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Renewable Energy 32 (2007) 738–749

RENEWABLE ENERGY

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Wind shear coefficients and energy yield for Dhahran, Saudi Arabia

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Received 14 December 2005; accepted 28 March 2006
Available online 24 May 2006

Abstract

This study presents calculated values of wind shear coefficients (WSE) using measured values of wind speed at 20, 30, and 40 m above ground level (AGL), for Dhahran, Saudi Arabia. The study also includes the air density estimated using measured air temperature and surface pressure and effect of wind shear coefficient on energy yield from a wind farm of 60 MW installed capacity developed using 40 wind turbines of 1500 kW size. The data used in the determination of wind shear coefficient covered a period of almost 5 years between 4 October 1995 and 30 November 2000.

The study suggests a value of 0.189 of wind shear coefficient for the calculation of wind speed at different heights if measured values are known at one height. No regular seasonal trend was observed in the values of wind shear coefficients. In case of diurnal variation, higher values were observed during nighttime and early hours of the day and comparatively smaller values during day light hours. The air density, calculated using measured temperature and pressure was found to be 1.18 kg/m^3. The energy yield obtained using RetScreen software, showed that the actual wind shear coefficient presented in this paper produced around 11–12% more energy compared to that obtained using 1/7 power law. Accordingly, 2–3% higher plant capacity factors were achieved using actual site-dependent wind shear coefficient instead of 1/7th wind power law exponent for the calculation of wind speed at hub-height.

Keywords: Wind shear coefficients; Air density; Wind power potential; Wind farm; Wind speed; Wind energy

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0960-1481/$ - see front matter
doi:10.1016/j.renene.2006.03.014

1. Introduction

An accurate wind resource assessment is an important and critical factor to be well understood for harnessing the power of the wind. It is well known that an error of 1% in wind speed measurements leads to almost 2% error in energy output. Hence precise measurements of wind speed at a site minimize the risk of huge investments. Moreover, the wind measurements are usually made at a height different than the hub-height of the wind machine. The wind speed is extrapolated to the hub-height by using the well-known 1/7th wind power law. In fact, the wind speed, at a given site, increases with height by a power factor known as wind shear factor or coefficient. This coefficient is highly dependent on the site where the measurements are made. So, if the wind shear coefficient is greater than 1/7 then wind power law will lead to under estimation of wind speed and hence the wind energy otherwise overestimation. Hence accurate knowledge of wind shear coefficient is essential for actual wind power estimates.

The other important parameter that directly affects the energy production estimates is the air density. The air density depends on the air temperature and the surface pressure of the site of interest. So an assumed value of air density will result into either under or over estimation of energy production. Hence actual air density at the specific site should be obtained using the local temperature and pressure measurements to facilitate accurate energy estimation.

The wind shear values are seldom known because the wind speed measurements are made only at one specific height at most of the meteorological data collection stations in the world. There are few locations, mostly in developed countries, where wind speeds are measured at more than one height. Recently, Farrugia [1] presented wind shear coefficients for a Mediterranean island of Malta using wind speed measured at 10 and 25 m above ground level. He found that the wind shear coefficient varied with season with a maximum value of 0.45 in January to a minimum of 0.29 in July and August. He also reported higher values during nighttime and lower during daytime. According to Sisterton et al. [2], wind shear coefficients of the order of 0.5 may be found between 30 and 150 m and in extreme case may reach as high as 1.0.

Bailey [3] predicted the vertical wind speed profiles as a function of time of the day and wind speed measured near the ground surface and found that the power law exponent depends on atmospheric stability, wind speed, roughness length, and the height interval. A wind resource assessment study for Texas, USA [4] reported wind shear exponent value in the range of 0.15–0.36 for most of the 17 sites analyzed. Michael et al. [5] calculated wind shear coefficients for 12 Minnesota sites that have been in operation since 1995 or earlier. They found considerable variation (0.2–0.4) in the values of wind shear exponent from location to location. According to Michael [6], higher exponents are usually associated with rougher terrain and taller vegetation or other nearby obstacles. The wind shear coefficients were found to vary from 0.16 to 0.27 at all Iowa Wind Energy Research Institute sites and over all months with an overall average of 0.21 [6].

