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Potential of Establishment of Wind Farms in Western Province of Saudi Arabia

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Abstract

In the present study, the economic feasibility of development of 15 MW wind power plant (wind farm) at Taif, Western Province of the Kingdom of Saudi Arabia (K.S.A) has been investigated by analyzing long-term wind speed data. Western province has relatively better wind energy resources. Data analysis indicates that monthly average wind speeds of Taif (*21°29′ N, 40°32′ E*) range from 3.1 to 4.8 m/s at 10 m height. The wind farms simulated consist of different combinations of 600 kW commercial wind machines (50 m hub-height). NREL's (HOMER Energy's) HOMER software has been employed to perform the techno-economic assessment.

The study presents monthly variations of wind speed, cumulative frequency distribution (CFD) profiles of wind speed, monthly and yearly amount of energy generated from the 15 MW wind farm (50 m hub-height), cost of generating energy (COE, $/kWh), capacity factor (%), etc. The CFD indicates that the wind speeds are less than 3 m/s for 46% of the time during the year. This implies that wind electric conversion systems (WECS) will not produce energy for about 46% of the time during the year. The annual energy produced by 15 MW wind farm (50 m hub-height) has been found to be 19939 MWh. The cost of wind-based electricity by using 600 kW (50m hub-height) commercial WECS has been found to be 0.0576 US$/kWh. With the development of 15 MW wind farm, about 453 tons/year of carbon emissions can be avoided entering into the local atmospheric. The paper also attempts to address various aspects (such as: effect of hub-height, etc.) of wind farm establishment

Keywords:: Commercial wind machines; wind farms; hub-heights; cost of energy (US$/kWh), wind speeds

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1. Introduction

In the wake of ever increasing cost of oil and uncertainty in supply of oil since the mid-1970s, utilisation of energy from wind has gained appreciable momentum and is being widely disseminated for displacement of oil-produced energy, and eventually to reduce the catastrophic effects of fossil fuel energy on environment. Literature indicates that wind energy (being free, sustainable, site-dependent, promising, non-polluting, benign) is being rigorously pursued by a number of developed and developing countries (with average wind speeds in the range of 5 m/s – 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 282000 MW as of 2012**.** Currently, the price of generating energy using commercial WECS is in the range of 4 to 5 cents per kWh. The technology of the wind machines has improved remarkably over the last five years**.** WECS in the range of 3.2 MW are commercially available. The above facts have stimulated the rate of increase in installed capacity during the last ten years and it is in the range of 25 - 30 percent per annum [7]. Typical wind power applications include (but not limited to)**:** lighting, military installations, communication/gas stations, electricity for remote settlements (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 (i.e. wind resources are seldom consistent). Energy storage provides the ability to store power generated by wind farms at times of low demand and release that energy at times of high demand (contribute in electrical peak load shaving). The strengths and weaknesses of wind farms are addressed in Ref [6]. More often, wind farms are deployed in grid-connected mode (grid-friendly). Many countries are exploiting wind resource with different scales ranging from demonstration projects to commercial size wind farms. Literature highlights that substantial efforts are being made world-wide in development and establishment of wind farms [8-13]. Wind-driven power systems are expandable (in view of modular concept), additional capacity may be added as the need arises. The cost of wind power system is about 1000$/kW and cost of battery is about 170$/kWh [14]**.**

The electrical power demand in Saudi Arabia is increasing at an alarming rate. The driving force for this demand is rapid population growth coupled with a large number of mega industrial/commercial projects. The installed generating capacity of the power plants reached 45000 MW and with a peak load of 41000 MW in 2009 [15]. The demand for electricity is expected to reach about 55,000 MW by 2020.. Since, Saudi Arabia 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 CO_2 emission which is the principal cause of global warming. Literature indicates that addition of 1.5 MW WECS, capable of producing about 4 million kWh of energy/year, would eliminate 5.6 million tons of CO_2 [16-17]. Utilization of renewable sources of energy is a step forward to overcome the problems of global warming and environmental degradation.

