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Research paper

Wind characteristics observation using Doppler-SODAR for wind energy applications

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ABSTRACT

This paper presents an application of Doppler SODAR (Sound Detection and Ranging) system for the assessment of wind characteristics at an onshore site in Tamil Nadu, India. The wind speed is statistically analyzed by means of Weibull distribution function and results were used to compute several characteristics parameters related to wind energy applications and no significant discrepancies were observed. The characteristics of wind shear coefficient were evaluated for different altitudes. The vertical profile of wind speed measured from SODAR system was compared with existing models. Furthermore, the turbulence characteristics were analyzed and compared along with the turbulence intensity. From the economic point of view the SODAR system was found to be cost-effective at higher heights. The results of this study are expected to provide useful information for the deployment of remote sensing instruments for wind energy development in India.

1. Introduction

The wind energy sector is gaining a growing attention worldwide with an intention to alleviate the degradation of the natural resources. The wind energy plays a significant role in fulfilling country's electricity demand and secondary the efficient use of it will mitigate the challenges leading to the depletion of fossil fuel. Keeping the above points, the wind energy sector has gained a huge attention in the past decade and has emerged as an alternative to meet electric demands. Now a days the wind turbine installation are getting broad attention towards forests, hilly, complex and mountainous terrain as well as in offshore region and modern wind turbines are gaining higher heights, therefore the detail and accurate assessment of wind characteristics is essential in the development stage of wind farm site [1].

The monitoring of wind characteristics is done by standard cup anemometer mounted on meteorological mast as per IEC standard 61,400-12-1 [2]. However, the modern wind turbines are constantly getting higher hub heights and larger rotor diameter which increases the need for taller and multiple masts for larger wind farm. It results in addition of extra cost to the project and technical difficulties for installation and maintenance [3]. Besides, the mast leads to a measurement biases due to interference effect because of the presence of supporting structure, the local wind field is distorted by the tower supporting an anemometer and also affects the readings of the anemometers [4,5]. M. A. Baseer et al. [5] studied the performance of cup anemometer installed on a tall mast at different heights. Hence ground-based remote sensing techniques SODAR (Sound Detection and Ranging) and LiDAR (Light Detection and Ranging) and airborne remote sensors are extensively being used for wind energy development. The remote sensing technique has the ability to measure wind characteristics at higher altitudes [6]. The remote sensing technique has several advantages in comparison with traditional meteorological mast technique. First, it measures the vertical wind profiles and measure the wind field over a much larger volume [1,7] encourages carrying out the evaluation of economic feasibility and design of wind turbine. Second, it can be used at offshore, onshore, complex and mountainous region [8]. More importantly, easy installation and portability, low visual impact and operates unattended for long periods of time.

Particularly, the Sound Detection and Ranging (SODAR) systems have been broadly applied to measure wind characteristics. The various previous studies show the fidelity of the measurement of SODAR systems [9,10]. Behrens Paul et al. [11] presented the development of a multisodar from a five-beam SODAR to investigate nature of wind in both complex and flat terrain and validated it against 60 m meteorological mast and found a tight correlation in homogenous terrain with RMS error of 0.4 m/s and R^2

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Nomenclature

SODAR	Sound detection and ranging
RMSE	Root mean square error
R^2	Coefficient of determination
MAPE	Mean absolute percentage error
M	Maximum Deviation
RPE	Relative percentage error
k	Shape parameter of Weibull distribution
c	Scale parameter of Weibull distribution (m/s)
MLM	Maximum likelihood method
MMLM	Modified maximum likelihood method
WPD	Wind power density
IEC	International Electro-technical Commission
V	Wind speed (m/s)
TC	Turbine capacity
CF	Capacity factor
Y	Annual energy production
F	Export fraction
T_c	Total cost of turbine
O_c	Operating cost
G_c	Unit cost of electricity generation
W_c & W_m	Wind monitoring and maintenance cost
P_b	Payback period
n	Number of observations
v_i	Wind speed measured at the interval i.
$f(v_i)$	Frequency for wind speed ranging within bin i
F(v)	Cumulative distribution function
f(v)	Weibull, probability density function
$\bar{v}$	Mean wind speed (m/s)
V_{mp}	Most probable wind speed
V_{me}	Maximum energy carrying wind speed
U(z)	Wind speed at elevation z
k	Von Karman constant
Z_0	Aerodynamics roughness length

