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Wind power cost assessment at twenty locations in the kingdom of Saudi Arabia

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Abstract

The Kingdom of Saudi Arabia has vast open land and hence has great potential of harnessing solar and wind energy sources for domestic and industrial use. This study proposes to assess wind power cost per kWh of electricity produced using three types of wind electric conversion systems at 20 locations within the Kingdom. These sites cover the eastern, central, and western regions. Hourly values of wind speed recorded for periods of 5.5–13 years (between 1970–1982, in most cases) were used for all 20 locations. Wind duration curves were developed and utilized to calculate the cost per kWh of electricity generated from three chosen wind-machines.

1. Introduction

The long-term wind speed measurements at a given location provide fundamental and valuable information for the assessment of wind power availability and the economic viability of a wind energy conversion system and for technical design of such systems. The graphical representation such as wind speed frequency histograms, speed or wind power duration curves, monthly mean, and diurnal variation of wind speed or power are commonly used ways of summarizing the wind data. The winds,

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as every one knows, are inconsistent and vary from season to season, month to month, and year to year. The increasing global population, environmental pollution, and fast depleting reserves of fossil fuel have become matters of social and economic concern to individuals, environmentalists, engineers, meteorologists, scientists, and politicians for several years. The power of wind is a clean, inexhaustible, and free source of energy. This source has served humankind for many centuries by propelling ships and driving wind turbines to grind grain and pump water (Johnson [1]).

Wind and solar energy sources are being encouraged these days. In spite of the high cost of wind power, compared to the cost of coal, nuclear, and other sources, it may become a major source of energy in time to come. Broadly speaking, a hybrid system, consisting of wind and solar (photovoltaic) generators in combination with a battery storage option, can be used for the supply of small electrical loads at remote locations [2]. Remote applications may include an electricity supply to military installations, desalination plants, gas stations, pipeline cathodic protection, telecommunication stations, alpine huts, or remote stations for data logging of environmental parameters, irrigation and water pumping, and agribusiness operations etc. [3]. The Kingdom of Saudi Arabia offers good opportunities for harnessing the power of the wind to supply remote locations that are not connected to the electrical power grid.

For proper and efficient utilization of wind power, knowledge of the statistical characteristics, persistence, availability, diurnal variation, and prediction of wind speed are very important. These wind characteristics are needed for site selection, performance prediction, and planning of windmills. Of these characteristics, the statistical analysis of historical wind data is of great importance for site selection of wind machine installation. This analysis also enables the selection of an optimal size of the wind machine for a particular site.

The work on wind data collection in Saudi Arabia dates back to 1970. The first published work on wind data appeared in the Saudi Arabian Wind Energy Atlas, SAWEA [4] in 1986. Not much work is reported in the literature on wind energy related topics for this area. Rehman and Halawani [5] calculated shape and scale parameters of a Weibull density distribution function for ten locations in Saudi Arabia. They found numerical values of the shape parameter of between 1.7 and 2.7, while that of the scale parameter was between 3 and 6. In another study Rehman and Halawani [6] performed wind persistence and stochastic time series analysis of wind data for several locations of the Kingdom. The authors found good agreement between the correlograms and the actual diurnal variation of hourly mean wind speed values for all locations. They also concluded that stochastic time series analysis is suitable for the description of autoregressive models involving time lags of 1 and 24 h. Mohandes et al. [7] used a neural networks technique for the prediction of daily mean values of wind speed for Jeddah, Saudi Arabia. They compared the predicted values with the measured and the auto regression model predicted values and found that the neural networks predicted values outperformed the auto regression predictions.

This paper utilizes the mean hourly values of wind speed to draw the wind duration curves and to calculate the wind power cost per kWh of electricity produced using three wind machines of capacity 2500, 1300, and 600 kilowatt.