Research work related to renewable energy in Saudi Arabia has been subject matter of several earlier studies [18-24]. **I**n the present study, long-term wind speed data (of the period 1970-1982) of Taif (Western Province of K.S.A.) has been analyzed to assess the techno-economic feasibility of development of wind power plant (wind farm). Long-term data indicates that the monthly average wind speeds vary from 3.1 to 4.8 m/s at 10 m height. Attention has been focused on the feasibility of development of 15 MW wind farm. The wind farms simulated consist of different combinations of 600 kW (50 m hub-height) commercial wind machines. National Renewable Energy Laboratory's (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 farm. HOMER is a recognized tool or computer model that facilitates design of renewable wind/solar power systems. Therefore, the output of HOMER contributes for reliability of energy yield of wind farms [25]. The study presents the monthly variations of wind speed, cumulative frequency distribution (CFD) profiles of wind speed (i.e. availability of wind in different wind speed bins), etc. CFD is a tool or frame of reference to assess the potentiality/reliability of a site. Emphasis has been placed on estimation of monthly and yearly amount of energy that can be generated from the proposed 15 MW wind farm (50 m hub-height). Attention has also been focused on diurnal power. Furthermore, the study estimates the cost of wind-based electricity (COE, US$/kWh) and capacity factor of wind power plants for the proposed location by using 600 kW (50m hub-height) commercial WECS.

2. Background information

The Kingdom of Saudi Arabia is basically an arid/desert land with long hot summers and short cold winters. The topographic features of the Kingdom 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 sea areas in the east and west, respectively. To the west of K.S.A., the Gulf of Aqaba and the Red Sea form a coastal border of almost 1,800 kilometers. The K.S.A. is located within the latitudes 16^o N and 32^o 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 are characterized by availability of wind speed resource. The long-term wind speed data used in the present study covers the period 1970-1982 [26].

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 in 2008 in the country [27].

3. Wind speed data and frequency distribution

The long-term (1970-1982) daily average wind speeds of Taif are demonstrated in Fig. 1. In general, the monthly average wind speed (of the location considered) ranges from 3.1 to 4.8 m/s at 10 m height [26]**.** It can be depicted from Fig. 1. that wind speed is relatively higher during the summer months (May to August) as compared to other months *(this is due to topography, this is a welcome characteristic because the load is high in summer in this part of the world.).* This implies that WECS (if installed) would produce more energy during summer time. The data also exhibits 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. Also, wind is faster, less turbulent and yields more energy at 30 m or more heights above the ground (therefore WECSs are mounted on tall towers). The effect of hub-height is also depicted in Fig. 1.

The cumulative frequency distribution (CFD) of wind speed and daily average wind speed of Taif are illustrated in Fig. 2. 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 commercial wind machines **(**CWMs**)** with the long-term hub-height wind speed data**.** The characteristics of the 600 kW CWMs (and other study assumptions for simulations) including operation and maintenance cost (about 3% of the initial system cost) are furnished in Table 1. The power-curve of the 600 kW wind machine is shown in Fig. 3. Today's best wind machines can achieve an overall efficiency of about 35 percent [28-29]**.** It may be mentioned that further technological milestones, may change the scenario. However, many nations are putting efforts in development of wind farms [30-32]

In general, the cut-in wind speed (speed at which wind machine starts producing useable energy) of most of the CWMs is in the range of 3 m/s- 4 m/s [19-20]. The CFD indicates that the wind speeds are less than 3 m/s for 46% of the time during the year (as shown in Fig 2.) at Taif. This implies that wind electric conversion systems (WECS) will not produce energy for about 46% of the time during the year.and hence cannot meet load demand on a continuous basis.

