Effect of Wind Shear Coefficient for the Vertical Extrapolation of Wind Speed Data and its Impact on the Viability of Wind Energy Project

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Abstract: The importance of characterizing the wind shear at a specified location for the utilization of wind turbine is of vital importance. Such study is considered necessary both for the turbine design and prediction of its power output. In situations where the wind speed at different heights is required if measured values are known at one height then, generally it is extrapolated to the hub height by using the one-seventh power law. The exponent in this case has a value of 1/7 but it is observed that, the value of exponent varies with the type of terrain therefore; the one-seventh power law is not suitable for wind speed extrapolation and energy estimation. It has been found that, the one-seventh power law has a tendency to miscalculate the actual long-term average wind speeds. Hence, for accurate estimation of wind speed at a height, both monthly or seasonal and diurnal values of wind shear coefficient (WSC) have to be used. In this paper, the power law exponent for three sites located over coastal sites in South of Pakistan, i.e., Katibandar, Jati and Gharo, is established using wind speeds measured at heights 10 m and 30 m above the ground (AGL). Wind data is obtained from Pakistan Meteorological Department (PMD). Mean values of WSC were found to be 0.318 at Jati, 0.321 at Gharo and 0.269 at KatiBander. In addition, yearly, monthly and diurnal variation for WSC is also analyzed. The research showed that, the wind shear coefficient significantly fluctuates by seasonal and diurnal changes. Comparisons has been made for discrepancies in energy estimation, payback period and cost of energy (Cents/Kwh) using wind speed values extrapolated from 10 m, for one-seventh power law and overall mean WSC as exponent. The study showed that, if wind speed is extrapolated with WSC of 0.143, the energy is underestimated by 16-33% at Gharo, 12-25% at Katibandar and 28-51% at Jati for all considered hub heights. Error in the Payback period is estimation as 19–34% at Gharo, 16–27% at Katibandar and 31–48% at Jati for all considered hub heights, for 10 m wind data extrapolated with WSC of 0.143. The percentage change in the COE estimation for the two wind shear factors and three sites under study show that, if 10 m wind data extrapolated with WSC 0.143, the COE overestimated is between 19-34% for Gharo, 16-27% for Katibandar and 31- 48% for Jati for all considered hub heights. It is evident from results that, the 1/7 power law, tends to produce misleading results for the feasibility study.

Keywords: Wind energy yield, Wind shear coefficients, coastal sites, Southern Pakistan, one-seventh power law, capacity factors.

1. INTRODUCTION

Near to the vicinity of earth's surface, in the inertial sub layer of the atmospheric boundary layer, wind speed gradually varies with height, this behavior is known as wind shear. It follows a logarithmic (or power law) and is due to friction between wind speed and surface roughness [1]. The study of wind shear for a region cannot be over emphasized as it is useful for the extrapolation of wind speed. For feasibility studies it is important to properly predict the wind speed at different hub heights. Commercially available turbine hub heights have reached values ranging up to 120 m with a radius ranging from 40 m to 80 m [2]. High meteorological towers are costly to operate and maintain, wind speed observations are generally taken at a height lower than the turbine hub height [3]. The Estimation of wind speed at different hub heights is usually workout by the famous power law [4, 5]. If the value of exponent is chosen as 1/7, it is well-known as one-seventh power law. WSC is a site specific factor as it depends on atmosphere, wind speed and terrain nature [3, 4]. The importance of site specific estimation of WSC is that, if the wind shear coefficient of a site is greater than 1/7 then the wind power law [4, 5] underestimates the wind speed. Otherwise, it would overestimate the energy production. Although one-seventh power law is easy to use, many studies have discussed its limitations [6-8]. Hence, correct information of the wind shear coefficient is essential for valid feasibility studies in case where there is no wind data available at the required hub height. Furthermore, wind shear is one of the most important factors that influence the uncertainty of the power curve measurements [9,10]. Urban areas with tall buildings (α = 0.40), modest towns (α = 0.30), or areas with several trees (α = 0.24) have large values of WSC, whereas,

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lower values (α = 0.10) are established, over flat rigid ground and lake or oceans [11]. In principle, the 1/7 (0.143) value is a rough estimate to be used as exponent. A precise estimation of WSC is generally made by wind speed measurements at two or three heights for at least one year period.

Different studies for the estimation of WSC have been reported. Some of these studies include Farrugia [7] estimated WSC for the island of Malta, wind speed observations at 10 m and 25 m above ground level was used. In this study of seasonal variation of the wind shear coefficient, highest value of 0.45 for January and smallest value of 0.29 for the months of July and August were found. Furthermore, the study revealed a diurnal variation in WSC. Lower values of WSC during day time and higher values during night time were observed. These results reflects quite different values of WSC than the assumed exponent, which gives 0.20 – 0.24 for the type of terrain used in the study. Sisterton *et al*. [12] used wind speed at 30 m and 150 m to estimate WSC, and reported values of WSC of the order of 0.5. Rehman and Al-Abbadi [13] studied variation in wind shear coefficients over the coast of Dhahran, Saudi Arabia. Wind observations at 20 m, 30 m and 40 m were used in the study and reported a value of 0.189 for WSC. Over a mountainous site in New Mexico Jaramillo and Borja [14] using a dataset of 2.5 years wind dataset for heights between 25 m and 40 m. height, WSC value of 0.24 was reported. In a location in Hungary, Tar [15] using a wind dataset of 2 year and heights between 20 m and 50 m, estimated mean WSC value of 0.45 to 0.50 were reported. Brewster, Rogers [16] estimated an annual average WSC of 0.38 between 38 and 49 m. Giovanni and Sauro [17] estimated the wind shear coefficients for three sites situated over the coastal area in Southern Italy. The height of wind mast for all three sites were kept as 10 m and 50 m. WSC overall mean values were found to be 0.271 at Brindisi, 0.232 at Portoscuso and 0.150 at Termini. They also analized yearly, monthly and diurnal variation in WSC. Bechrakis and Sparis [18] showed that, assumed values for WSC cannot be used successfully. Using wind data between the heights of 20 m and 10 m found a value of WSC of 0.20 for a smooth site, for which a value of 0.16 was assumed. Maeda, *et al*. [19] used wind data between 20 m and 30 m, for a site in Japan with complex terrain, they over estimated the average wind speed at 100 m by more than 20% using the one-seventh power law. Ebubekir Fırtın *et al*. [20] used one year (2008-2009) wind data of Balıkesir, to study the result of WSC on energy estimation. This study showed that, the difference between wind energy production using one-seventh power law and energy production using observed WSC at hub height was up to 49.6%. It is important to consider the variation of wind shear for wind energy assessment, otherwise estimation are not reliable [21,22].

