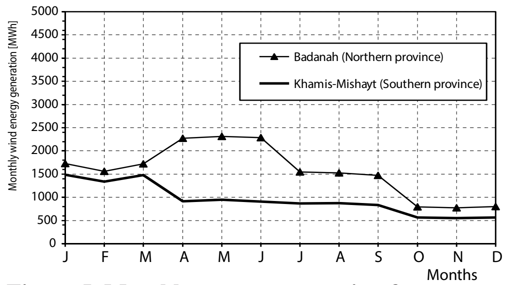

Figure 5. Monthly energy generation from 15 MW wind farm (600 kW machines, hub-height 50 m) at different provinces/ /locations of Saudi Arabia

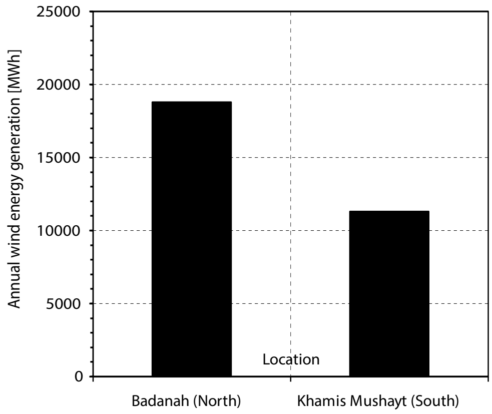

Figure 6. Annual wind energy generation from 15 MW wind farm 600 kW wind machines, hub-heigh 50 m for all selected locations/regions

The annual wind energy generated from 15 MW wind farms (cluster of 600 kW wind machines, 50 m hub-height) at the two selected sites is demonstrated in fig. 6. It can be observed that annual wind energy yield at Northern (Badanah) province is relatively more as compared to the Southern (Khamis Mushayt) province. The annual energy produced by the proposed 15 MW wind farms (50 m hub-height) has been found to be 18778 and 11314 MWh at Northern (Badanah) and Southern (Khamis-Mushayt) provinces, respectively.

Diurnal power generated from 15 MW wind farm at Northern (Badana) province is shown in fig. 7. It is also evident from fig. 7 that the power generated is higher during day time as compared to night time. This reflects that the diurnal pattern of the wind-generated power matches with the diurnal pattern of the electric energy demand (wind could provide a good complement to meet the peak loads).

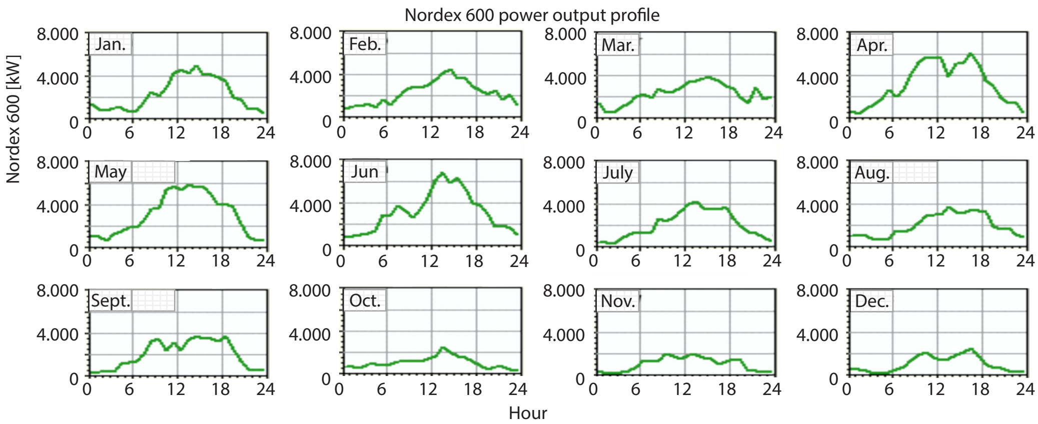

Figure 7. Diurnal power generated from 15 MW wind farm at Badana (Norther Province)

Cost of wind based electricity ($/kWh)

The energy supply market is very competitive, led by utilities and fuel companies that meet nearly all our energy demands. Alternative energy sources like wind power provides new options and must be competitive with conventional energy sources, they also must be economical. A wind energy system requires a large initial capital investment.

The COE, (US$/kWh) is one of the important issues in the wind energy industry. The WECS are generally designed to achieve high efficiency at low cost [13]. The cost of a wind system has two-components: initial installation costs and operating (O&M) cost. The installation cost includes the purchase price of the complete system (including tower, wiring, utility interconnection or battery storage equipment, power conditioning unit, *etc.*) plus delivery and installation charges, professional fees and sales tax. The total installation cost can be expressed as a function of the wind system's rated electrical capacity. A grid connected residential-scale system (1-10 kW) generally costs between \$2400 and \$3000 per installed kilowatt (*i. e.* \$24000-\$30000 for a 10 kW system). A medium-scale, commercial system (10-100 kW) is more cost-effective, costing \$1500 and \$2500 per kW. Large-scale systems of greater than 100 kW cost in the range of \$1000 to \$2000 per kW. In general, cost rates decrease as machine capacity increases. The other cost component, *i. e.* operation and maintenance cost is incurred over the lifetime of the wind system. Operating costs include maintenance and service, insurance and any applicable taxes. A rule of thumb, estimate for annual operating expenses is about 3% of the initial system cost [38].