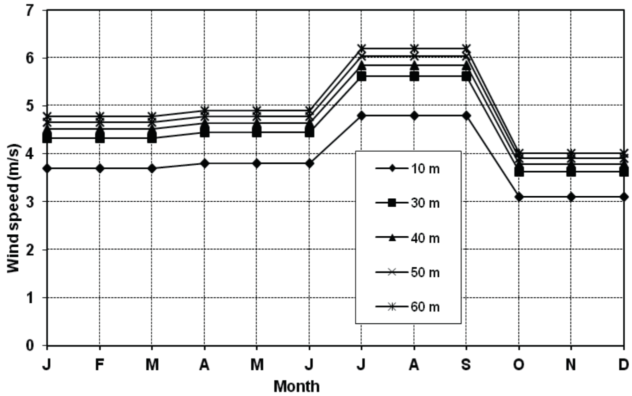

Figure 1. Monthly average wind speeds (t Taif , K.S.A.) at different heights

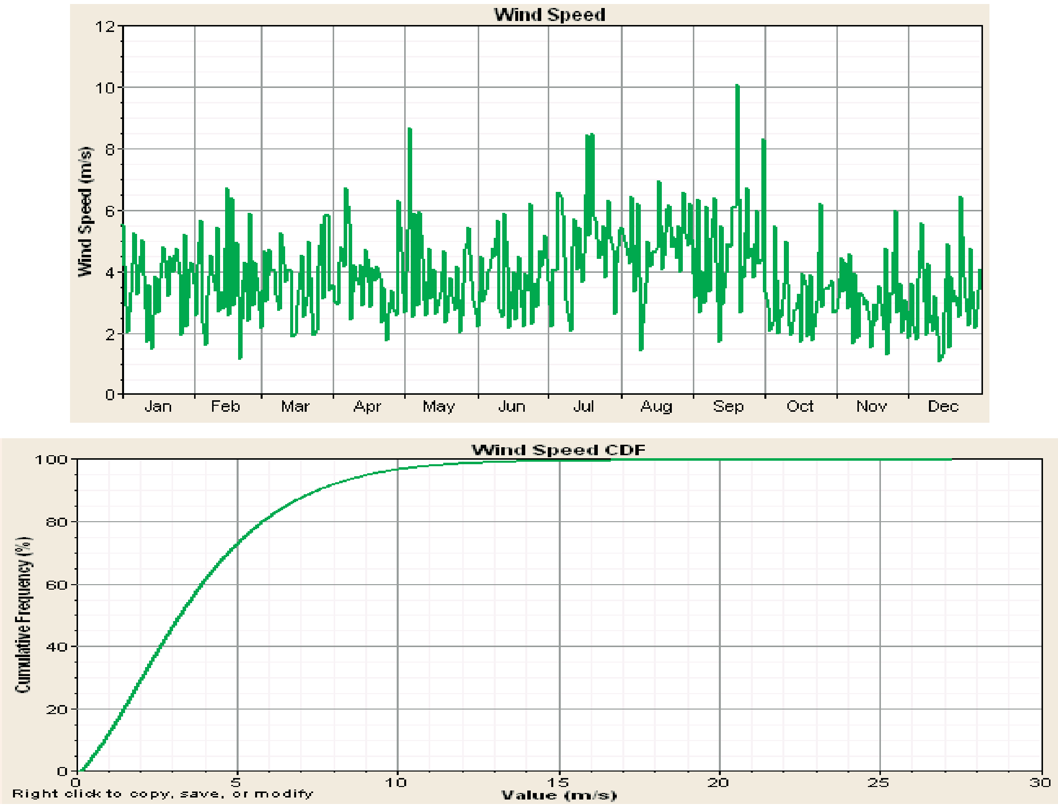

Figure 2 Daily average wind speed data and frequency distribution of wind speeds at Taif (Western Province, K.S.A.)

Table 1. Power-wind characteristics and details of 600 kW commercial wind machine

Wind machine model	Rated Power (Kw) Rp	Rated Speed (m/s) Vs	Cut-in Speed (m/s) Vci	Cut-out Speed (m/s) Vco	Rotor Dia-meter (m)	Hub heights (m)	Capital cost (US$)	O & M cost (US$ / year)	Turbine life time (years)
NORD EX 600	600	13.0	3	25	43	40, 50, 60	575,000	13,000	20

Rp is the maximum power obtained from the WECS, Vci is the speed at which WECS starts producing energy, Vs is the speed at which generated power reaches Rp, Vco is the speed at which WECS no longer produces power.