2. Description of data used

There are 20 locations in the Kingdom of Saudi Arabia and maintained by the government, where hourly mean values of meteorological parameters are measured and recorded. These measured parameters include mean, maximum, and minimum values of wind speed, wind direction, dry bulb temperature, wet bulb temperature, relative humidity, rain, visibility, and cloud type. The data collection program in Saudi Arabia was started in 1970. Hourly values of wind speed recorded for periods of 5.5–13 years (between 1970–1982, in most cases) were used for all 20 locations. Table 1 shows names, latitude, longitude, and the altitude of the locations. It also includes the height at which the anemometer was installed and the number of available hourly records at each location. As seen from Table 1, these stations cover the whole of Saudi Arabia from east to west and from north to south, including the central area.

3. Wind duration and wind power estimation for chosen wind machines

Wind duration curves are important to know the availability of wind speed in terms of number of hours the wind remained between certain wind speed intervals

Table 1
Summary of hourly wind data for 20 locations in Saudi Arabia

Location	Latitude[a]	Longitude[a]	Altitude[a] (m)	Instrument Height(m)	No. of Records
Dhahran	26° 06′	50° 10′	22	10	113,817
Riyadh	24° 42′	46° 44′	624	10	102,191
Jeddah	21° 30′	39° 12′	17	10	101,586
Tabouk	28° 22′	36° 35′	771	9	94,253
Gizan	16° 52′	42° 35′	5	8	81,909
Al-Jouf	29° 56′	40° 12′	562	7	71,881
Al-Wajh	26° 14′	36° 26′	22	10	100,364
Gassim	26° 18′	43° 58′	648	7	75,278
Medina	24° 33′	39° 43′	646	10	101,407
Nejran	17° 34′	44° 14′	1275	8	48,252
Badanah	30° 54′	41° 08′	542	6	75,743
Bisha	19° 58′	42° 40′	1167	5	77,223
Khamis- Mushait	18° 18′	42° 48′	2060	9	87,748
Qaysumah	28° 20′	46° 07′	359	8	84,459
Rafha	29° 38′	43° 29′	443	12	83,692
Sulayel	20° 28′	45° 40′	615	10	74,160
Hail	27° 31′	41° 44′	992	9	98,996
Taif	21° 29′	40° 32′	1471	8	101,467
Turaif	31° 41′	38° 40′	827	8	76,587
Yanbo	24° 07′	38° 03′	6	10	86,748

[a] Taken from Ansari et al. [4]

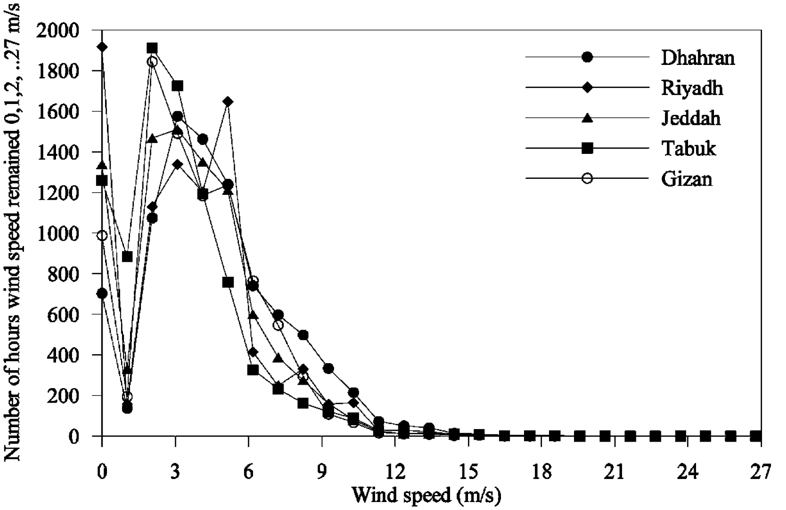

Fig. 1. Wind duration curves for five cities of Saudi Arabia.

during the year. It further helps in choosing a particular wind energy system with certain cut-in, cutout, rated, and survival wind speeds. The wind duration, in terms of number of hours, is used to calculate the kilowatt-hour of electricity produced using a particular chosen wind machine. Figs. 1–4 show the wind duration curves for all the locations analyzed in this study. These curves are obtained by counting the number of hours wind speed remained 0, 1, 2, 3, ….27 m/s during entire period of data collection. For a better understanding, number of hours during which the wind speed remained 0, 1, 2, 3, ….27 m/s per year were also calculated for each location.