The COE is computed by using the following equation**:**

$$\text{Cost per kWh} = (\text{Annual cost}) / (\text{Annual energy output}) \tag{1}$$

where Annual energy output is the projected annual energy output,

$$\text{Annual cost} = (\text{Initial cost})/(\text{Expected life}) + \text{Annual operating costs}$$

The cost of generating energy per kWh from commercial 600 kW WECS (50 m hub-height) has been computed (for the considered locations) by using eq. (1) with a discount rate of 5% and is shown in fig. 8. The cost/study assumptions used in estimating COE are furnished in tab. 2. Based on the study assumptions of tab. 2, the COE has been determined for all locations. The cost of wind-based electricity (COE, US\$/kWh) has been found to be 0.0612 US\$/kWh and 0.1016 US\$/kWh for Badanah and Khamis-Mushayt, respectively. The topic of COE of WECS of other countries is subject matter of studies by several researchers [10, 11, 13]. From investors point of view, the cost of electricity determines the economic attractiveness of a wind park. Therefore, in crisis, a trade-off need to be established between different options of power generation.

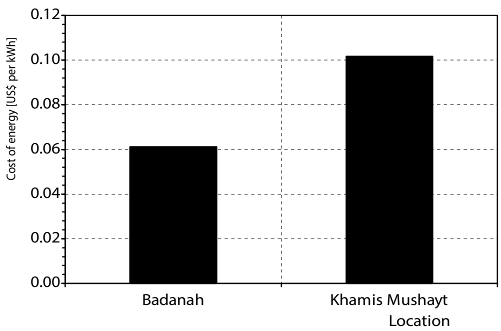

Figure 8. The COE (US\$/kWh) for different selected locations (for 600 kW wind machine, 50 m hub-height)

Capacity factor of wind-based power plants for different locations

The capacity factor is given as the ratio of the actual energy output to the theoretical maximum output, if the machine was running at its rated power during all the 8760 hours of the year. The annual energy yield is understood as the total number of kilowatt-hours actually produced by a wind turbine installation or a wind farm in a year (at a given hub-height). The capacity factor is an important indicator in measuring the productivity of a wind turbine. The capacity factors are calculated using the following equation [39]:

$$\text{Capacity factor [\%]} = [\text{Actual energy output} / (\text{Rated capacity} \cdot 8760)] \cdot 100$$

The capacity factor of wind-based power plants at different locations of the Kingdom are presented in fig. 9. The capacity factors, fig. 9, have been found to vary between 9-15% (by using 600 kW WECS, 50 m hub-height). The larger the capacity factor, the better the WECS. The capacity factor of Badana (Northern region) is higher as compared to other location. The capacity factor of Badana is about 15%. This represents about 1252 hours of full

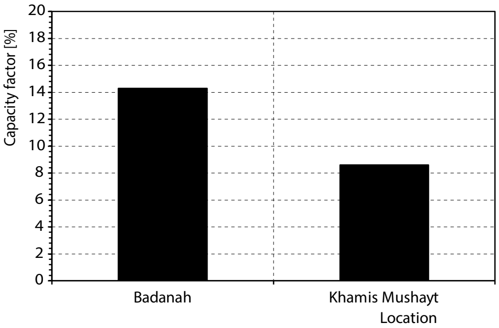

Figure 9. Capacity factor of wind farms for different selected locations (for 600 kW wind machines, 50 m hub-height)

load operation. Discussions on capacitor factor of wind power plants in other Gulf countries are reported in literature [9, 10, 12].

Conclusions

The present study has discussed in appreciable depth the techno-economic feasibility of development of 15 MW wind power plants (wind farms) at two geographically distinct sites covering different non-coastal locations/provinces of the Kingdom of Saudi Arabia. Specifically, attention has been focused on the monthly/seasonal variations of wind speed, frequency distribution profiles of wind speed, monthly and yearly amount of energy that can be generated from the proposed 15 MW wind farms (50 m hub-height), cost of energy (US$/kWh), capacity factor (%)*, etc.*

The cumulative frequency distribution of wind speeds indicates that the wind speeds are less than 3 m/s for 48% and 59% of the time during the year at Northern and Southern provinces, respectively. This implies that wind farms (if installed in Northern and Southern province of Saudi Arabia) will not produce any energy for 48% and 59% of the time during the year.

The annual energy produced by 15 MW wind farms (50 m hub-height) has been found to be 18778, and 11314 MWh at Northern (Badanah) and Southern (Khamis-Mushayt) provinces, respectively.

The cost of wind-based electricity (US$/kWh) by using 600 kW (at 50 m hub-height) commercial WECS has been found to be 0.0612 and 0.1016 US$/kWh for Badanah and Khamis-Mushayt, respectively. This indicates that Northern province is relatively better candidate for installation of WECS as compared to other province.

Attempt has been made to determine the capacity factor of wind-based power plant, the capacity factor has been found to vary between 9 to 15% for considered locations of the Kingdom. The present methodology may be used as a reference for assessing the feasibility of other locations.

Acknowledgment

The authors acknowledge the support of the Research Institute of the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. The authors are very thankful to NREL and HOMER Energy for making available freely HOMER software for design of electric power systems. The authors extend special thanks to Dr. Tom Lambert and Dr. Peter Lilienthal for their support and cooperation.

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Submitted: October 25, 2017
Revised: January 27, 2018
Accepted: March 10, 2018