Greek letters

ρ	Density of surrounding air (kg/m^3)
Γ	Gamma function
σ	Standard deviation
α	Power exponent or wind shear exponent
u_*	Frictional velocity
τ_0	Surface shear stress

0.98. Noord et al. [12] reported the SODAR calibration for wind energy application, measurement of power performance of wind turbine using SODAR and operational characteristics. Barthelmie R. J et al. [13] used ship mounted SODAR to determine wind turbine wakes and vertical profile and compared the result with meteorological mast on two offshore and one coastal mast installed at the same site. Hayashi T. et al. [14] showed the comparative results of wind observation from a mini Doppler SODAR and standard cup anemometer at 70 m height, the wind speed showed the good correlation coefficient R = 0.88 to 0.94 at all heights. Ormel FT et al. [15] performed measurement at both offshore and onshore region to compare two SODAR against meteorological mast at lower as well as at higher altitude, results shows that at 40 m height the SODAR measurement deviated 100 percent from mast measurement (no correlation), correlation coefficient gets improve to 0.97 to 0.99 as height increases for both wind direction and wind speed at onshore site however in offshore region at 10 m height 50 percent deviation was observed for wind speed as those indicated by mast and at 20 m height less difference is observed. Apart from ground based SODAR system as addressed here, Doppler LIDAR [16–19] airborne SAR (Synthetic Aperture Radar) [20], Scatterometer are also used for observation of wind characteristics at onshore as well as in offshore area.

SODAR systems were primarily associated in atmospheric research, very few studies were directed on the assessment of wind energy potential and observation of wind characteristics in India. It is assumed that the results presented in this study will encourage the research interest of wind-SODAR profiling and wind energy development in India. National Institute of Wind Energy, Chennai (autonomous research institute under Ministry of New and Renewable Energy, Govt. of India) has already announced the National offshore wind energy policy for the development of offshore wind in India [21] and has started demonstration projects and strategic planning. National Institute of Wind Energy is so far the only government body that conducts wind monitoring using SODAR (Sound Detection and Ranging) and LiDAR wind profilers. The main aim of this study is to prove the wind community in India that wind resource assessment can be easily done in a cost-effective way using a SODAR system, compared to the traditional but expensive met mast system, without compromising on the quality of your measurements – as a SODAR system can be quickly deployed anywhere and flexible to be moved around.

The outcome of this study is expected to provide important information for the assessment of wind resources at higher altitude, economic feasibility of wind turbine project and for future offshore wind energy development in India. It is essential to verify wind measurements from SODAR and decrease the uncertainty of SODAR measurements. In this study, measurements from ground-based SODAR over various heights have been performed to prove its effectiveness. In addition, the economic assessment is shown in order to highlight the economic feasibility of SODAR instrument. Moreover, this paper includes a detailed description of experimental site and instruments in Section 2, Section 3 shows the reliability assessment of SODAR measurements which is done by comparing with the measurement from a nearby meteorological mast; Section 4 presents the comprehensive analysis of wind characteristics measured by SODAR; Section 5 shows the comparative economic assessment of meteorological mast measurement and SODAR measurement at different heights; Section 6 summarizes the conclusion based on this study.

2. Description of experimental site and instrument

The Fig. 1 shows the location 120 m installed meteorological mast and 2 MW Kenersys make wind turbine. The geographical location of site is 08° 57′ 44.27″ N is latitude and 77° 43′ 10.80′' E longitude and the site features are gently sloping towards the western direction. The roughness length of the site is 0.3 m [22] and the yearly average temperature and relative humidity of the site is 42 °C and 72 percent respectively. The surrounding area of SODAR and met mast is covered with agricultural land, shrubs and trees within a distance of about 250 m. The measurement site is located at a distance of one km or more from small villages and small towns with few sheltering (5–8 m high).