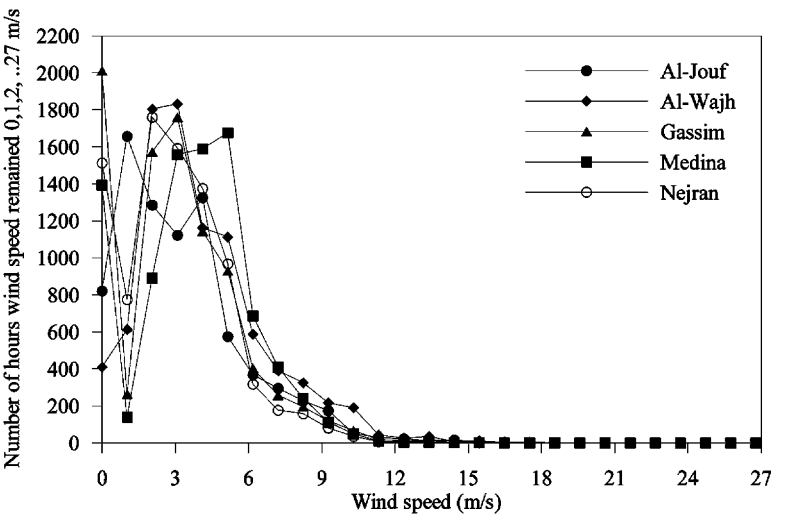

Fig. 2. Wind duration curves for five cities of Saudi Arabia.

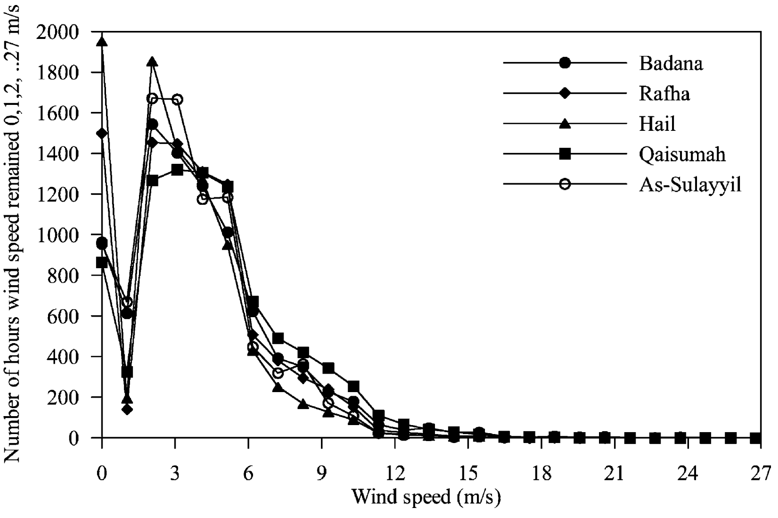

Fig. 3. Wind duration curves for five cities of Saudi Arabia.

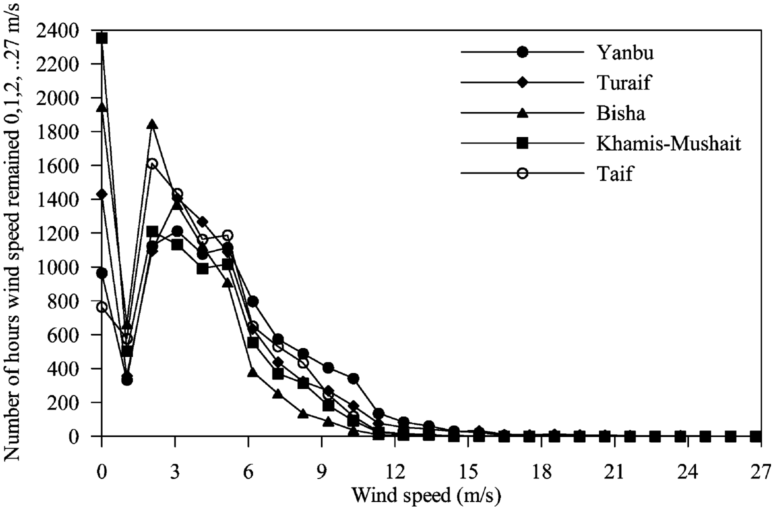

Fig. 4. Wind duration curves for five cities of Saudi Arabia.

