Empirical Correlation between Hub Height and Local Wind Shear Exponent for Different Sizes of Wind Turbines

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ABSTRACT

Alarmingly increasing rates of adverse environmental happenings have lead the people from all walks of life towards utilization of clean and renewable sources of energy. Due to technological advancement and availability of efficient wind turbines of few tens of kilowatts to multi-mega-watt seizes which covers all human applications have made the utilization of wind power as the technology of choice. For its optimal utilization, site dependent analysis of the wind and its variation with height and then economics of increasing the tower height (hub height) have become necessary factors. This paper proposes a new correlation for the estimation of optimal hub height for harnessing the power of the wind on economically competitive basis. For this purpose, seven empirical correlations have been developed for seven sites for wind turbines of rated power of 600 to 5000kW. Wind speed measurements made at 20, 30, and 40 meters at seven sites have been used in the present work.

Keywords: Wind speed, wind power, hub height, wind shear exponent, wind turbine

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1. Introduction

In this highly competitive, extremely materialistic and up-to-date know how scenario, smart and optimal utilization of sources of energy has become essential. Exponentially increasing global and regional population, widening of gap between the production and demands of essential commodities, environmental pollution levels, and resulting adverse climatic changes, have become the matters of concern to individuals, engineers, environmentalists, and even politicians in the recent years. To conserve fossil fuel and combat the adverse effects of changing climatic conditions on the environment, clean and renewable sources of energy are being developed and utilized on global, regional, and local scales both onshore and offshore. Still, there are more than 2billion people who have not experienced the delight of grid connected electricity both in developed and developing countries [1]. Due to fast wind power generation technology development, commercial acceptability, robust design, ease of operation and maintenance, and economic compatibility with traditional sources of energy; power of the wind is being utilized globally for both grid connected utility scale and small isolated grid applications. It is very important and critical to conduct wind resources assessment of the site of interest because the energy output is highly dependent on the wind conditions of the geographical location [2-4].

Wind power is a clean, economical, and intermittently available source of energy. Today's modern wind turbines can be installed quickly and easily. It is the leading electricity generation technology in the fight against climate change, enhancing energy security, stabilizing electricity prices, cleaning up air and creating thousands of jobs in the manufacturing sector. Global Wind Energy Council's (GWEC's) prediction of 12% growth in the wind sector was generally greeted with disbelief and derision but the global market grew by 41% in 2009, demonstrating that wind power is increasingly the power technology of choice. The annual cumulative wind power installed capacity reached 237.669 GW in 2011 compared to 197.637GW in 2010 and 158.5GW in 2009, an increase of 20.62% and 24.69%, respectively, GWEC [5]. This represents a year-on-year growth of 31.7%. One third of these additions were made in China, which doubled its installed capacity yet again. Since 2005, the global wind power growth has been always been more than 25%. For the second consecutive year, Asia remained the world's largest regional market for wind energy, with capacity additions amounting to 20.929GW and 15.4GW in 2011 and 2010, respectively.

Wind speed increases with height which means more power at higher hub heights [6]. Furthermore, hub height optimization is a key towards profitable wind power projects. Hub height is defined as the distance between the platform and the rotor of the wind turbine [7], as shown in Fig. 1. The additional cost for higher hub heights differs greatly from one manufacture to another [8]. According to Hoffmann et al. [8], the profitability can be enhanced from 2.1% to 37.6% by choosing the optimal available hub height rather than standard hub height provided by the manufacturer. The height of the hub of a wind turbine can determine success or failure of the wind power project. There are two primary factors to be considered when determining how high a tower need to be to enable a wind turbine to be effective and efficient [9]. The first factor is that the wind speed increases with height. Hence a wind turbine will be able to extract more power from the wind if it is installed on a higher tower. The second consideration when determining the hub height is the minimization or avoidance of the turbulence. Turbulence decreases the effectiveness of the turbine resulting in decreased electricity generation and tends to increase the wear and tear on the turbine resulting in increased maintenance and decreased operational life.