In the present study effect of wind speed extrapolation on feasibility of wind project have been considered. For all sites, three computations i.e. Energy yield, Payback period and Cost of energy (cents/KWh) from 10 m data using the site-specific overall mean WSC and WSC of 0.143 have been considered. A thorough analysis of diurnal and monthly variation of wind shear coefficient is also performed.

2. THE METHODOLOGY

The methodology for analyzing the effect of WSC on economic viability of wind turbines consists of following steps:

- Estimation of wind speed from reference height to hub height is performed by the wind power law given in Eq. (1), it is also known as the Hellmann's power law [23].

$$V = V_{ref}\left(\frac{H}{H_{ref}}\right)^{\alpha} \tag{1}$$

- where V and V_{ref} are the wind speeds at heights H and H_{ref} respectively. α is the wind shear coefficient or Hellman exponent. When the value of α is taken as 1/7 it is generally referred to as the one-seventh power law. The one-seventh power law is derived from Blasius theory [8]. The wind shear coefficient is determined using following equation.

$$\alpha = \frac{\ln(V) - \ln(V_{ref})}{\ln(H) - \ln(H_{ref})} \tag{2}$$

- Estimation of the annual energy yield from the selected wind turbine using WINDOGRAPHER®. The annual energy yield is an estimation of a chosen wind turbine of certain rated power (1000 kW) at different hub heights (40, 50, 60, 70, 80, 90, and 100 m) and calculation of percentage of error in annual energy yield estimated with the wind speed extrapolated for each 10 m increase in hub height due to wind shear coefficient.

- Total cost. An estimation or assumption of percentage incremental total cost for each 10 m increases in hub height.
- the payback period and COE per KWh is estimated using WIND POWER ® [24] software and calculation of percentage of error in payback period and COE (cents/Kwh) for each 10 m increase in hub height using wind speeds being extrapolated through both WSC. (i.e constant α =0.143 and site specific WSC).

2.1. Study Areas and Data Description

The investigations are performed on a dataset of 4 years (2002–2005) using average wind speed, measured at 26 meteorological stations. The data is obtained from Pakistan Meteorological Department (PMD) [25]. In this period, observation meteorological towers were set up in 42 sites across the coastal sites of Pakistan. In the present study three sites have been investigated, i.e., Jati, KatiBanbder and Gharo which are all situated in South of Pakistan (Figure **1**).

The measurements at these sites were taken at two different heights (i.e., 10 m and 30 m AGL). The details of the observation sites (whose common locations are encircle in Figure **1**) and the site related information is summarized in Table **1**. The average wind speeds at the measured height of 10 m and 30 m are given in Table **2**.

3. RESULTS AND DISCUSSION

Table **1** shows KatiBander has a relatively good potential amongst the three sites understudy. The average wind speed at 10 m and 30 m, are 4.52 m/s and 6.12 m/s, respectively. Average wind speeds for Gharo at 10 m and 30 m heights are 2.9 m/s and 5.50 m/s, respectively, while Jati station has lowest values of wind speeds amongst the three sites understudy, i.e. 5.05 m/s and 2.9 m/s at 10 m and 30 m, respectively.

3.1. Wind Shear Characteristics

It is important to consider seasonal effects on the value of wind shear parameters. It is an indication of how much the surrounding surface roughness

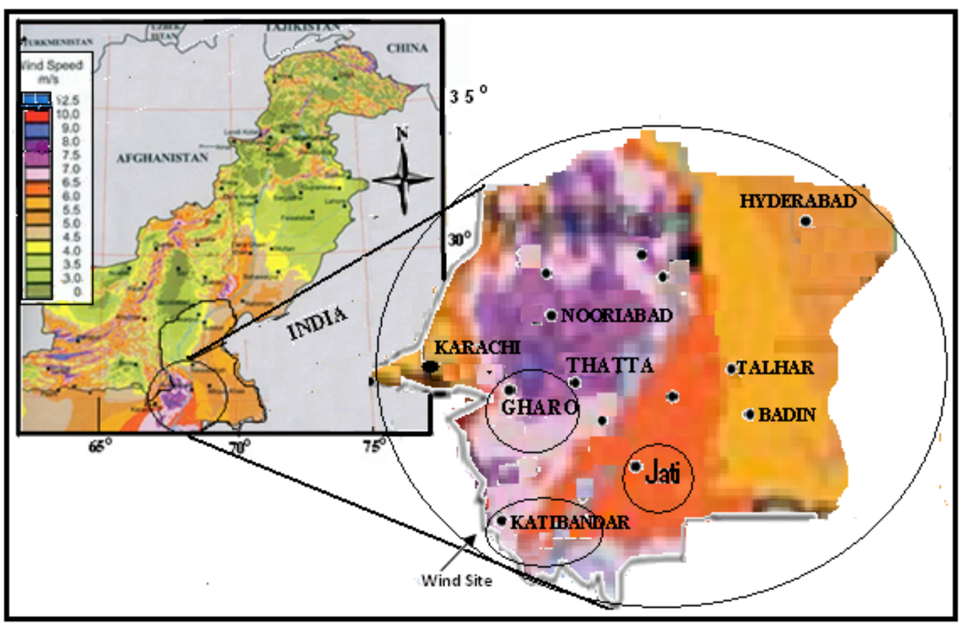

Figure 1: Locations of the three analysed coastal sites in Southern Pakistan. The monitored stations are encircled in the study areas.