There were no obstacles in the vicinity of the SecondWind Triton SODAR during measurement campaign and the instruments were pre-programmed to measure wind data at 10 different heights of 30, 50, 60, 80, 100, 120, 140, 160, 180 and 200 m. This study shows the observation of 10 minute average time series wind characteristics evaluated through SODAR instrument at 60 m, 80 m, 100 m and 120 m only. The time series wind data were recorded in chorus by cup anemometer mounted on 120 m high lattice structure meteorological mast at different height for the same period of time.

The layout of a 120 m high meteorological mast and a SecondWind Triton SODAR system at a time of measurement campaign is shown in Fig. 2. The SecondWind Triton SODAR and 120 m me-

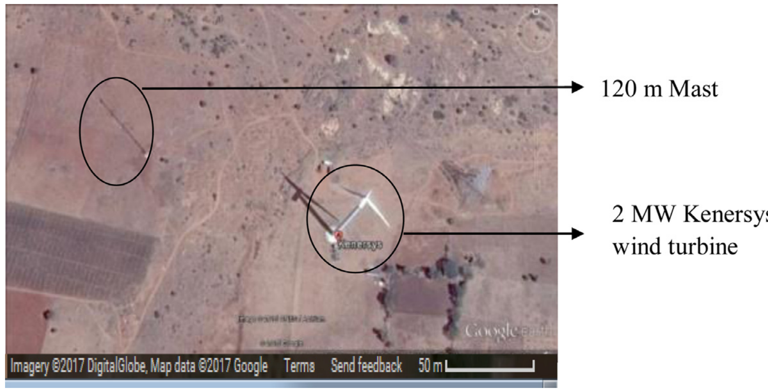

Fig. 1. Kenersys 2 MW Wind Turbine with 120 m Mast installed at Kayathar, Tamil Nadu, India.

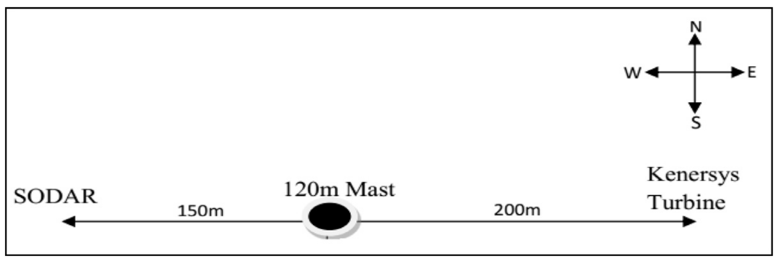

Fig. 2. Measurement campaign layout of MAST and SODAR at the site.

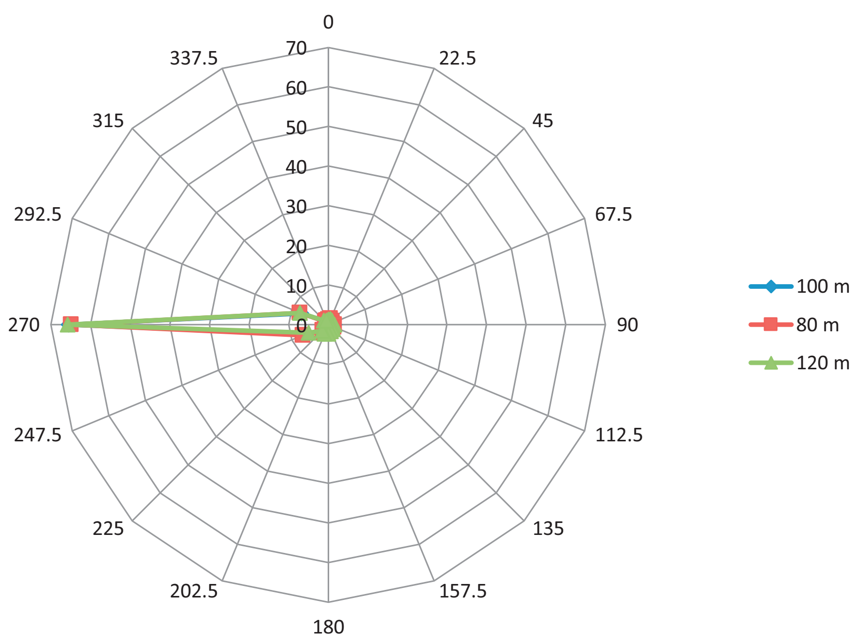

Fig. 3. Wind rose at different height.