Wind is a naturally occurring phenomenon and is beyond human's manipulation, but there is one thing that can be done to increase the wind speed experienced by a wind turbine at a given location; go upwards by increasing the tower height [10]. As mentioned in reference [10], as wind gets closer to the ground it loses some of its speed due to friction as it rubs against any 'surface roughness'. For each 1 meter increase in the hub-height of a farm wind turbine the annual energy production increases by 1%, [10]. According to Firtin et al. [11], a difference of up to 49% in energy yield may be obtained if using extrapolated wind data based on constant values of wind shear exponent and energy production using measured wind data at hub height. Therefore it is preferable financially to opt for the highest tower available for wind turbine installation. In modern times, wind turbines have been made larger and softer to increase profitability. Due to this technological advancement in wind turbines sizes, tower optimization becomes more important, as towers account for 20–30% of turbine cost Yoshida [12]. Yoshida [12] developed a wind turbine tower optimization program using a genetic algorithm which allowed a rational analysis to reduce the mass of turbine towers by considering the distributions of its diameter and wall thickness, and the positions of flanges and access ports to navigation lights.

The present work utilized wind speed measurements made at 20, 30, and 40 meters above ground level at Arar, Dhahran, Dhulom, Gassim, Juaymah, Rawdat Ben Habbas (RBH) and Yanbo stations in Saudi Arabia in conjunction with wind turbines of rated power of 600, 1000, 2000, 3000, 3600, and 5000kW for the development of empirical correlations to determine the optimal height as a function of local wind shear exponent. The local wind shear exponent is determined using wind measurements at different heights at these sites as reported in [13-19]. The next section provides the procedure adopted over reaching the proposed empirical correlations.

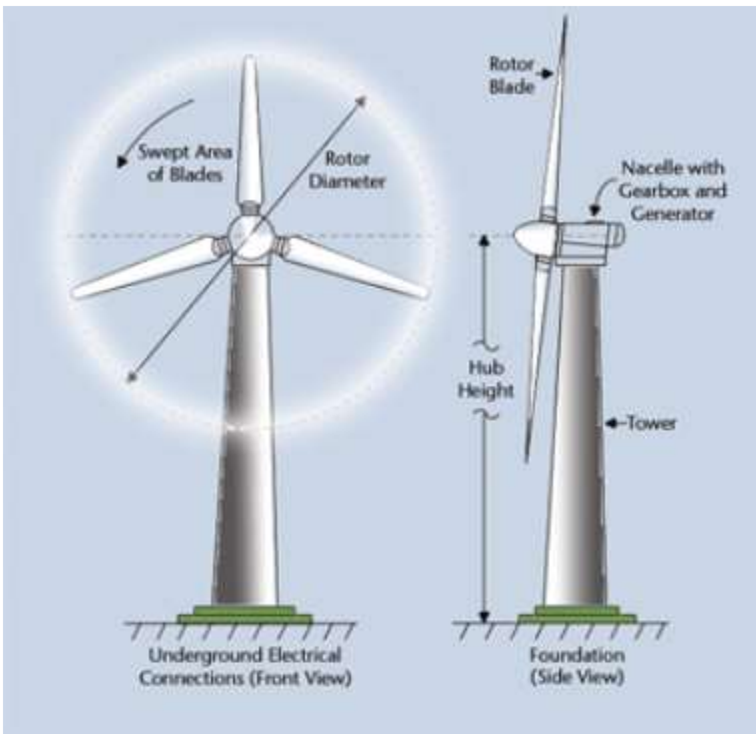

Fig. 1. Pictorial representation of wind turbine hub height [7]

2. Procedure for Empirical Model Development

An attempt has been made to develop an empirical model for the estimation of near optimal hub height based on local wind shear exponent. To the best of author's knowledge, this will be the first attempt towards development of an empirical model for the estimation of optimal hub height. Following steps are followed to the set objective:

1. Annual energy yield is estimation for a chosen wind turbine of certain rated power (600, 1000, 2000, 3000, 3600, and 5000kW in the present case) at different hub heights (40, 50, 60, 70, 80, 90, 100, 110, 120 m in the present case)
2. Estimation of percent increase in annual energy yield for each 10m increases in hub height
3. Cost of chosen wind turbine (capital + installation + operation + maintenance)
4. Estimation or assumption of percent incremental total cost for each 10m increase in hub height
5. Plotting of percent incremental change in annual energy yield and the corresponding percent costs against hub height increase
6. The point where the two curves cross each other is taken as the optimal or near optimal hub height

The point at which the two curves cross each other, the percent rate of increase in annual energy yield becomes very small and the rate of increase in percent total cost starts increasingly higher and higher.