In Saudi Arabia, work on wind resource assessment dates back to 1986 when a wind atlas was developed by using wind speed data from 20 locations [7]. This atlas presented the monthly mean wind speed contours and frequency distribution for all the months during the year. Rehman [8] presented the energy output and economical analysis of 30 MW installed capacity wind farms at five coastal locations in terms of unadjusted energy, gross energy, renewable energy delivered specific yield and wind farm capacity factor using wind machines of 600, 1000 and 1500 kW. In another study, Rehman [9] performed a detailed analysis of wind speed in terms of energy yield, effect of hub-height on energy yield, plant capacity factor, etc. for an industrial city situated on the northwest coast of Saudi Arabia. The long-term wind speed at the site was 4.63 m/s which reached more than 5.0 m/s at 50 m above ground level. Moreover, the frequency distribution showed that a wind speed of 3.5 m/s and above was available for 59% of the time during entire year at 10 m above ground level.

Rehman and Aftab [10] performed wind power potential assessment for coastal locations in Saudi Arabia. Rehman et al. [11] computed the cost of energy generation at 20 locations in Saudi Arabia using net present value approach. Mohandes et al. [12,13] used the neural networks method for the prediction of daily mean values of wind speed and concluded that the performance of the neural network model was much better than the traditionally used auto-regression model. Rehman and Halawani [14] presented the statistical characteristics of wind speed and its diurnal variation. The autocorrelation coefficients were found to match the actual diurnal variation of the hourly mean wind speed for most of the locations used in the study. Rehman et al. [15] calculated the Weibull parameters for 10 anemometer locations in Saudi Arabia and found that the wind speed was well represented by the Weibull distribution function. With growing global awareness of the usage of clean sources of energy, wind energy in particular, a lot of work is being carried out in Saudi Arabia, as can be seen from [16–21].

This paper utilized the wind measurements made at 20, 30, and 40 m above ground level to calculate the wind shear coefficients. The site-specific air density was calculated using temperature and pressure measurements made at ground level. The analysis also included the effect of wind shear factor on energy yield and plant capacity factor of a 60 MW installed capacity wind farm developed using 40 wind machines of 1500 kW rated power.

2. Site and data description

The meteorological data (wind speeds, wind direction, air temperature, relative humidity, surface station pressure, global solar radiation) was collected at Dhahran by King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi Arabia [22,23]. The site-related information is summarized in Table 1. The wind mast at Dhahran was surrounded by a single storied building of about 4 m high in the south, gulf sea shore on its west and the highway on the north of the tower.

Data was recorded every 30 min on a removable data card. The wind speed data was collected at 20, 30, and 40 m above the ground. At each height two sensors were installed (opposite to each other) and recorded data was tagged as WS1 & WS2 at 20 m, WS3 & WS4 at 30 m, and WS5 & WS6 at 40 m. The wind direction data was recorded at 30 and 40 m as WD1 and WD2, respectively. The surface air temperature (°C), relative humidity

Table 1
Summary of site-related information at Dhahran

Latitude (Degrees)	Longitude (Degrees)	Altitude (m)	Data collection period
26.1°N	50.1°E	3	4 October 1995–30 November 2000

Table 2
Operating ranges and accuracies of various sensors used for data collection

S. no.	Parameter	Sensor type	Operating range	Accuracy
1	Wind speed	NRG #40 maximum anemometer	1.0–96.0 m/s	0.1 m/s
2	Temperature	NRG #110S with radiation shield	−40.0–52.5 °C	±1.11 °C
3	Pressure	NRG #BP20 barometric pressure sensor	15.0–115 kPa	±1.5 kPa maximum
4	Relative humidity	RH-5	0–95%	±5%
5	Wind direction	200 Series wind vane	0–360°	N.A.
6	Global solar radiation	Li-Cor #LI-200SA Pyranometer	0–3000 W/m^2	±3%

(%), surface station pressure (in. of Hg), and global solar radiation (W/m^2) data was collected at 3 m above the ground surface. The operating ranges and accuracies of various sensors used for the measurements are given in Table 2.