teorological mast were used to record the time series wind data simultaneously to obtain wind parameters at various heights on same time. The meteorological mast is located on a western side of the wind turbine at a distance of 200 m, while SODAR is placed at a distance of 150 m from the base of the mast. The Fig. 3 shows a prevailing wind direction at each height. The data involved in this study were recorded during high wind season. This measurement campaign shows the observation of wind parameters at four different heights 60 m, 80 m, 100 m and 120 m by the use of Doppler SODAR.

2.1. Meteorological mast

The meteorological mast installed on the wind farm is of a lattice structure with a cross-sectional area of 800 mm x 800 mm shown in Fig. 4. The height of the mast is 120 m and is equipped with six cup anemometers at different altitudes. A top mounted anemometer is positioned at a height of 120 m. Three side mounted cup anemometers (NRG #40C) along with wind vane (NRG 200P) are installed at three different altitudes i.e. at 120 m, 80 m and 60 m, one ultrasonic cup anemometer is located at 100 m and two other cup anemometer are located at 10 m and 30 m, all

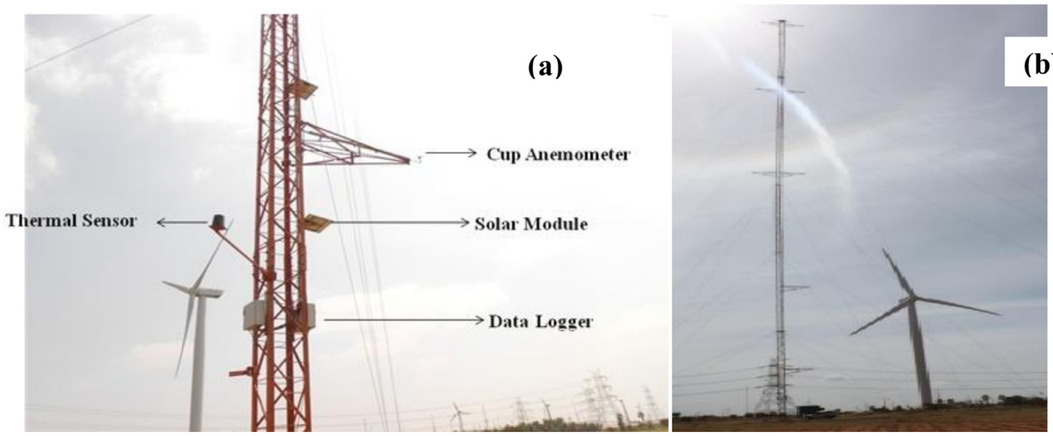

Fig. 4. (a) Instrumentation and (b) 120 m meteorological mast (installed at Kayathar).

Table 1
Calibration details of cup anemometers (source: National Institute of Wind Energy, Chennai, India).

Sensor	Model	Manufacturer	Height	Deviation*	Notes
Anemometer	NRG#40C	NRG Systems, Hinesburg, Vermont, USA	60 m	R = 0.9999 M = −0.058 m/s at 15.819 m/s	Calibrated (MEASNET)
			90 m	R = 0.9999 M = −0.040 m/s at 15.783 m/s	Calibrated (MEASNET)
			95 m	R = 0.9999 M = −0.029 m/s at 15.795 m/s	Calibrated (MEASNET)
			120 m	R = 0.9999 M = 0.051 m/s at 10.928 m/s	Calibrated (MEASNET)

* R = coefficient of correlation, M = Maximum deviation

Table 2
Technical specification of instruments anemometers (source: National Institute of Wind Energy, Chennai, India).