Table 1: Summary of Geographical Information of Three Investigated Sites in Sindh

Stations	Latitude	Longitude	Elevation (ASL) m
Gharo	24.73^0	67.58^0	28
KatiBander	24.13^0	67.43^0	8
Jati	24.35^0	68.27^0	12

Table 2: MET Tower Measured Monthly Mean Wind Speeds and Monthly Mean Temperature

Site	Height	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Gharo	wind speed (m/s) at 10m	2.1	2.4	2.7	4.5	6.1	6.5	6.1	5.8	5.1	2.1	1.8	2
	wind speed (m/s) at 30m	3.6	3.9	4.2	6.3	8.2	8.3	8	7.7	6.8	3.5	3	3.5
	Temperature ^{0}C	17.9	20.6	24.7	27.3	28.7	29.5	28.2	27.3	26.7	26.7	23.3	19.5
KatiBandar	wind speed (m/s) at 10m	2.8	3.1	3.4	5.6	6.5	6.7	7.1	6.5	5.2	2.8	2.1	2.9
	wind speed(m/s) at 30m	4.1	4.7	5.1	7.4	8.3	8.4	9.1	8	6.5	4.2	3.5	4.2
	Temperature ^{0}C	18	20.3	24	26.4	27.8	28.7	27.6	26.7	26.2	26.4	23.5	19.7
Jati	wind speed(m/s) at 10m	2	2.1	2.5	3.4	4.4	5.4	4.8	4.7	3.3	1.8	1.6	1.9
	wind speed(m/s) at 30m	3.8	3.9	4.2	5.4	6.5	7.7	6.8	6.7	5.2	3.3	3.3	3.8
	Temperature ^{0}C	16.8	19.8	24.5	27.8	29.2	30	28.4	27.3	26.8	26.3	22.3	18.4

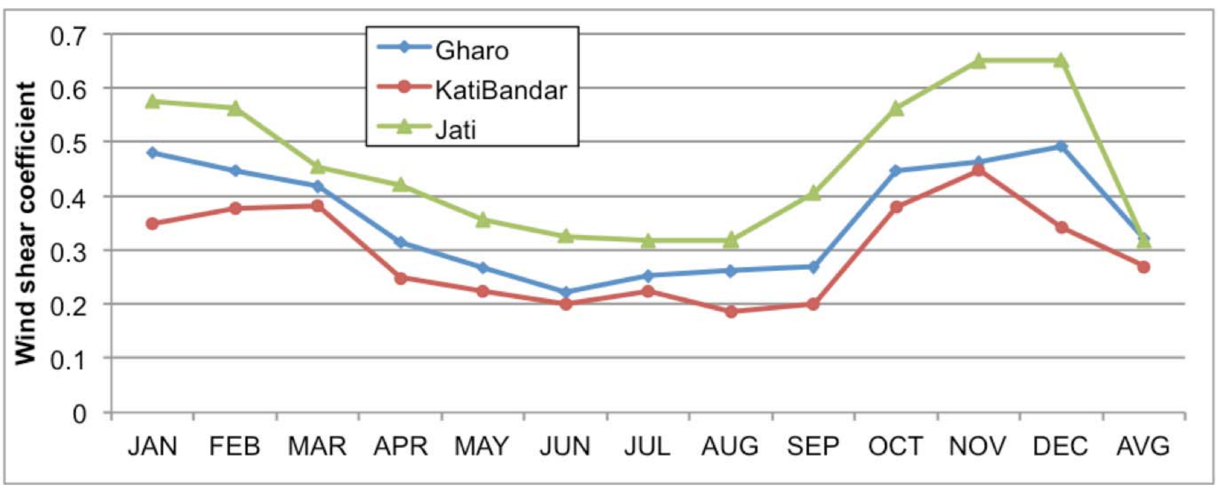

Figure 2: Monthly variation of (10 to 30 m) WSC measured by the three monitoring stations (2002 to 2005).

elements change seasonally. Figure **2** shows the monthly pattern of wind shear whereas Figure **3** shows the seasonal diurnal pattern of wind shear at the investigated sites. WSCs are estimated using Eq. (2) and wind speeds between the heights of 10 m and 30 m. Overall estimated mean values (μ) and standard deviations (σ) for Gharo were found to be $\mu = 0.321$ and $\sigma = 0.104$, for Jati are $\mu = 0.269$ and $\sigma = 0.091$ and for KatiBander are $\mu = 0.318$ and $\sigma = 0.128$.

The variation of WSC strongly related to the thermal conditions of the region and can be explain on the basis of Thermal Stratification, [26]. Winter months shows Higher values of the WSC whereas summer months shows lower values. Specifically, during the months from December to February. the WSC shows the highest values and the lowest values during June to August Figure **3**. This behavior can be justified, since during summer the ground temperatures are higher, it can cause brisk expansion of air in the vicinity of the surface and hence, better merger of the air takes place over the ground, which results in low values of the WSCs, while, during the winters the ground becomes much cooler than higher air, and hence, higher values of WSCs are obtained. This is known as stable stratification. As suggested by authors [7,13,17,27], this tendency is consistent at KatiBander, some inconsistency appear at jati, where WSC increases but it follows a same trend.