3. Calculations of wind shear coefficients and air density

The wind shear coefficient α was calculated using the following equation:

$$\alpha = \frac{\ln(V_2) - \ln(V_1)}{\ln(Z_2) - \ln(Z_1)}, \tag{1}$$

where V_1 is the wind speed at height Z_1 and V_2 is the wind speed at height Z_2. These values of α, calculated using Eq. (1), were used to find the annual, seasonal, and half-hourly means. The air density was calculated using the following equation:

$$\rho = \frac{P}{RT} \quad (\text{kg/m}^3), \tag{2}$$

where P is the air pressure (Pa or N/m^2), R the specific gas constant for air (287 J/kg°K) and T the air temperature in degrees Kelvin (°C + 273).

4. Results and discussion

The overall half-hourly mean wind speed, temperature, global solar radiation, surface pressure, and relative humidity are summarized in Table 3. These averages were obtained using all the data collected over entire data collection period. The last column of Table 3 gives the percent of data values used in the statistical calculation for each parameter. At 20 m above ground level the mean wind speeds were found to be 4.8 and 4.7 m/s corresponding to two wind speed sensors. These averages were obtained using 99.5% of the measured values as shown in the last column of the Table 3.

At 30 m above ground level the wind speeds were 5.1 and 5.2 m/s corresponding to WS3 and WS4 wind speed sensors, respectively. In this case also, almost 100% of the measured values were used to obtain the mean wind speed. At 40 m above ground level the wind speed values corresponding to WS5 and WS6 sensors were 5.3 m/s. In case of WS5 only 74% of the measured values were found to be correct and used in the calculation of its mean. The mean values of wind direction at both the heights were found to be 330 degrees from North. At Dhahran, the temperature was found to vary between a minimum of 9.5 °C and a maximum of 49.6 °C, while the mean remained as 28.9 °C. The mean values of global

Table 3
Overall half-hourly statistics for Dhahran station for the years 1995–2000

Parameters	Units	Min.	Max.	Mean	% of values
Wind speed (WS1 at 20 m)	m/s	0	17.7	4.8	99.62
Wind speed (WS2 at 20 m)	m/s	0	18.2	4.7	99.52
Wind speed (WS3 at 30 m)	m/s	0	18.6	5.2	99.72
Wind speed (WS4 at 30 m)	m/s	0	19.1	5.1	99.78
Wind speed (WS5 at 40 m)	m/s	0	19.3	5.3	74.25
Wind speed (WS6 at 40 m)	m/s	0	19.3	5.3	99.59
Wind direction (WD1), Degrees from north	Degrees	0	359	330	100
Wind direction (WD2), Degrees from north	Degrees	0	359	330	100
Temperature	°C	9.5	49.6	28.9	76.46
Global solar radiation	W/m^2	0.1	1039.4	393.5	49.04
Pressure	In of Hg	29.0	30.35	30.15	76.46
Relative humidity	%	7	100	52	99.68

** Statistics for 90,433 records for the period from 4 October 1995–30 November 2000.

Table 4
Wind shear coefficients calculated using half-hourly mean values of wind speeds at different heights

Wind shear between	Based on long-term mean wind speed
α_1–30 and 20 m (WS3 and WS1)	0.189
α_2–40 and 30 m (WS5 and WS3)	0.119
α_3–40 and 20 m (WS5 and WS1)	0.160
α_4–30 and 20 m (WS4 and WS2)	0.186
α_5–40 and 30 m (WS6 and WS4)	0.140
α_6–40 and 20 m (WS6 and WS2)	0.167

solar radiation, surface pressure, and the relative humidity were found to be 393.5 W/m^2 (3.738 $kWh/m^2/day$), 30.15 inches of H_g, and 52%, respectively. The detailed discussion on the results is presented in terms of annual, seasonal, and diurnal variation of wind shear coefficients and air density in the forthcoming paragraphs.