3. Data and Site Description

The geographical details including the latitude, longitude and the altitude of all the stations are summarized in Table 1. The wind speed measurements were made at 20, 30 and 40 meters above ground level (AGL) and the wind direction sensors were installed at 30 and 40m AGL, as shown in Fig. 2. The meteorological sensors such temperature, relative humidity, pressure, and global solar radiation were installed at 1.5m AGL. The technical specifications of all the sensors used in this study are summarized in Table 2. The values of local WSE are summarized in Table 3.

Table 1
Site specific information of data collection stations.

Location	Latitude (°)	Longitude (°)	Altitude (m)	Period
Rawdat Ben Habbas	29.14°N	44.33˚E	443	Sep. 2005 to Apr. 2010
Juaymah	26.80°N	49.90˚E	20	Jul. 2006 to Apr. 2009
Dhahran	26.10°N	50.10°E	3	Oct. 1995 to Nov. 2000
Arar	30.80˚N	41.30˚E	550	Jun. 1995 to Dec. 1998
Gassim	26.30°N	43.97°E	648	Dec. 1995 to Oct. 1998
Yanbo	23.90°N	38.30°E	11	Sep. 1996 to Oct. 1999
Dhulom	22.74°N	42.18°E	1117	Nov. 1998 to Oct. 2002

Table 2
Details of the equipment installed at an isolated village.

Item Description	Technical Information
Wind speed sensor, NRG#40	AC sine wave, Accuracy: 0.1 m/s, Range: 1-96 m/s
Three cup anemometer	Output: 0-125 HZ, Threshold: 0.78 m/s
Wind direction vane, NRG#200P	Accuracy: 1%, Range: 360^o Mechanical, Output: 0-Exc. Voltage,
Potentiometer	Threshold: 1 m/s, Dead band: Max - 8^o and Typical 4^o
Temperature sensor #110S	Accuracy: ±1.1 ^{o}C, Range: -40 ^{o}C to 52.5 ^{o}C, Output: 0 – 2.5 volts
Integrated circuit	DC, Operating temperature range: -40 ^{o}C to 52.5 ^{o}C
Barometric pressure sensor BP20	Accuracy: ±15 mb, Range: 150 – 1150 mb, Output: Linear voltage
Relative humidity sensor RH-5	Accuracy: ±5%, Range: 0 – 95 %
Polymer resistor	Output: 0 – 5 volts, Operating temperature range: -40 ^{o}C to 54 ^{o}C
Pyranometer Li-Cor #LI-200SA	Accuracy: 1%, Range: 0 – 3000 W/m^2 , Output: Voltage DC,
Global solar radiation	Operating temperature range: -40 ^{o}C to 65 ^{o}C

Fig. 2. Wind and meteorological data measurement tower.

Table 3
Site dependent roughness length, class and description.

Location	WSE	Roughness length, m	Roughness class	Roughness description
Rawdat Ben Habbas	0.302	1.81	4.41	Suburban
Juaymah	0.228	0.239	2.72	Many trees
Arar	0.181	0.138	2.27	Few trees
Dhahran	0.161	0.056	1.52	Crops
Gassim	0.249	1.070	3.97	Suburban
Yanbo	0.073	0	0	Smooth
Dhulom	0.185	0.134	2.25	Few trees

4. Hub Height Optimization Correlation

To establish empirical correlations of optimum hub height (HH) with wind shear exponents, ten minutes average wind speed data from seven stations listed in Table 1 was used. The measured wind speed data at 20, 30, and 40m above ground level was first used to estimate the wind shear exponent. These wind shear exponent values (given in Table 3) were sued to estimate wind speed at 50, 60, 70, 80, 90, and 100m AGL. For wind turbines of 2000, 3000 and 4000, and 5000kW the wind speeds were extrapolated to 110 and 120m as well. As third step, these extrapolated wind speed values were used in conjunction with wind power curves of chosen wind turbines from different manufacturers to estimate the energy output. The wind power curve of the chosen wind turbines are shown in Fig. 3. The technical specifications of the chosen wind turbines are summarized in Table 4. The resulting annual wind energy yields from 1000kW rated power (Model AAER A-1000) wind turbine at different heights for all the stations are summarized in Table 5 and are also compared in Fig. 4. It is evident from data given in Table 5 and the Fig. 4, that energy yield increases with increasing hub height.