For the study of diurnal pattern of wind shear coefficients entire data set is used. The diurnal

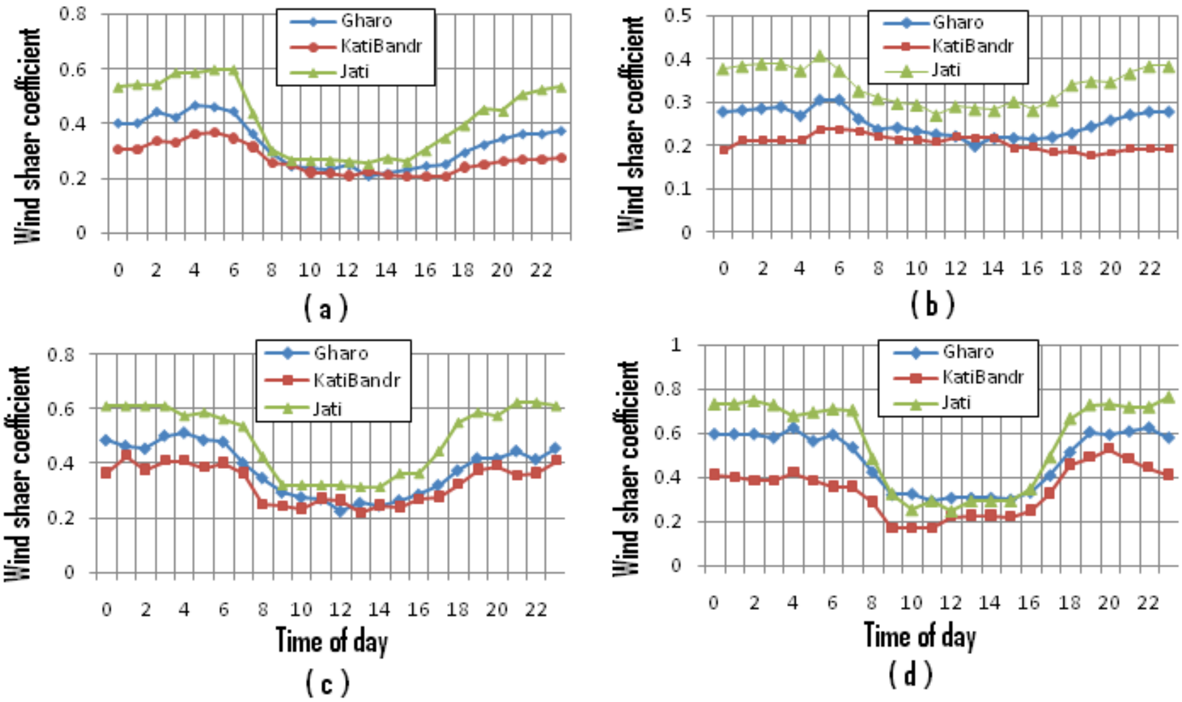

Figure 3: Seasonal diurnal variation in wind shear measured for three monitored sites (**a**) Spring (Mar-May) (**b**) Summer (Jun to Aug) (**c**) Autumn (Sep-Nov) (**d**) Winter (Dec-Feb).

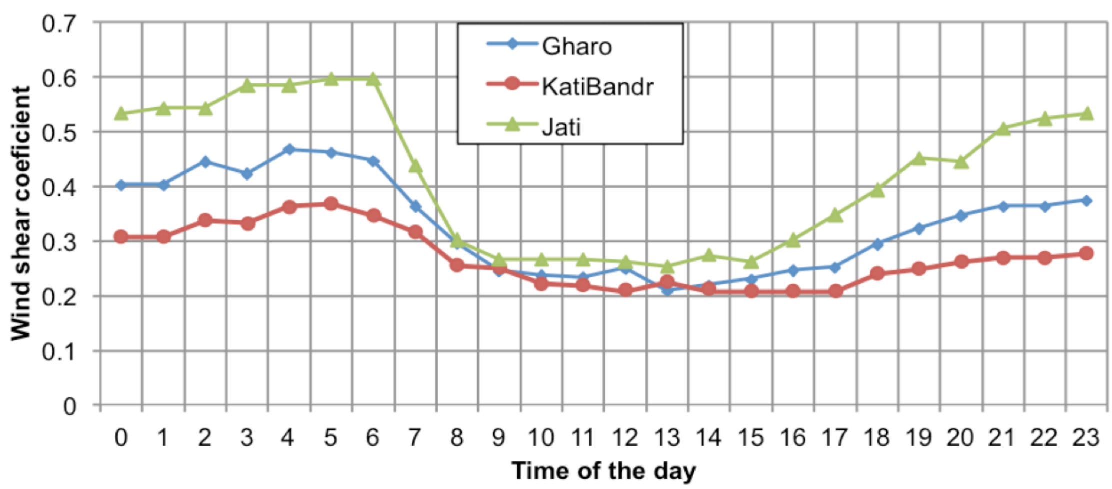

Figure 4: Diurnal variation of 10m to 30 m WSC measured at the three monitored sites.

variations are shown in Figure **4**. It is evident that the heating and cooling phase of air adjacent to the earth during 24 hours of the day influences the WSC. The diurnal heating/cooling effect on the variations of WSC can be seen in (Figure **4**). In the early hours of the day, i.e. between 00:00 and 06:00 hours, the temperature near the ground is greater than at upper heights due to solar irradiation, higher and nearly constant values of WSC were monitored. Whereas, from 06:00 hours onwards, as temperature of the earth surface and the air on top of it increases, values of WSC decreases and after attaining a minimum value at 08:00 hours, remain stable up to 15:00 hours. After 15:00 hours, the values of WSC increases again and reaches a maximum value at 19:00 hours and remains steady during rest of the night time, thus producing large wind shear. This pattern is in agreement with a number of findings in literature [6, 17,20, 28].

3.2. The Effect of WSC on Extrapolating the Wind Speed at Hub Height

To study the affect of wind shear exponent (α) on the feasibility of wind project, average wind speed from

Table 3: Annual Average Wind Speed at Different Hub Heights Extrapolated Using Site Specific Wind Shear Exponent and Constant Shear Exponent (1/7)

SNO.	Hub height (m)	Average wind speed at hub height at Gharo		Average wind speed at hub height at katiBandar		Average wind speed at hub height at Jati	
		shear exponent (α = 0.146)	shear exponent (α = 0.36)	shear exponent (α = 0.146)	shear exponent (α = 0.29)	shear exponent (α = 0.146)	shear exponent (α = 0.46)
1	50	6.01	6.61	6.59	7.11	5.43	6.32
2	60	6.16	7.0209	6.76	7.50	5.57	6.85
3	70	6.30	7.39	6.91	7.84	5.69	7.34
4	80	6.41	7.7267	7.04	8.15	5.80	7.79
5	90	6.52	8.0376	7.15	8.43	5.90	8.21
6	100	6.62	8.3272	7.26	8.70	5.98	8.61

the three stations listed in Table **2** were used. The measured wind speed data at 10 m and 30 m AGL were first used to estimate the wind shear exponent. These wind shear exponent values were used to estimate the wind speed at 50 m, 60 m, 70 m, 80 m, 90 m and 100 m AGL. the estimated average wind speed from the three stations is listed in Table **3**. It is apparent that the estimated wind speeds are beyond doubt different for both wind shear exponents.