The technical data of the chosen wind machine is given in Table 2. The information given Table 2 is obtained from references [8], [9], and [10] for wind machines of 2500, 1300, and 600 kW capacities, respectively. The cut-in speed for 2500 kW wind machines is 4 m/s while for other two 3 m/s. The cutout speed is 25 m/s for all the three machines. The expected life of the machines, rotor diameter, hub height, and their survival speeds are also included in Table 2. The Table 3 summarizes the cost of the wind machine, the civil construction cost, and operation and maintenance

Table 2
Technical data of wind machines used in the analysis

Wind Machine	Cut-in speed (m/s)	Cutout speed (m/s)	Rated speed (m/s)	Survival speed (m/s)	Rated output (kW)	Hub height (m)	Rotor diameter (m)	Expected life (years)
Nordex N60/2500	4	25	14	65	2500	60	80	20
Nordex N60/1300	3	25	15	65	1300	60	60	20
Nordex N43/600	3	25	13.5	70	600	50	43	20

Table 3
Cost related data of wind machines used in the analysis

Wind Machine	Investment Cost (US$)	Tower foundation cost (US$)	Control room cost (US$)	Total civil work cost (US$)	O & M Cost (US$)	PVC (US$)
Nordex N60/2500	1,455,000	27,500	7500	35,000	35,000	1,969,000
Nordex N60/1300	772,000	18,500	7500	26,000	35,000	1,324,000
Nordex N43/600	395,000	12,500	7500	20,000	35,000	965,000

costs. The last column of the table gives the present value cost (PVC), to be discussed later, of power produced per year. Table 4 summarizes the number of hours the wind speed remained 0, 1, 2, 3, …27 m/s per year for Dhahran, Saudi Arabia. This table also includes the power output in kW for a chosen wind machine of 2500 kW. The last column of the table gives the kilowatt-hours of electricity produced by the chosen wind machine during different wind speed ranges during the year. The total wind power produced during the year by the chosen wind machine of 2500 kW was found to be 4246998.3 kWh for Dhahran. Similar type of values of wind power produced during one whole year was calculated for other two wind machines of capacity 1300 and 600 kW for all the locations.

The total wind power output values are summarized in Table 5. As seen in Table 5, the maximum power of 4941487.2 kWh was obtained at Yanbo for 2500 kW wind machine while the minimum was found for Nejran (1639959.3 kWh). More than 3,500,000 kWh of wind power was found for Dhahran, Qaisumah, Badana, and Turaif from 2500 kW machine. At most of the stations the power output was found to be between 2,000,000–3,500,000 kWh. Similarly the maximum kWh output from 1300 and 600 kW machines was obtained for Yanbo.

Table 4
Wind speed, power output, and kilowatt-hour for Dhahran for 2500 kW wind machine, Saudi Arabia