The corresponding percent increases in annual energy yield with increase in hub height are summarized in Table 6. As seen from Table 6, maximum increase in annual energy is observed while increasing hub height form 40 to 50m. In order to find out the optimal hub height, the cost of wind turbine including the capital and installation cost was obtained from Morthorst [20] to be 900Euro/kW for a hub height of 40meters. The cost of the wind turbine as a whole and hub height in addition has been estimated by considering various costs such as blades, hub, pitch mechanisms and bearings, spinner, nose cone, drive train, nacelle, low-speed shaft, bearings, gearbox , mechanical brake, high-speed coupling, and associated components, generator, variable-speed electronics, yaw drive and bearing, main frame, electrical connections, hydraulic and cooling systems, nacelle cover, control, safety system, and condition monitoring, tower, foundation/support structure, transportation, assembly and installation, electrical interface/connections, and engineering permits.

The increase in hub height of a turbine basically adds the civil construction and installation cost which varies from 6 to 20% of the total investment cost. Based on initial cost and incremental cost, the total cost of wind turbine with incremental hub height was worked out to be as summarized in Table 7. As next step, the percent increase in energy yield and the total wind turbine cost with increasing hub height for 1000kW rated power wind turbine is plotted for each station, as shown in Figs. 5(a) to 5(g) for Arar, Dhahran, Dhulom, Gassim, Juaymah, Rawdat Ben Habbas (RBH) and Yanbo, respectively. The optimal hub height is defined as the height where two curves cross each other. For Arar, as seen from Fig. 5(a), the two curves cross each other at point where the hub height is 68meters. Similarly the optimal hub heights for Dhahran, Dhulom, Gassim, Juaymah, and Raddat Ben Habbas were found to be 64, 66, 81, 70 and 82 meters, respectively as can be seen from Figs. 5(b) to 5(f). In case of Yanbo [Fig. 5(g)], the two curves did not cross each other due to abnormally small value of wind shear exponent, so the optimal hub height is assumed to be 50m in this case.

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)
Suzlon S.52	52	600	4	13	25
AAER A-1000	58	1000	3	12	22
Repower MM92	92.5	2000	3.5	11	24
Vestas V112	112	3000	2.5	11	25
Siemens SWT-3.6	107	3600	3	14	25
Repower 5M	126	5000	3.5	13	25

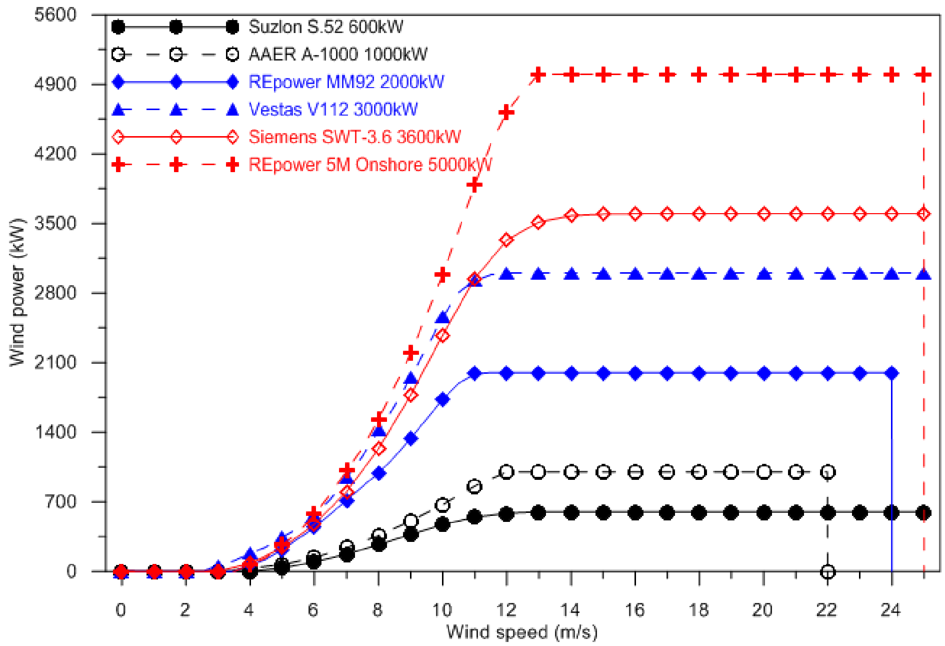

Fig. 3. Wind power curves of wind turbines used for energy estimation.