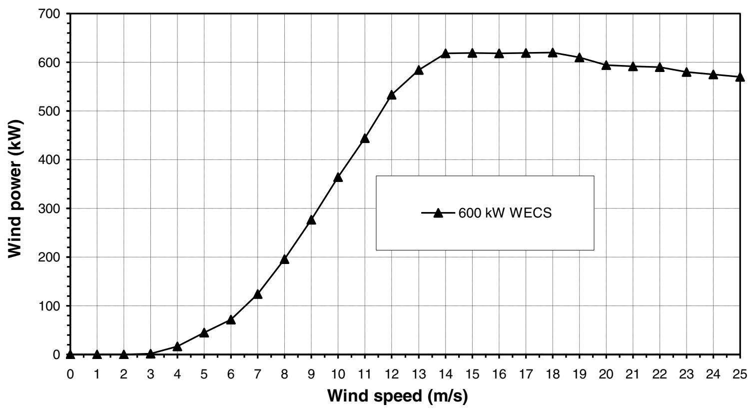

Figure 3. Power curve of commercial 600 kW wind machine

4. Results and discussions

The techno-economic feasibility of development of wind power plant (wind farm) has been carried out (by analyzing long-term wind speed data) for Taif. The key 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, cost of energy, and capacity factor issues are discussed in the following sub-sections:

4.1 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. HOMER is a system design software that facilitates design of electric power systems. Input information to be provided to HOMER includes: renewable resources data (eg. wind speed data), component technical details/costs, etc. HOMER is an simplified optimization model 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 [25].

Fig. 4. shows the monthly wind energy generation/yield from 15 MW wind farm (cluster of 600 kW wind machines, 50 m hub-height). It can be noticed that the power generated during summer months (March to July) is greater as compared to other months. This is a favorable characteristic because the load

is high during summer months in this part of the world. This indicates that Taif is a suitable candidate for installation of WECSs or wind farms. The annual wind energy generated from 15 MW wind farm (cluster of 600 kW wind machines, 50 m hub-height) at the selected site has been found to be 19939 MWh.

Diurnal power generated from 15 MW wind farm at Taif site is shown in Fig. 5. It is also evident from Fig. 5 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).

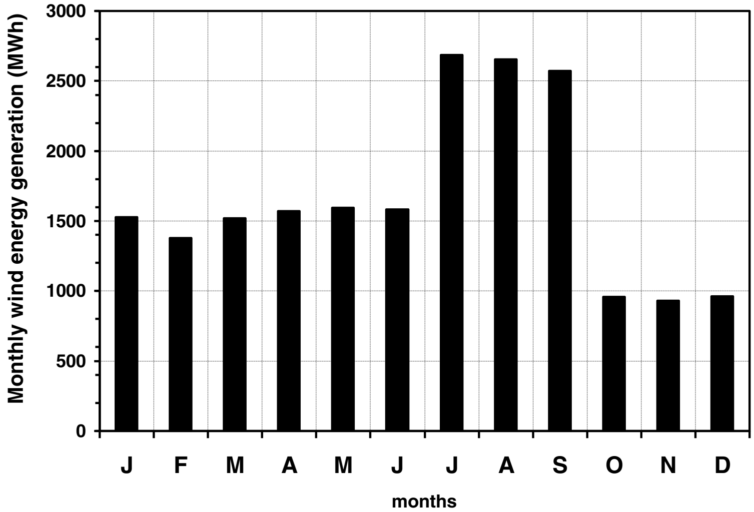

Figure 4. Monthly energy generation from 15 MW wind farm (600 kW machines, hub-height 50 m) at Taif,