3.3. The Effect of WSC on Estimation of the Energy Output of Wind Turbine

In order to study the effect of wind shear coefficient on the energy yield, estimation of the Energy Output of Wind Turbine was carried out using extrapolated wind speeds at hub heights using both values of (one-seventh and site specific) wind shear coefficient for the exponent. WINDOGRAPHER® software was utilized to estimate energy output for two different circumstances. The wind power curves of the chosen wind turbines are shown in Figure **5**. The technical specifications of the chosen wind turbines are summarized in Table **4**.

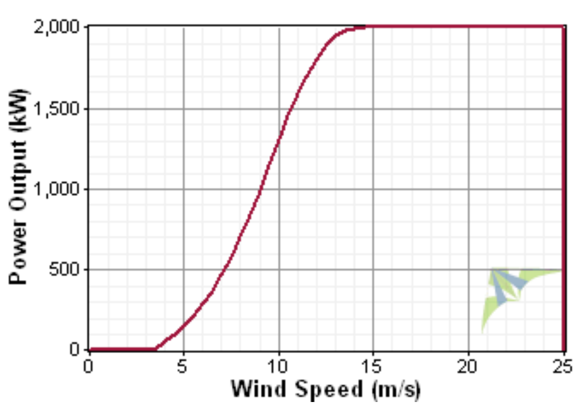

Figure 5: Wind power curve of wind turbine used for energy estimation.

The net energy yield is estimated by considering the array soiling, down time and other losses (9%). A Comparison of Annual energy yield from a 2000 KW wind turbine at Gharo, katiBandar and Jati at 50 m, 60 m, 70 m, 80 m, 90 m and 100m hub heights for both values of the shear exponent is presented in Table **5**.

The annual energy production from the wind turbine at Gharo increases with turbine hub height. 4.33 GWh of energy is produced at 50 m hub height, reaching 6.63 GWh at 100 m height with shear exponent α = 0.36 at katiBandar, 4.9 GWh of energy is produced at 50 m hub height, reaching 6.9 GWh at 100 m height with shear exponent α = 0.29. Whereas 3.88 GWh of energy is produced at 50 m hub height at Jati, reaching 7.11 GWh at 100 m height with shear exponent α = 0.46.

The percent error in the energy estimation for the two wind shear factors and three investigated sites is shown in Figure **6**. It is obvious from the figure that if 10 m wind speed is extrapolated with WSC of 0.143, the energy is underestimated by 16 to 33% at Gharo, 12 to 25% at Katibandar and 28 to 51% at Jati for all considered hub heights. The topography plays an important role, results in a dramatic wind energy yield discrepancy. Actual error in AEP is more where the value of shear exponent is comparatively more. It is obvious from this comparison that WSC of 0.143 used as exponent tends to underestimate the energy production in the cases considered. The results are similar to other studies [17, 22, 28, 29]. These discripences must be adopted when performing pre-feasibility studies for energy production assessments.

3.4. The Financial Analysis

The affect of WSC on the financial assessment of the Wind Power Project is performed with WIND

Table 4: Technical specifications of the wind turbines used in the present analysis

Wind turbine	Rotor diameter (m)	Rated power (KW)	Cut-in speed (ms)	Rated speed (m/s)	Cut-out speed (m/s)
vistas V90	80	2000	3.5	15	25

Table 5: Comparison of Annual Energy Yield from a 2000 kW Wind Turbine at Different Hub Heights for Three Investigated Sites Using Constant Shear Exponent (α = 0.146) and Site Specific Shear Exponent

SNO.	Hub height (m)	Annual energy yield (MWh) at Gharo		Annual energy yield (MWh) at katiBandar		Annual energy yield (MWh) at Jati	
		shear exponent α = 0.36	shear exponent α = 0.146	shear exponent α = 0.29	shear exponent α = 0.146	shear exponent α = 0.46	shear exponent α = 0.146
1	50	4336841	3626889	4905464	4328722	3888307	2782187
2	60	4869896	3830907	5386306	4548644	4622908	2960896
3	70	5359539	4006603	5817389	4737613	5316514	3117062
4	80	5814103	4160993	6210892	4903623	5965409	3255782
5	90	6238548	4298728	6563791	5049716	6560476	3380966
6	100	6636414	4423016	6891566	5183364	7110532	3495036