Table 5
Annual energy yield from 1000kW wind turbine at different hub heights.

HH	Annual energy yield (MWh)						
	Arar	Dhahran	Dhulom	Gassim	Juaymah	Rawdat	Yanbo
40	1225.4	1137.9	1162.5	635.2	1338.0	1256.8	988.4
50	1353.3	1252.9	1451.9	758.6	1530.3	1533.7	1029.6
60	1467.4	1355.4	1585.2	880.4	1703.1	1774.9	1067.9
70	1594.9	1446.3	1703.5	996.0	1858.4	2008.9	1101.0
80	1700.1	1528.0	1810.1	1109.1	2008.8	2251.2	1130.2
90	1796.5	1602.5	1907.0	1206.1	2125.9	2409.8	1156.3
100	1884.9	1670.7	1995.8	1324.9	2243.4	2664.5	1180.0

The energy yield and respective percent increase with incremental change in hub height was calculated for wind turbines of rated power 600, 2000, 3000, 3600, and 5000kW and data similar to what presented in Tables 5 and 6 and Fig. 4 was obtained. To find out the optimal height, the percent increase in energy yield and the cost were plotted for above wind turbines similar to Fig. 5, but are not shown here to contain the length of the paper.

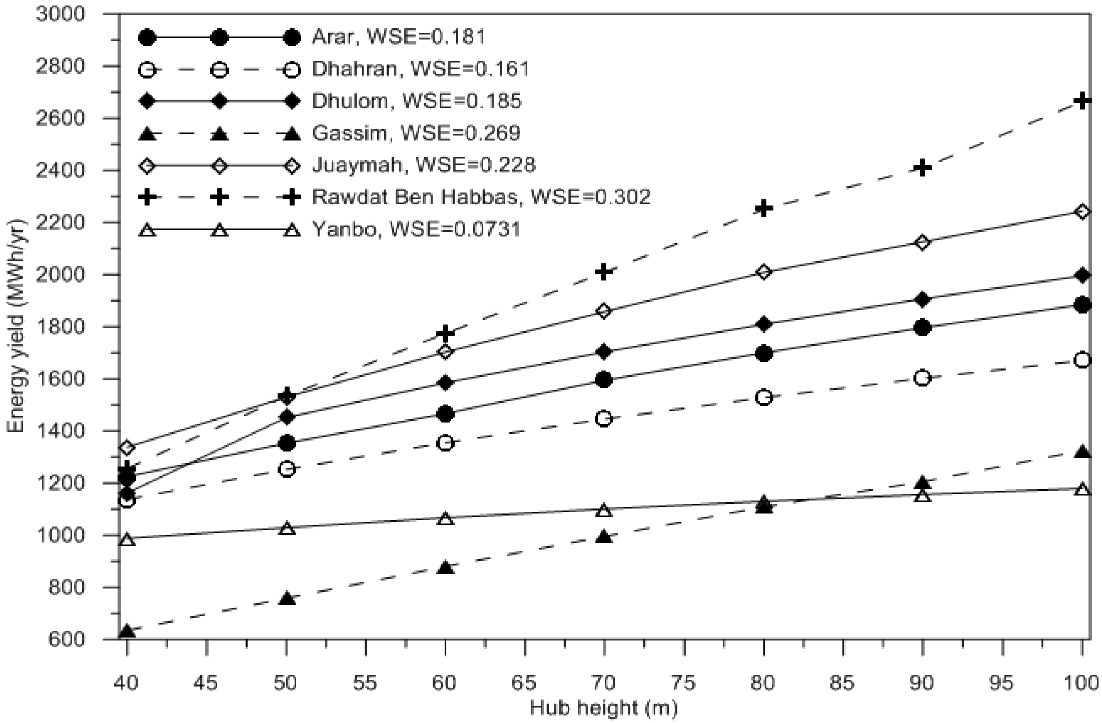

Fig. 4. Comparison of annual energy yields from 1000kW wind turbine at different hub heights with wind shear exponents.

Table 6
Percent increase in annual energy yield with increase in hub height for 1000kW wind turbine.