4.1. Wind shear characteristics

The wind shear coefficients were calculated using Eq. (1) and six pairs of wind speeds, three on each side of the wind measurement mast. The wind shear coefficients calculated between 30 and 20, 40 and 30, and 40 and 20 m using wind speed pairs WS3 and WS1, WS5 and WS3, and WS5 and WS1 were designated as α_1, α_2, and α_3, respectively while those calculated using wind speed pairsWS4 and WS2, WS6 and WS4, and WS6 and WS2 were named as α_4, α_5, and α_6. The long-term averages of these six coefficients are summarized in Table 4.

As given in Table 4, the average value of α_1 was 0.189. It was obtained using long-term mean wind speeds WS3 and WS1. The mean wind shear coefficient between 40 and 30 m was 0.119 while between 40 and 20 it was 0.16. The smaller values of α_2 and α_5 in Table 4 conforms to the fact that at higher altitudes the surface effects tends to minimize due to better mixing and lesser surface effects. The wind shear coefficients were also calculated for

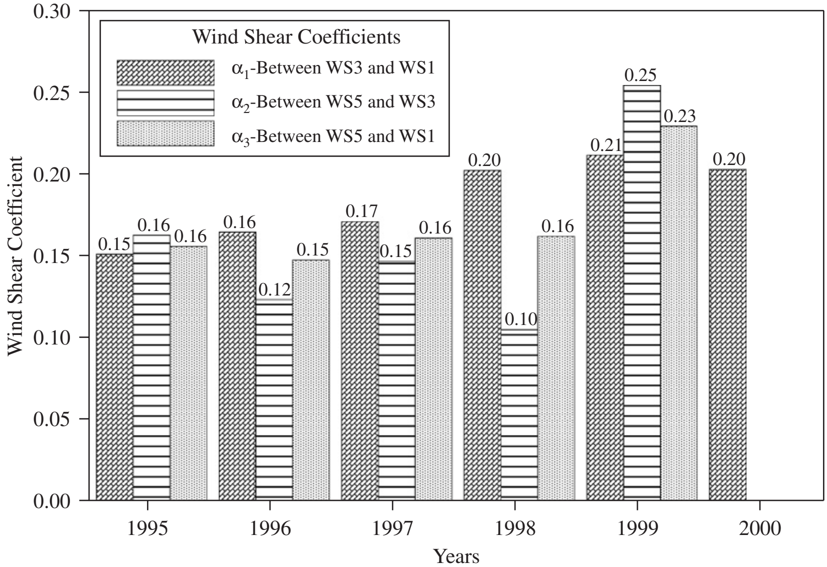

Fig. 1. Yearly variation of wind shear for Dhahran city obtained using half-hourly mean values of the wind speed on the left side of the tower.

each year using yearly mean values of wind speeds. The variation of α_1–α_3 values with year is shown in Fig. 1.

As seen from this figure, the maximum value of α_1 (0.21) was observed in the year 1999 and minimum of 0.15 in 1995, while the overall mean during all years was found to be 0.189. The maximum value of α_2 (0.25) was observed in 1999 while minimum of 0.1 in 1998. The maximum value of 0.23 (α_3) was found in 1999 while minimum of 0.15 in 1995. During rest of the years the value of α_3 remained 0.16. On an average, an increasing trend was observed in the values of α_1, α_2 and α_3 from 1995 to 1999. Fig. 2 shows the annual variation of $\alpha_{4,}$ $\alpha_{5,}$ and α_6 values for Dhahran. In this case also an increasing trend was noticed in the values of $\alpha_{4,}$ $\alpha_{5,}$ and α_6 from 1995 to 2000.

The seasonal variation of wind shear coefficients is shown in Figs. 3 and 4. Relatively higher values of α_1, α_2 and α_3 coefficients were observed during April–July compared to those during rest of the months. As seen from Fig. 3 values of α_1 were the highest, α_3 the smallest and α_2 lied in between the two. The values of α_4, α_5, and α_6 were found higher during winter months and lower in summer months. Maximum values were observed in the month of February while the minimum in August. This conforms to the physical reasoning that during summer time the temperature are higher and hence better mixing of the air takes place above the ground, which results into smaller values of shear coefficients. On the other hand, during winter time, the air above the ground experiences less mixing due to lower temperatures and hence higher values of wind shear coefficients.