Wind speed (m/s)	Wind speed at hub height (m/s)	No. of hours per year	Power output (KW)	Kilowatt-hour (KWh)
0	0	702.47	0	0
1.03	1.33	137.38	0	0
2.06	2.66	1074.44	0	0
3.09	3.99	1574.79	15	23,621.91
4.12	5.32	1461.88	165.9	242,526.72
5.15	6.65	1240.14	362.35	449,367.26
6.18	7.98	740.87	676.83	501,443.92
7.21	9.31	597.10	1079.83	644,765.95
8.24	10.64	497.97	1541.02	767,378.18
9.27	11.97	333.26	1973.52	657,697.64
10.3	13.31	214.27	2337.52	500,866.02
11.33	14.63	71.50	2464.63	176,223.70
12.36	15.96	50.18	2494.35	125,170.47
13.39	17.29	40.33	2494.35	100,597.13
14.42	18.63	12.85	2500	32,133.15
15.45	19.96	8.23	2500	20,588.31
16.48	21.29	0.77	2500	1924.14
17.51	22.62	0.62	2500	1539.31
18.54	23.95	0.46	2500	1154.48
19.57	25.28	0.15	0	0
20.6	26.61	0.15	0	0
21.63	27.94	0	0	0
22.66	29.27	0	0	0
23.69	30.60	0	0	0
24.72	31.93	0	0	0
25.75	33.26	0.08	0	0
26.78	34.59	0.08	0	0
Power output per year (kWh)=				4,246,998.3

4. Wind power cost estimation

The economics of a wind energy conversion (WEC) system depends mainly on the operator specific boundary conditions. A simplified approach to calculate the cost of electricity per kilowatt-hour includes investment costs, operation and maintenance costs, and capital costs. The investment costs include the WEC costs, extras, foundation, grid connection, planning and licensing. The operation and maintenance costs include the repair, insurance, monitoring and management, while the capital costs consist of interest and repayment of loan. The wind availability during which the wind machine will generate electricity is taken as 85%.

In order to calculate the present value of costs (PVC) of electricity produced per year, following expression, given by Lysen [11] and referred by Alnaser [12] and Habali et al. [13] is used in the present study as well:

Table 5
Summary of cost (US$/kWh) of wind power generation at 20 locations using three types of wind machines

Location	N80/2500 (kWh)	Cost/kWh (US$)	N60/1300 kWh)	Cost/kWh (US$)	N43/600 (kWh)	Cost/kWh (US$)
Dhahran	4,246,998.3	0.0273	2,290,274.6	0.0340	1,130,392.5	0.0502
Riyadh	2,710,156.5	0.0427	1,477,139.2	0.0527	732,574.0	0.0775
Jeddah	2,564,250.2	0.0452	1,407,966.0	0.0553	699,222.3	0.0812
Tabouk	1,934,604.0	0.0599	1,086,682.1	0.0717	542,089.2	0.1047
Gizan	2,933,952.0	0.0395	1,647,571.0	0.0473	802,547.0	0.0707
Al-Jouf	2,280,209.0	0.0508	1,256,500.2	0.0620	613,036.0	0.0926
Al-Wajh	3,112,494.1	0.0372	1,693,724.3	0.0460	838,780.3	0.0677
Gassim	2,153,133.0	0.0538	1,210,031.0	0.0643	590,204.4	0.0962
Medina	2,553,334.3	0.0454	1,414,740.0	0.0550	703,474.2	0.0807
Nejran	1,639,959.3	0.0706	939,512.0	0.0829	468,969.0	0.1210
Badana	3,811,271.0	0.0304	2,053,478.4	0.0380	1,000,327.0	0.0567
Rafha	2,769,147.1	0.0418	1,526,348.2	0.0510	744,456.2	0.0762
Hail	2,034,386.0	0.0569	1,136,101.3	0.0685	567,019.5	0.1000
Qaisumah	4,519,481.0	0.0256	2,463,725.0	0.0316	1,201,035.3	0.0472
As-Sulayyil	2,587,999.3	0.0447	1,418,345.1	0.0549	703,990.0	0.0806
Yanbo	4,941,487.2	0.0234	2,636,062.2	0.0295	1,295,196.5	0.0438
Turaif	3,837,214.0	0.0302	2,103,487.1	0.0370	1,025,089.5	0.0554
Bisha	1,850,271.0	0.0626	1,024,549.0	0.0760	504,237.0	0.1125
Khamis-Mushait	2,531,504.0	0.0457	1,396,532.0	0.0558	692,596.2	0.0819
Taif	3,459,278.0	0.0335	1,912,984.1	0.0407	935,247.1	0.0607

$$PVC = I + Comr\left(\frac{1+i}{r-i}\right) \times \left[1-\left(\frac{1+i}{1+r}\right)^n\right] - s\left(\frac{1+i}{1+r}\right)^n \qquad (1)$$