HH	Percent increase in annual energy yield with change in hub height						
	Arar	Dhahran	Dhulom	Gassim	Juaymah	Rawdat	Yanbo
40	-	-	-	-	-	-	-
50	10.4	10.1	24.9	19.4	14.4	22.0	4.2
60	8.4	8.2	9.2	16.1	11.3	15.7	3.7
70	8.7	6.7	7.5	13.1	9.1	13.2	3.1
80	6.6	5.7	6.3	11.3	8.1	12.1	2.6
90	5.7	4.9	5.4	8.7	5.8	7.0	2.3
100	4.9	4.3	4.7	9.8	5.5	10.6	2.0

Table 7
Total incremental cost of 1000kW wind turbine.

HH	Total capaital and installation cost of 1000kW wind turbine (Euro)	Percent increase in total cost
40	900,000	-
50	954,000	6
60	1,020,780	7
70	1,112,650	9
80	1,235,000	11
90	1,395,600	13
100	1,618,900	16

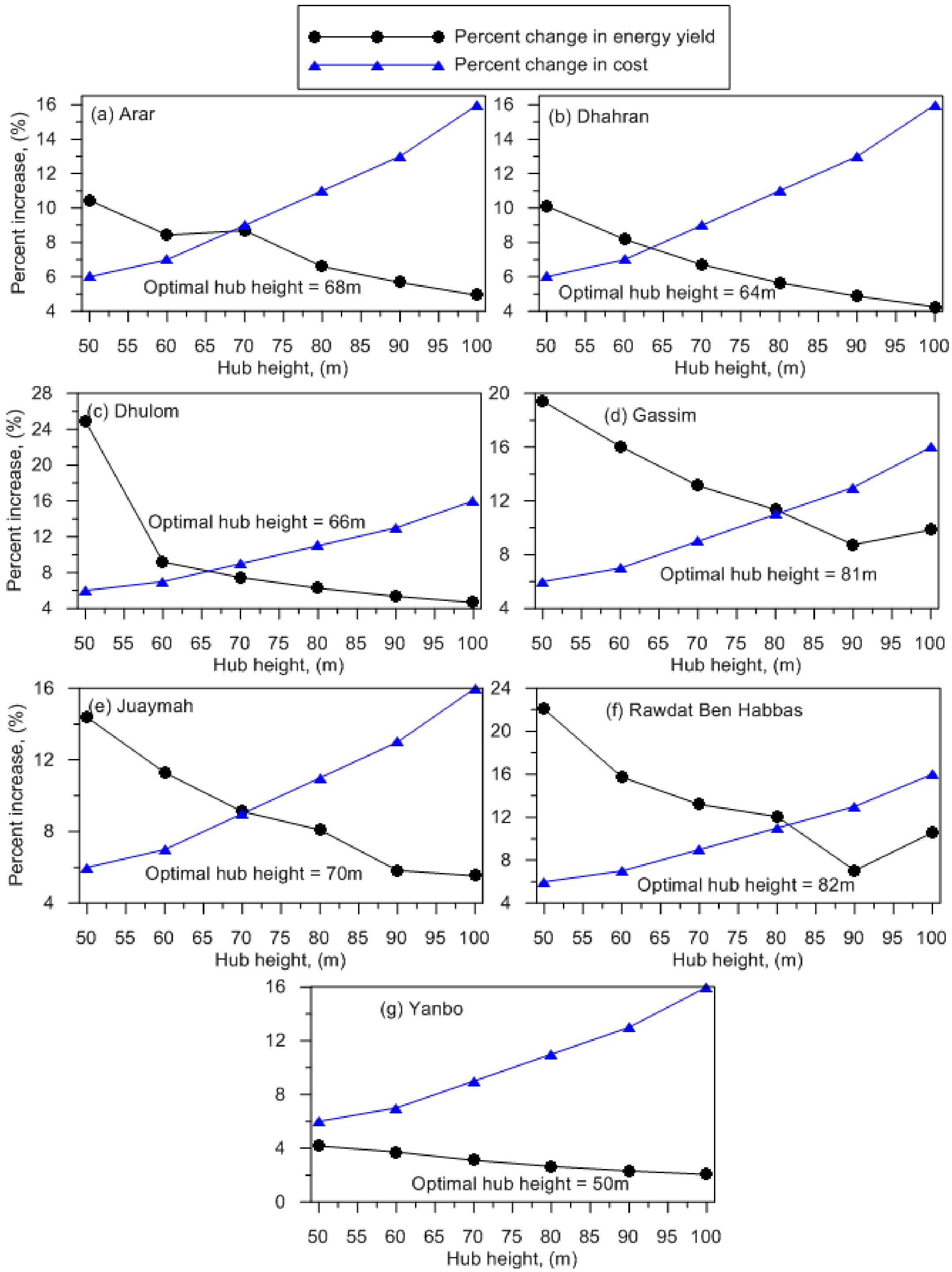

Fig. 5. Percentage increase in energy yield from 1000kW wind turbine and the total cost of installation with increasing hub height.