In order to study the diurnal pattern, half-hourly mean values of wind speeds were used to obtain the wind shear coefficients α_1–α_6. The diurnal variation of α_1, α_2, α_3 and α_4, α_5, α_6 are shown in Figs. 5 and 6, respectively. From these figures, it is evident that the heating and cooling cycle of the air adjacent to the earth during 24 h of the day influences the wind shear coefficients. During early hours of the day i.e. between 00:00 and 07:00 h, higher and

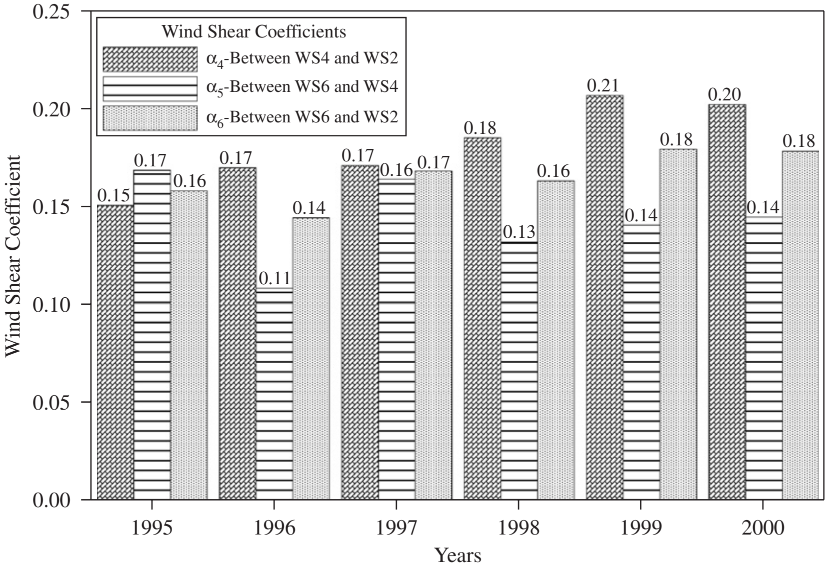

Fig. 2. Yearly variation of wind shear for Dhahran city obtained using half-hourly mean values of the wind speed on the right side of the tower.

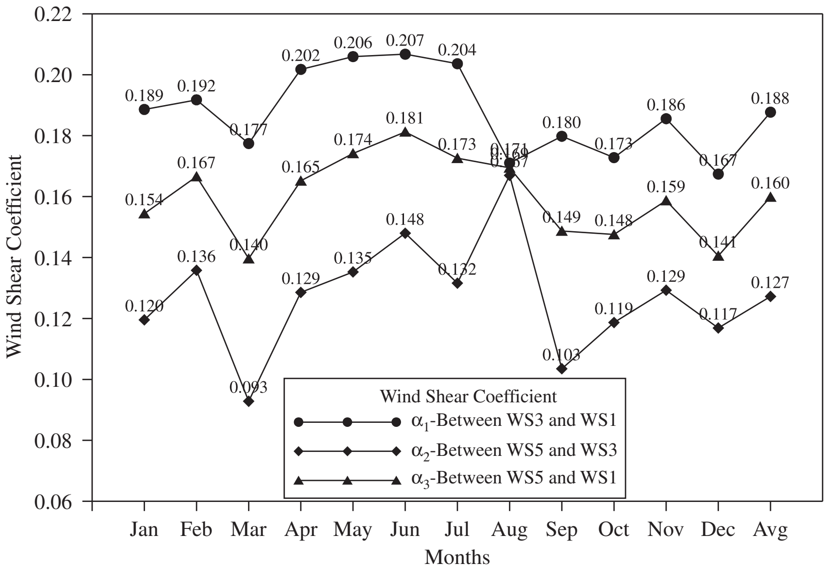

Fig. 3. Monthly variation of wind shear for Dhahran city obtained using half-hourly mean values of the wind speed on the left side of the tower.