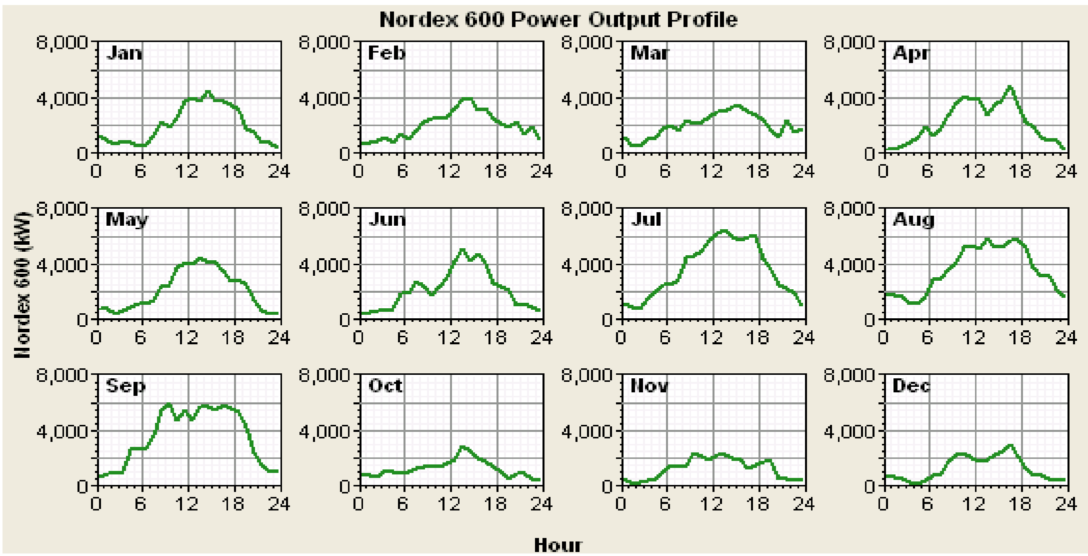

Figure 5. Diurnal power generated from 15 MW wind farm at Taif

4.2 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 cost of energy (COE, US$/kWh) is one of the important issues in the wind energy industry. WECSs are generally designed to achieve high efficiency at low cost [8]. 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.$24,000-$30,000 for a 10 kW system). A medium-scale, commercial system (10-100 kW) is more cost-effective, costing $1,500 and $2,500 per kW. Large-scale systems of greater than 100 kW cost in the range of $1,000 to $2,000 per kW..In general, cost rates decrease as machine capacity increases. The other cost component, i.e. operation & 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 [33].

Cost of energy (COE) is computed by using the following equation:

Cost per kWh = (Annual cost) /(Annual energy output)

Where Annual energy output is the projected annual energy output,

Annual cost = (Initial cost)/(Expected life) + Annual Operating Costs

The cost of generating energy (COE) per kWh from commercial 600 kW WECS (50 m hub-height) has been computed by using equation (1) with a discount rate of 5%. The study assumptions used in estimating COE are furnished in Table 1. Based on these study assumptions, the COE has been determined. The cost of wind-based electricity (COE, US$/kWh) by using 600 kW (50m hub-height) commercial WECS has been found to be 0.0576 US$/kWh. The topic of COEs of WECS of other countries is subject matter of studies by several researchers [8, 10]. From investor's point of view, the cost of electricity determines the economic attractiveness of a wind park. Therefore, in crisis, a trade-off needs to be established between different options of power generation.

4.3 Capacity factor of wind-based power plants

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. Although capacity factors may theoretically vary from 0% to 100%, in practice they usually range from 20% to 70%. The capacity factors are calculated using the following equation [34]:

Capacity factor (%) = [Actual energy output ÷ (Rated Capacity x 8760)] x100

The capacity factor of wind-based power plant at Taif has been found to be 15%. (by using 600 kW WECS, 50 m hub-height). This represents about 1314 hours of full load operation. The larger the capacity factor, the better the WECS. Discussions on capacitor factor of wind power plants in other Gulf countries are reported in literature [9, 10].

5. Conclusion

The present study has discussed in appreciable depth the economic feasibility of development of 15 MW wind power plant (wind farm) at Taif, Western Province 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), diurnal power, cost of energy (US$/kWh), capacity factor (%), etc. The cumulative frequency distribution indicates that the wind speeds are less than 3 m/s for 46% of the time during the year at Taif. This implies that wind electric conversion systems (WECS) or wind farms (if installed at Taif) will not produce energy for about 46% of the time during the year. The annual energy produced by 15 MW wind farms (50 m hub-height) has been found to be 19939 MWh. The cost of wind-based electricity by using 600 kW (50m hub-height) commercial WECS has been found to be 0.0576 US$/kWh. This indicates that Taif is a suitable candidate for harvesting wind power Attempt has been made to determine the capacity factor (CF) of wind-based power plants, the CF has been found to be 15%. With the development of 15 MW wind farm, about 453 tons/year of carbon emissions can be avoided entering into the local atmosphere.

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