Finally, in order to find an empirical relation between optimal hub height and the wind shear exponent (α), the two are plotted in Fig. 6(a) and best fit curves were obtained for 600kW wind turbine. Three types of best fit curves obtained for 600kW wind turbine are viz. Linear fit

(Equation 1), Log fit (Equation 2), and Power fit (equation 3). The values of the coefficient of determination for the three best fit curves were found to be 0.97, 0.94, and 0.97, respectively. The linear and power fit equations were found to be the best approximation of optimal hub height with wind shear exponent given by equation 1 and 3. Similar types of correlations were obtained for 1000kW, 2000kW, 3600kW, and 5000kW wind turbines as shown in Figs. 6(b), 6(c), 6(d), 6(e), and 6(f); respectively. The resulting empirical equations (linear, log and power fit) along with square of coefficient of determinations are summarized in Table 8. As observed form the data in Table 8, the best correlation was obtained for wind turbine of 1000kW rated with R^2 value always more than 95%. Among three approached used for obtaining the empirical correlations, power law yielded in the best results whereas R^2 values was concerned.

Linear fit equation:

HH = 142.035 * (α) + 40.33 (1)

Residual sum of squares = 20.30 Coeff. of determination, R-squared = 0.97

Residual mean square, sigma-hat-sq'd = 4.06

Log fit equation:

HH = 22.533 * ln(α) + 106.79 (2)

Residual sum of squares = 46.357 Coeff. of determination, R-squared = 0.94

Residual mean square, sigma-hat-sq'd = 9.27

Power fit equation:

ln(HH) = 0.35 * ln(α) + 4.81 (3)

Alternate (HH) = [(α)**0.3501] * 122.7449

Residual sum of squares = 0.0055 Coeff. of determination, R-squared = 0.97

Residual mean square, sigma-hat-sq'd = 0.0011

Table 8
Hub height estimation empirical correlations for different ranges of rated power of wind turbines.

Rated Power (kW)	Empirical correlation			Correlation coefficient (R^2)		
	Linear	Log	Power	Linear	Log	Power
600	154.49*x+41.55	25.33*ln(x)+115.22	0.342*ln(x)+4.916	0.81	0.83	0.86
1000	142.03*x+40.33	22.53*ln(x)+106.79	0.331*ln(x)+4.810	0.97	0.94	0.97
2000	127.12*x+55.16	21.57*ln(x)+117.03	0.297*ln(x)+4.872	0.75	0.82	0.84
3000	129.95*x+55.17	22.09*ln(x)+118.48	0.291*ln(x)+4.889	0.76	0.84	0.86
3600	145.75*x+56.08	25.26*ln(x)+127.89	0.350*ln(x)+4.994	0.80	0.92	0.91
5000	150.58*x+56.45	26.27*ln(x)+130.93	0.384*ln(x)+5.027	0.78	0.91	0.91