almost constant values of α_1, α_2, and α_3 were observed while from 07:00 h onwards, as heating of the ground surface and the air above it took place, these values started decreasing and after reaching a minimum at 09:00 h remained almost constant up to 16:30 h. After 16:30 h, the values of α_1, α_2, and α_3 again started increasing and after

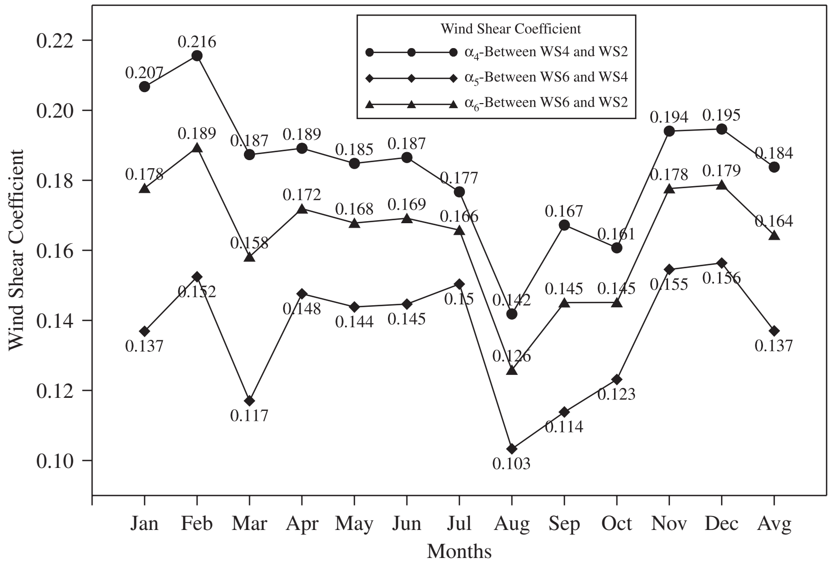

Fig. 4. Monthly variation of wind shear for Dhahran city obtained using half-hourly mean values of the wind speed on the right side of the tower.

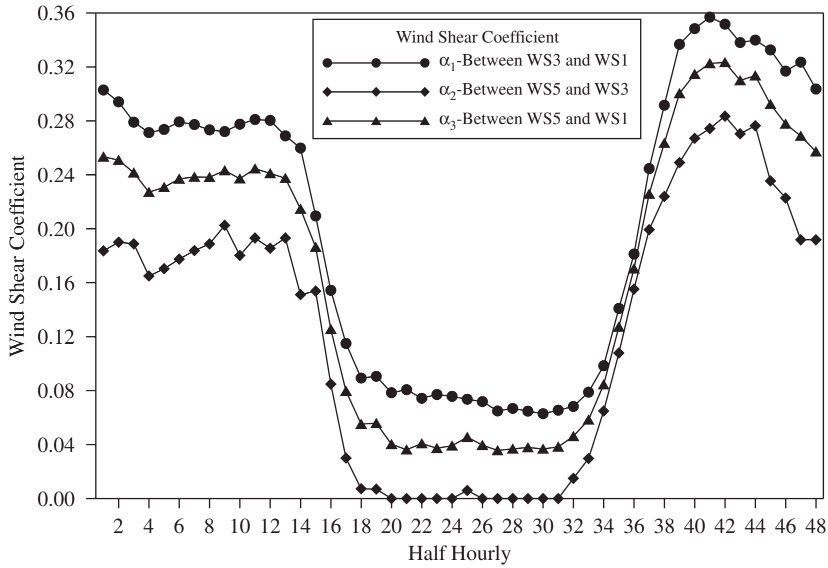

Fig. 5. Diurnal variation of wind shear for Dhahran city obtained using half-hourly mean values of the wind speed on the left side of the tower.

reaching a maximum at 20:00 h showed a decreasing pattern during rest of the night hours, which may be accounted for cooling of the ground surface and the air above it. The values of α_4 and α_5 behaved in a similar way as α_1, α_2, and α_3. The values of α_6 showed a small effect of diurnal change.