In this Eq., I is the investment cost of the wind machine, cost of civil works, and the connection cables to the grid; n is the life of machine; $Comr$ is the operation and maintenance costs; s is the scrap value (10% of the capital cost excluding the civil construction and cable costs); r is the discount rate (8%), and i is the inflation rate (6%). In order to calculate the cost of wind power generation per kilowatt-hour at different locations in the kingdom of Saudi Arabia, three types of wind machines have been chosen. The technical data of the chosen wind machines is given in Table 2, as mentioned earlier.

The civil construction cost was calculated by designing the sizes of the foundation for three types of wind machines. The design of foundation is based on the static weight of the nacelle, weight of rotor, weight of the tower, and the dynamic wind load for a survival speed of 65 m/s. The civil construction also included the cost of a control room for housing computer, control devices, regularly required inventory items, and space for human occupancy. The cost of concreting, including reinforcement and labor, is taken as 107 US$/m3. The sizes of the foundation so calculated are 45 ft×25 ft×8 ft or (13.7 m×7.6 m×2.4 m) for 2500 kW machine, 40 ft×22 ft×7 ft or (12.2 m×6.7 m×2.1 m) for 1300 kW machine and 35 ft×18 ft×7 ft or (10.7

m×5.5 m×2.1 m) for 600 kW machine. The construction cost of foundation for three wind machines of sizes 2500, 1300, and 600 kW are found to be approximately 27,500, 18,500, and 12,500 US$, respectively. The room size is taken as 25 ft×15 ft or (7.5 m×4.5 m) and its cost is estimated as 7500 US$. The operation and maintenance cost is taken as 35,000 US$ per annum which is sufficient as per the existing pay scale and other accessories are concerned. Moreover, the new generation machines are very rigid and require minimal parts during the expected service life.

The present value costs (PVC) obtained using Eq. (1) are given in Table 3 in the last column. The present value cost (PVC) of wind machines of 2500, 1300, and 600 kW sizes are found to be approximately US$ 1,969,000; 1,324,000; and 965,000 respectively. The cost electricity per kWh at each location is obtained by dividing the PVC by the total kWh for each location and is given in Table 5. The minimum cost of 0.0234 US$ per kWh is obtained for Yanbo for wind machine of 2500 kW.

5. Discussion of results

The cost of generating the wind power in US$ per kWh is obtained by dividing the present value cost (PVC) by total kilowatt-hours (kWh) for each location. The total kilowatt-hours and the costs, so obtained for each location and for all the chosen wind machines are given in Table 5. The costs presented in Table 5 do not include the cost of deployment of manpower and various equipment and machines to the actual site of the wind electric conversion system. From Table 5 it is clear that maximum electricity in terms of kilowatt-hours was obtained at Yanbo (4,941,487 kWh from a 2500 kW machine, 2,636,062 kWh from a 1300 kW machine, and 1,295,196 kWh from a 600 kW wind machine). The minimum value of 1,639,959 kWh was obtained at Nejran from 2500 kW wind machine while 939,512 and 468,969 kWh were obtained from other two chosen machines.

The cost of electricity produced using a 2500 kW wind machine was minimum (0.0234 US$/kWh) at Yanbo while the corresponding maximum cost was 0.0706 US$/kWh at Nejran. The minimum cost of producing each kWh of electricity from 1300 kW wind machine was 0.0295 US$ at Yanbo while the maximum was 0.0829 US$ at Nejran. The minimum and the maximum costs for 600 kW machine were 0.0438 and 0.121 US$/kWh corresponding to Yanbo and Nejran respectively.