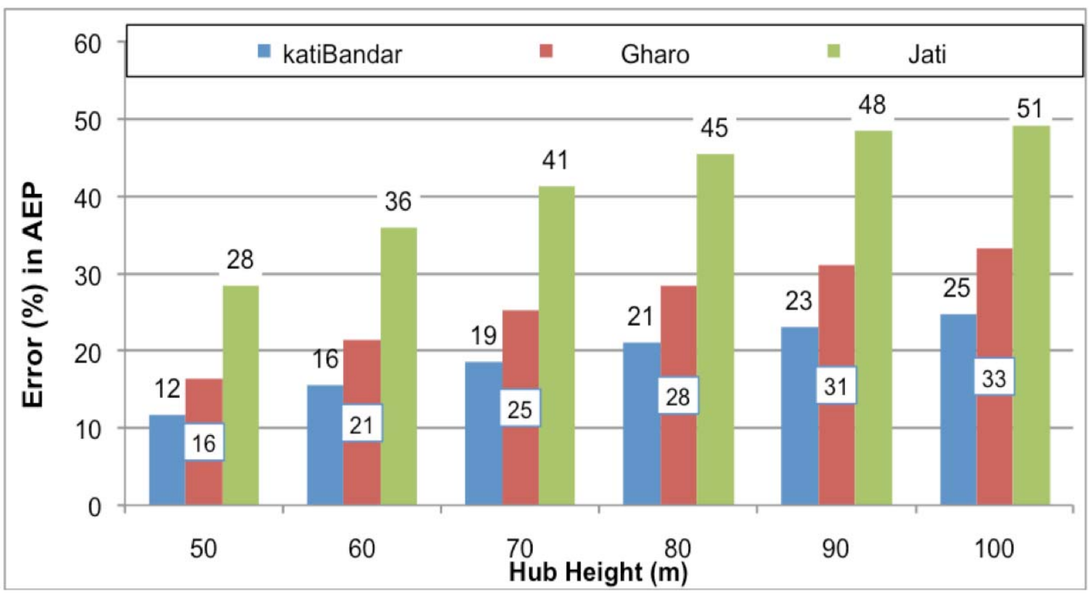

Figure 6: Percent error in annual energy yield for three sites if considering the site specific shear exponent with increase in hub height for a 2000 kW wind turbine.

POWER® software. These costs are addressed from the initial or investment cost standpoint and from the annual or recurring cost standpoint. Its calculated financial feasibility output parameters (e.g. Simple payback, COE $/KWh.) allows the appreciation of the effects of WSC on financial assessment. The following economic indicators are used to assess the effect of WSC on viability of the wind energy project.

3.4.1. The Effect of WSC on the Payback Period of Wind Project

The payback period is chosen to perform a comparative cost/benefit analysis. The simple payback is the number of years it takes for the cash flow (excluding debt payments) to equal the total investment. The purpose of calculating the simple

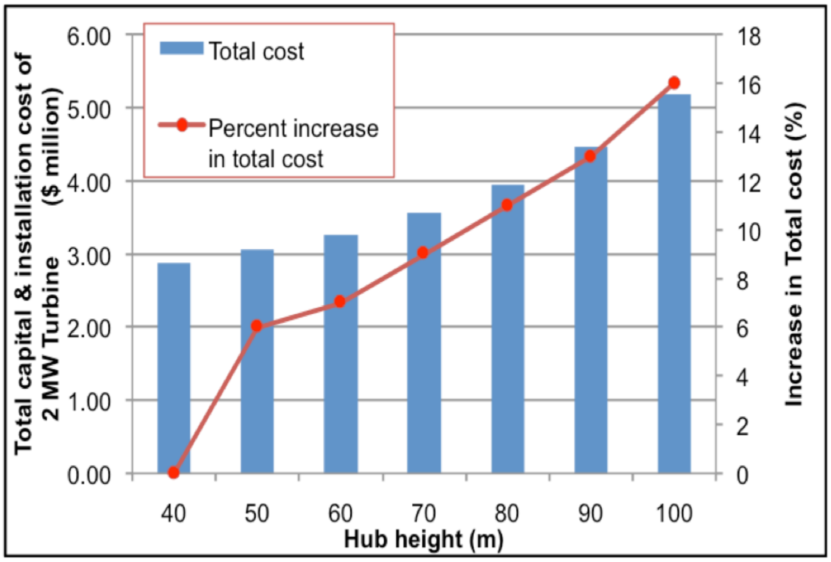

Figure 7: Total incremental cost of a 2000 kW wind turbine.

payback period is to determine the point in time at which the capital invested in a project will be recovered by the annual net income or savings. The simple payback is mathematically defined by relating the capital invested to the annual returns as; the basic premise of the simple payback method is that the more quickly the cost of an investment can be recovered, the more desirable is the investment.

The payback period, calculated in WIND POWER® ,is used to compare the effect of WSC on payback period under different WSC. In order to find the Pay back, the cost of the wind turbine including the capital and installation cost obtained from for hub heights of 40 m to 100 m. The increase in hub height of a turbine is caused by adding the civil construction and installation cost. The cost of the wind turbine as a whole and hub height in addition was estimated by considering various costs [30-32]. The total cost of a wind turbine with incremental hub height is worked out. The Total incremental cost of a 2000 kW wind turbine with hub height is shown in Figure **7**.

Payback period computations at Gharo, Katibandar and Jati sites, reported are in Table **6** when using a single 2000-kW power (Vestas V90) turbine, provided higher Payback period for data extrapolated using the 1/7 factor. Conversely, when data was extrapolated by using site specific WSC, a lower Payback period is observed at all study sites. The percent change in the Payback period estimation for the two wind shear factors and three investigated sites is shown in Figure **8**. It is obvious from the Figure that if 10 m wind data is extrapolated with WSC of 0.143, the Payback period is overestimated by19–34% at Gharo, 16–27% at Katibandar and 31–48% at Jati for all considered hub

Table 6: Comparison of Payback Period (years) from a 2000 kW Wind Turbine at Different Hub Heights for Three Investigated Sites Using Constant Shear Exponent (0.146) and Site Specific Shear Exponent

SNO.	Hub height (m)	payback period (years) at Gharo		payback period (years) at katiBandar		payback period (years) at Jati	
		$\alpha = 0.36$	$\alpha = 0.142$	$\alpha = 0.29$	$\alpha = 0.142$	$\alpha = 0.46$	$\alpha = 0.142$
1	50	6.09	7.52	5.25	6.08	6.73	9.78
2	60	5.78	7.46	5.22	6.32	6.12	9.52
3	70	5.7	7.85	5.2	6.48	5.70	9.95
4	80	5.77	8.41	5.44	7	5.77	10.57
5	90	6.26	9.51	5.8	7.7	6.02	11.00
6	100	6.74	10.3	6.3	8.7	6.52	12.70