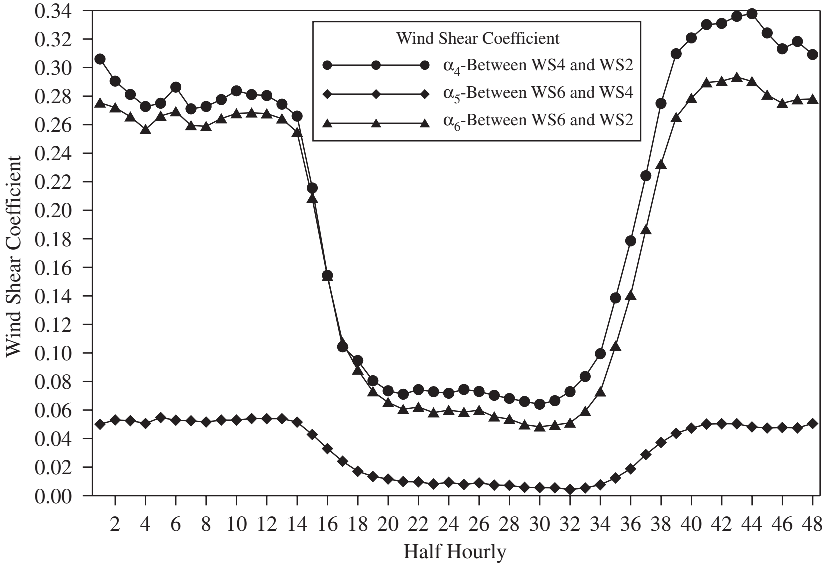

Fig. 6. Diurnal variation of wind shear for Dhahran city obtained using half-hourly mean values of the wind speed on the right side of the tower.

Table 5
Mean air density values for Dhahran at different heights

Air density (kg/m^3)	Min.	Max.	Mean	% of values
At 20 m	1.09	1.26	1.18	100
At 30 m	1.09	1.26	1.18	100
At 40 m	1.09	1.26	1.18	100

4.2. *Air density characteristics*

The air density is an important parameter whereas wind power density calculation is concerned. The wind power density is directly proportional to the air density. Denser the air, the higher is the wind power density and vice versa. In the present paper, the air density was calculated using the measured values of temperature and pressure recorded near ground surface every half hour over the entire period of data collection. The mean values of air density at different heights are given in Table 5. At all heights these values varied between a minimum of 1.09 kg/m^3 and a maximum of 1.26 kg/m^3 while the mean remained as 1.18 kg/m^3.

The annual mean values of the air densities were computed for all the years of data collection period and are shown in Fig. 7. In 1995, the mean air density was 1.199 kg/m^3 at 20 m and 1.197 kg/m^3 and 1.196 kg/m^3 at 30 and 40 m, respectively. The density values in the year 1995 were found to be higher compared to other years, as seen from Fig. 7. The reason was that in 1995 the data was collected only during wintertime i.e. October, November and December months and in wintertime the density is found to be relatively

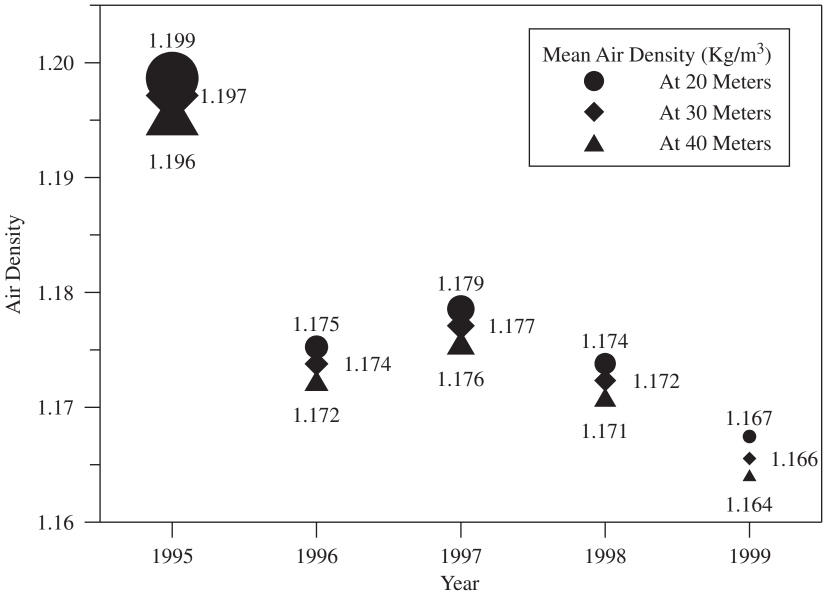

Fig. 7. Yearly variation of air density at different heights above ground level.