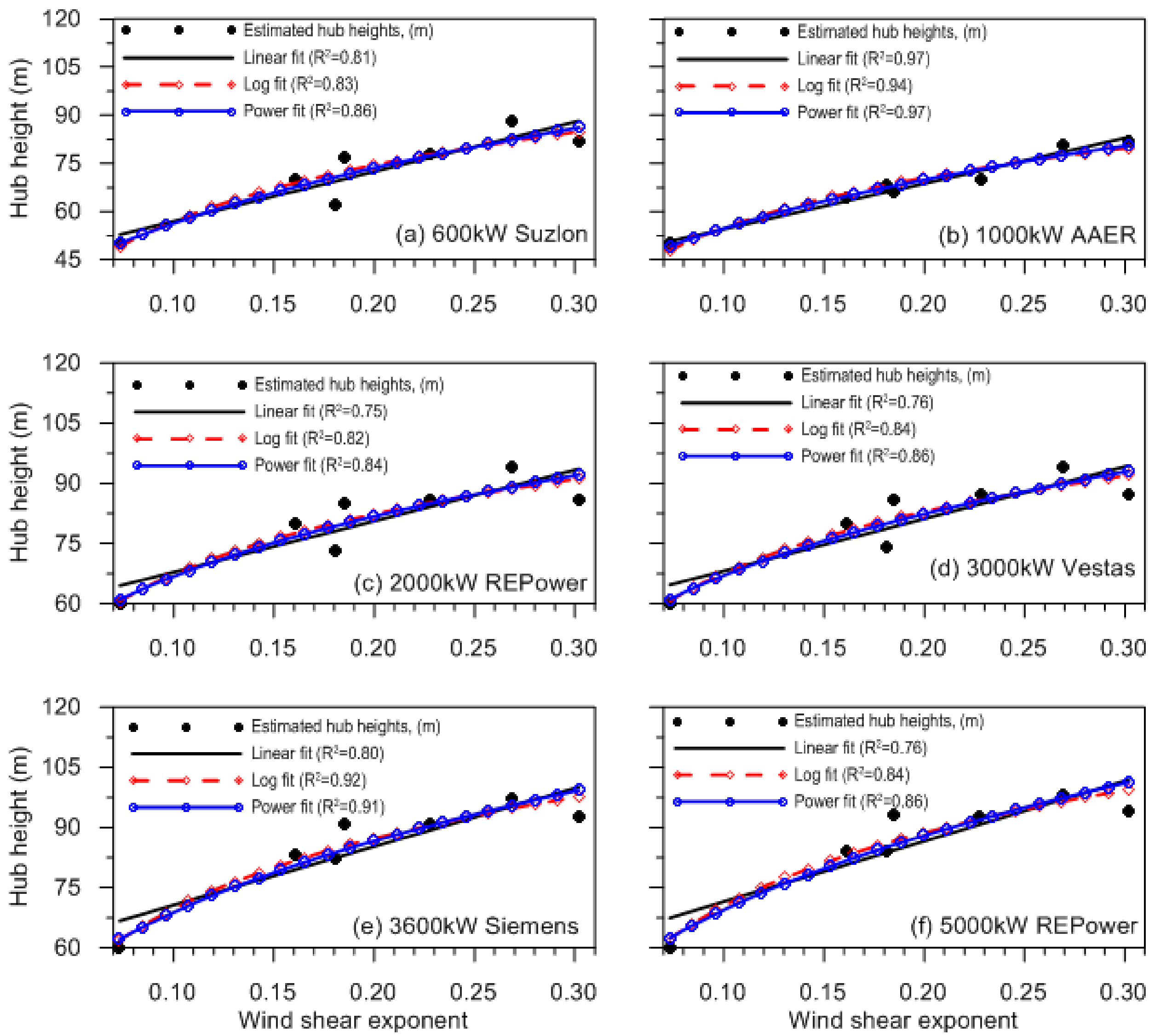

Fig. 6. Optimal hub height variation with wind shear exponent.

5. Conclusions

In the present study, as attempt has been made to correlate the optimal hub height with the local wind shear exponent which is a critical parameter used to extrapolate the wind speed to hub heights of the wind turbines which is usually much more than the actual height of wind measurements. For the purpose, wind speed measurements at 20, 30, and 40 meters above ground level were used to obtain the local wind shear exponents at Arar, Dhahran, Dhulom, Gassim, Juaymah, Rawdat Ben Habbas and Yanbo. These wind shear exponents were used to extrapolate the wind speed to different hub heights which in turn were used to get the energy yield from different chosen wind turbines of rated power 600, 1000, 2000, 3000, 36000, and

5000kW. Next, the incremental percent energy yield and the corresponding incremental percent costs were plotted to get the optimal or near optimal hub heights. Finally, these hub heights were used in conjunction with the local wind shear exponents to obtain the correlations between the local wind shear exponents and the hub height. Bets correlations were obtained for wind turbine of 1000kW with R^2 value always more than 95%. The Power law fit produced relatively better empirical correlations between the optimal hub height and the local wind shear exponents with higher values of coefficient of determination. These correlations can be used to obtain an optimal hub height to produce energy at the site of interest with maximum energy output at an optimal cost.

As future work of scope, this methodology should be used for as many sites as possible and other wind turbines to obtain the empirical correlations for more realistic output.

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