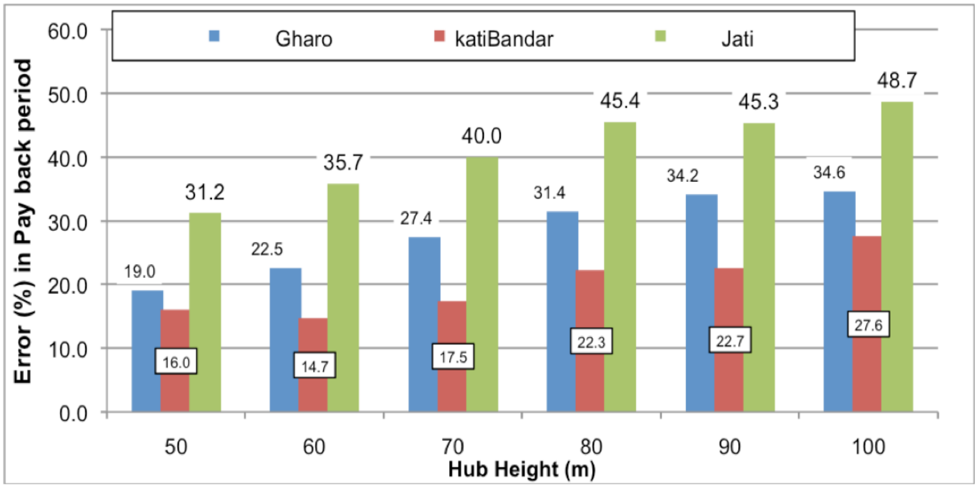

Figure 8: Percentage error in payback period for three investigated sites if considering the site specific shear exponent with increase in hub height for a 2000 kW wind turbine.

heights. It is evident from this that the 1/7 power law, or wind shear factor of 0.143, tends to overestimate the Payback period.

3.4.2. Comparison of the Cost of Wind Energy

There are several factors affecting the unit energy cost of electricity produced in the wind turbines. WSC played vital role in this regard because in vertical speed extrapolation, different speed values may be observed at considered.In general, the cost per unit energy is found by dividing the amount of energy produced to the total expenditures made in the certain time interval. COE computations at Gharo, Katibandar and Jati sites with different shear exponent is summarized in Table **7** and the corresponding percentage of error in COE (cent/kWh) with increasing hub height are shown in Figure **9**. From the cost analysis, it is seen that cost of energy output at considered heights is minimum for Katibander and is maximum for Jati. It is obvious from Figure **9** that if 10 m wind data is extrapolated with WSC of 0.143, the COE is overestimated by 19-34% at Gharo, 16-27% at Katibandar and 31-48% at Jati for all considered hub heights. It is evident from this Figure that the 1/7 power law or wind shear factor of 0.143, tends to overestimate the COE and shows that error increases with increasing WSC. Error is highest for Jati (31-48.9%) with shear coefficient of 0.46. The minimum error is for katibandar (16.2-27.4%) with shear coefficient of α = 0.29.

4. CONCLUSION

The aim of this study was to investigate the accuracy of generally used wind shear Power law (1/7 power law) and site specific WSC for exponents and its influence on the power production of a wind turbine, payback period and cost of energy. Four year wind speed data at 10 m and 30 m, above ground level were used to obtain the site specific WSC for three coastal sites in Southern Pakistan i.e., gharo, katibandar and

Table 7: Comparison of COE (cent/KWh) from a 2000 kW Wind Turbine at Different Hub Heights for Three Investigated Sites Using Constant Shear Exponent (0.146) and Site Specific Shear Exponent

SNO.	Hub height (m)	Cost (Cents/KWh) at Gharo		Cost (Cents/KWh) at katiBandar		Cost (Cents/KWh) at Jati	
		α = 0.36	α = 0.142	α = 0.29	α = 0.142	α = 0.46	α = 0.142
1	50	3.04	3.76	2.63	3.14	3.37	4.89
2	60	2.89	3.73	2.61	3.26	3.06	4.76
3	70	2.84	3.79	2.60	3.24	2.99	4.76
4	80	3.01	4.21	2.66	3.50	2.88	5.28
5	90	3.13	4.45	2.81	3.75	3.01	5.60
6	100	3.37	5.16	3.16	4.35	3.26	6.38

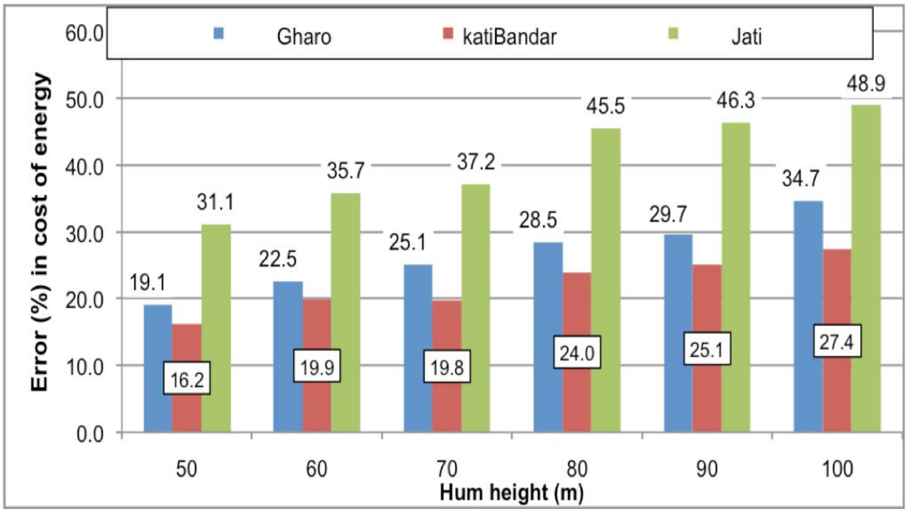

Figure 9: Percentage error in cost of energy for three sites if considering the site specific shear exponent with increase in hub height for a 2000 kW wind turbine.