higher compared to summer months. In other years, the density values were found in close agreement with each other. A decreasing trend was noticed in the air density values at all heights from 1997 to 1999. Since there were fewer data during the years 1995 and hence the values of air density in this year was less representative of yearly mean values compared to 1996–1999. The overall mean value of air density at Dhahran was found to be 1.18 kg/m^3 and is recommended to be used for all practical purposes. The air density was found to vary very slightly during day and night cycle. Slightly higher values were observed during night and early morning hours compared to those during day light hours.

5. Energy production

The energy yield from wind machines is highly dependent on the wind speed at hub height. Usually, the wind speed measurements are made at heights much lower than the hub heights of modern wind machines. For energy estimations from such machines, the wind speed at hub height is calculated using 1/7th wind power law which may underestimate or overestimate the wind speed which ultimately will provide wrong estimates of energy. Hence wind shear coefficient for the actual location of wind machine siting should be used. To see the effect of wind shear coefficient on the energy yield, a wind machine S70 of 1500 kW rated capacity from NORDEX was chosen. The technical details of the wind machine can be seen in Ref. [24]. The energy yield was calculated using RetScreen software [25].

The energy yield and the plant capacity factors (PCF) obtained from a wind farm of 60 MW installed capacity developed using 40 wind machines of 1500 kW-rated power are summarized in Table 6. The energy yield and PCF values were calculated using wind speed

Table 6
Energy yield and plant capacity factor of a 60 MW installed capacity wind farm developed using 40 wind machines of 1500 kW rated power

Year	Mean wind speed at 20 m	Wind coefficient factor 0.189		Wind coefficient factor 0.143	
		Energy yield (MWh/Year)	Plant capacity factor (%)	Energy yield (MWh/Year)	Plant capacity factor (%)
1995	4.7	112,144	21	100,359	19
1996	4.7	112,144	21	100,359	19
1997	5.0	130,370	25	117,833	22
1998	4.6	106,069	20	94,534	18
1999	4.8	118,219	22	106,183	20
2000	4.9	124,295	24	112,008	21

at 60 m above ground level. The wind speed at 60 m was calculated using wind shear coefficient of 0.143 and 0.189. In 1995 and 1996, the annual wind energy yield obtained using wind shear coefficient of 0.189 from a wind farm of 60 MW installed capacity was 112,144 MWh with a plant capacity factor of 21%. The annual energy yield obtained from the same wind farm but using a wind shear factor of 0.143 was 100,359 MWh with a plant capacity factor 19%. In general, 11–12% higher energy yield and 2–3% higher plant capacity factors were obtained with site-dependent wind shear coefficient compared to 0.143.

6. Consclusions

The wind shear coefficients and air density values presented in this paper are an addition to the literature. The wind shear coefficients were calculated using precise measurements of wind speeds at three different heights above the ground. The air density values were calculated using the surface temperature and pressure measurements. Air density values at different heights were calculated by finding the pressure at that height. The study suggests:

- That a wind shear coefficient of 0.189 should be used to calculate the wind speed at different hub heights if wind measurements are available at one height.
- That the wind shear coefficient does not change significantly with year.
- That the wind shear coefficients are influenced by the season, so for accurate calculations of wind power density or for any other application, monthly mean values of wind shear coefficients should be used.
- That the wind shear coefficients are significantly influenced by the diurnal heating and cooling cycle, and hence for precise applications hourly or daylight and nighttime mean values can be used.
- That the air density does not change with year and hence a constant value of 1.18 kg/m^3 can be used for Dhahran area.
- The wind shear coefficients directly affect the energy production and plant capacity factor and hence should be chosen carefully if wind measurements at different heights are not available at the site of interest.

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