To study the cost of electricity per kilowatt hour produced using different WECs on a regional basis, the Kingdom of Saudi Arabia is divided into three regions, namely:

- Region A: Dhahran, Qaisumah, Rafha, Badana, Turaif, Al-Jouf, Al-Wajh, Tabouk, and, Hail
- Region B: Riyadh, Gassim, Medina, Yanbo, Jeddah, and Taif
- Region C: Gizan, Nejran, Khamis-Mushait, Bisha, and As-Sulayyil

In Region A, the cost of each kWh electricity produced using the chosen wind machine of 2500 kW varied between a minimum of 0.0234 US$/kWh at Dhahran and a maximum of 0.0599 US$/kWh at Tabouk. Similarly the cost of electricity produced using a 1300 kW machine varied between a minimum of 0.0340 US$/kWh and a maximum of 0.0717 US$/kWh corresponding to Dhahran and Tabouk respectively. Whereas, it varied from 0.0502 to 0.105 US$/kWh when produced using a 600 kW wind machine. The average regional cost of producing electricity per kWh using a 2500 kW machine was 0.04 US$/kWh, from a 1300 kW wind machine it was 0.05 US$/kWh while with a 600 kW machine it was 0.07 US$/kWh. The cost of electricity production with a 600 kW wind machine was found 1.75 times more than that produced using a 2500 kW system.

In Region B, the cost of electricity produced from wind machine of capacity 2500 kW was found to vary between a minimum of 0.0234 US$ at Yanbo to a maximum of 0.0538 US$ at Gassim. Similarly the cost of electricity produced using 1300 kW machine varied between a minimum of 0.0295 US$/kWh and a maximum of 0.0643 US$/kWh corresponding to Yanbo and Gassim, respectively and it varied from 0.0438 to 0.0962 US$/kWh when produced using a 600 kW wind machine. The average costs of electricity production using 2500, 1300, and 600 kW machines were found to be 0.04, 0.05, and 0.0734 US$. In Region C the regional average costs were found to be 0.053, 0.053, and 0.078 US$ from 2500, 1300, and 600 kW wind machines, respectively. Here it was observed that the cost of electricity production using all the chosen wind machines was least in Region A, highest in Region C and in between the two in Region B.

Unlike the present analysis, a more detailed cost analysis of wind farms, using an optimal number of wind machines of different capacities, should also be made. Finally, a site should be selected in Region A to deploy wind machines of different sizes to study the equipment deployment costs and problems in transportation, civil construction problems and costs, performance, operation & maintenance problems, availability of skilled manpower, and various other related issues. The sizes and types of the machines will have to be based on the wind analysis presented in this study and on the availability of appropriate wind electric conversion (WEC) system. Consideration should also be made of ease of maintenance and availability of skilled manpower to coordinate, monitor, and maintain the whole system.

6. Conclusions

This study presented the data analysis of hourly mean values of wind speed at 20 locations in the Kingdom of Saudi Arabia, in order to know the wind power potential of the Kingdom. The data used in this study covers a period of 5.5–13 years from 1970 to 1982. On completion of the study, the following observations are made:

The wind duration analysis is an important aspect to be considered while selecting a site for developing a wind power generation facility. Accordingly, wind duration curves were prepared to find the duration of the availability of the wind at different locations in the useful range of the wind speed.

At coastal locations namely; Dhahran, Al-Wajh, Yanbo, Jeddah, and Gizan, the wind was available above the required wind speed for more than 50% of the time.

At some inland locations like Riyadh, Medina, Badana, Rafha, Qaisumah, Turaif, and Taif the required wind speed was available for 45±5% of the times per year. Only at Taif, Al-Jouf, Gassim, Nejran, Hail, and Bisha the required wind was available only 35±2% of the times per year.

The cost of each kilowatt-hour of electricity produced using wind was calculated for all the sites using the capital cost, investment cost, operation and maintenance cost, depreciation, inflation rate, and interest rate. The minimum cost of electricity generated using 2500, 1300, and 600 kW machines was found to be 0.0234, 0.0295, and 0.0438 US$/kWh at Yanbo, while the corresponding maximum was 0.0706, 0.0829, and 0.121 US$/kWh at Nejran.

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