jati. It has been demonstrated that the vertical wind profile, or the wind shear coefficient α, can change drastically depending on the time of day and the season. There is also a large change in the value of α depending on the time of day. α decrease during the day and increases during the nocturnal hours. The monthly variation showed lowest during the summer months and maximum values during the winters. These wind shear exponents were utilized to extrapolate the wind speed to various hub heights (50,60,70,80,90,and 100 m). Effect of WSC on viability of wind projects was studied with the help of annual energy yield, payback period and COE. If 10 m wind data is extrapolated using WSC of 0.143 instead of site specific WSC, a dramatic underestimation in case of Katibandar AEP 12 to 25% is observed, for gharo it was 16 to 33%. Whereas for Jati an underestimation of 28 to 51% is obtained. The error in the payback period estimation it increases with increasing WSC, with highest error obtained for Jati (31- 48.7%) using shear coefficient of 0.46. The minimum error is obtained for katibandar (16.2-27.4%) using shear coefficient of α = 0.29. the error in COE increases with increasing hub height. It shows that error also increases with increasing WSC and highest error is obtained for Jati (31- 48.9%) using shear coefficient of 0.46. The minimum error is for katibandar (16.2-27.4%) using shear coefficient of α = 0.29. To conclude, it is confirmed that 1/7 WSC default value could mislead the viability of wind project and should be avoided. Furthermore, the 1/7 default value of WSC should be used with caution for wind energy purposes to extrapolate 10 m wind speed aloft. This study showed a dramatic difference in long term measured WSCs to occur even over locations apparently of the same type.

REFERENCES

[1] Mohandes M, Rehman S, Rahman SM. Appl Energy 2011; 88: 4024-32. http://dx.doi.org/10.1016/j.apenergy.2011.04.015

[2] Frehlich R. IEEE Journal of Selected Topics in Applied Earth Observations And Remote Sensing 2008; 1(1): 42-47. http://dx.doi.org/10.1109/JSTARS.2008.2001758

[3] Del Franco M. Wind Power 2012; 9: 36-38.

[4] Peterson EA. Journal of Applied Meteorology 1977; 17: 390-394. http://dx.doi.org/10.1175/1520-0450(1978)017<0390:OTUOPL>2.0.CO;2

[5] Schwartz M, Elliott D. Proceedings of the 15th Conference on Applied Climatology, Savannah, Georgia, USA 2005.

[6] Sisterson DL, Frenzen P. Environmental Science & Technology 1978; 12(2): 218-221. http://dx.doi.org/10.1021/es60138a014

[7] Farrugia RN. Renewable Energy 2003; 28: 647-653. http://dx.doi.org/10.1016/S0960-1481(02)00066-6

[8] Schlichting H, Gersten K. Boundary-Layer Theory, 8th Edition, Springer-Verlag, Berlin Heidelberg, Germany 2000; pp. 286, 422, Chap. 10 & 15.

[9] Antoniou Pedersen SM. European Wind Energy Conference 2009.

[10] Manwell JF, McGowen Rogers AL. Wind Energy Explained: Theory, Design, and Application, Second Edition, Wiley & Sons, West Sussex, UK 2009; pp. 46-47, Chap.2.

[11] Bechrakis DA, Sparis PD. Wind Eng 2000; 24(2): 127-36. http://dx.doi.org/10.1260/0309524001495503

[12] Sisterton DL, Hicks BB, Coulter RL, Wesely ML. 1983; 31(2): 201-4.

[13] Rehman S, Al-Abbadi NM. 2007; 32: 738-49.

[14] Sandia National Laboratories. Global Energy Concepts, LLC, USA 2003.

[15] Tar K. Renew Sustain Energy Rev 2008; 12: 1712-24. http://dx.doi.org/10.1016/j.rser.2007.01.014

[16] Rogers AL. Technology Collaborative, FSRP0040-B 2008.

[17] Giovanni G, Sauro S. Renewable Energy 2011; 36: 1081-1094. http://dx.doi.org/10.1016/j.renene.2010.09.001

[18] Bechrakis DA, Sparis PD. Wind Engineering 2000; 24(2): 127-136. http://dx.doi.org/10.1260/0309524001495503

[19] Maeda T, Shimizu Y, Kamada Y, Homma S, Nakano M, Yokota T. Proceedings of European Wind Energy Association Conference, Madrid 2003.

[20] Fırtın E, Guler O, Akdag SA. Applied Energy 2011; 88: 4097-4105. http://dx.doi.org/10.1016/j.apenergy.2011.05.025

[21] Shata ASA, Hanitsch R. Renew Energy 2006; 32: 1183-202. http://dx.doi.org/10.1016/j.renene.2005.06.015

[22] Rehman S, Al-Abbadi NM. Energy Convers Manage 2005; 46: 2578-91. http://dx.doi.org/10.1016/j.enconman.2004.12.005

[23] Salzer H. wind energy. dordrecht (holland): d. reidel publishing co 1989.

[24] Wind Power program (Version 2.01) http://www.wind-power-program.com.

[25] Wind Power Potential of Sindh. Pakistan Meteorological Department. Technical Report 2007; no. PMD-07. URL: http://www.met.gov.pk/Projects/Wind_Project.html.

[26] Lange M, Focken U. Physical Approach to Short-Term Wind Power Prediction, Springer 2005.

[27] Bailey BH. Proceedings of the International Colloquium on Wind Energy, British Wind Energy Association, Brighton, UK, 1981; pp. 11-16.

[28] Greene S, McNabb K, Zwilling R, Morrissey M, Stadler S. Int J Global Energy 2009; 32: 191-211. http://dx.doi.org/10.1504/IJGEI.2009.030651

[29] Daniel C. Bratton Carole A. Womeldorf. Proceedings of the ASME 2011 5th International Conference on Energy Sustainability, USA 2011.

[30] Shafiqur Rehman AC, Al-Hadhrami LM, Alam M, Meyer JP. Sustainable Energy Technologies and Assessments 2013; 4: 45-51. http://dx.doi.org/10.1016/j.seta.2013.09.003

[31] Quraeshi S. Solar & Wind Technology 1987; 4(I): 55 58. http://dx.doi.org/10.1016/0741-983X(87)90008-7

[32] Morthorst PE. Costs and prices: wind energy - the facts, vol. 2. http://www.ewea.org/fileadmin/ewea_documents/documents/publications/WETF/Facts_Volume_2.pdf (accessed September, 2013).

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