Sensor	Model	Ranges	Operating temperature (°C)	Operating humidity range (%)	Threshold value
Cup anemometer	NRG#40C	1 – 96 (m/s)	−55 to 60	0 to 100	0.78 m/s
Wind vane	NRG#200P	360° mechanical, continuous rotation	−55 to 60	0 to 100	1 m/s
Temperature sensor	Galltec	−30 to 70	−30 to 70	0 to 100	–
Pressure sensor	Setra 205	25 PSI to 5000 PSI	0 to 175	0 to 100	Response time- 1 millisecond

these anemometer and wind vanes are placed at a distance of 4 m from the mast structure on horizontal boom (can be seen in Fig. 4).

In addition, two temperature sensors (Galltec) are installed at 10 m and 120 m along with humidity measuring sensor (Galltec) respectively and one pressure sensor (Setra) is placed at 5 m height. The data logging system is configured at 1 Hz to record the 10 minute average time series wind data. The Table 1 shows the calibration details of cup anemometer installed on a meteorological mast, the MEASNET procedure [23] (IEC 61,400-12-1) prescribes an absolute uncertainty less than 0.1 m/s at a mean wind velocity of 10 m/s that is 1 percent at 95 percent confidence level. The NRG cup anemometers were factory calibrated at all heights and all sensors compiles as per MEASNET requirement. No onsite calibration was performed for any of the sensors. The detailed specification is of the instruments is shown in Table 2.

2.2. Sonic Detection and Ranging (SODAR) system

It is a ground based remote sensing technique and works on Doppler principle. It transmits a short acoustic sinusoidal pulse vertically upward into atmospheric boundary layer through transmitter, while at the same time pulse is reflected back to the receiver. The wind speed, direction and turbulent structure depending on sonic frequency, system's power output, atmospheric stability and existing noise environment are determined by using intensity and Doppler shift of the returned signals at lower atmosphere approximately 2 km [1]. The detail specification of SODAR instrument is shown in Table 3. The SecondWind Triton SODAR used for measurement was placed at a distance of 150 m from 120 m mast to avoid the obstacle (mast shade) in the vicinity of the instrument.

3. Reliability assessment of SODAR measurement

In this study, the fidelity of SODAR measurement is evaluated by comparing with the measurements of cup anemometers which are installed on meteorological mast nearby at 60 m, 80 m, 100 m and 120 m respectively. The Table 4 illustrates the comparative mean wind speed, standard deviation, median, maximum wind speed and minimum wind speed for the measured wind speed at different height by cup anemometer and SecondWind Triton SODAR. The comparison of daily mean wind speed profile is shown in Fig. 5 below for the month of September (because of high windy period) at each height. Ali M Abdelsalem et al. [22] ensured the accuracy of SecondWind TRITON SODAR by comparing it with cali-

Table 3
Technical specification of SODAR [34,35].

Data capture	
Maximum height	200 m
Wind speed range	0–25 m/s (0–55 mph) Data recovery rate> 98% (at all Heights)
Filtered data recovery	>95% at 60 m; > 90% at 80 m;>90% at 120m
Data upload rate	Every 10 minutes, via communications link. Automatic data buffering and backfilling Protocol.
SD memory card socket	2 GB SD card records a minimum of 2years of 10 minutes data.
Power supply	
Power consumption	7 W (average)
Solar panels	2 Panels, each rated @ 85W
Operation	
Ambient temperature	−40 °C to + 65 °C (−40°F to + 150°F) Frequency if 4500 Hz (nominal), with automatic
Number of sound beam	3
Sound level at ear level	87 dBa at 0 m; 63 dBa at 50m
Accuracy	
Accuracy of instrument measurement interferences data capture and data quality.	2.4% (average), typical range (1.5 to 3.5%)
Vertical extrapolation	2.0% average, typical range (1 to 3%)
Wind speed frequency distribution. Long-term average wind speed	2.1% average, typical range (1–3%)

Table 4
Statistical parameter of wind speed at all measured heights.

Height	Assessment technique	Data recovery rate (%)	Mean wind speed (m/s)	Median (m/s)	Maximum wind speed (m/s)	Minimum wind speed (m/s)
60 m	MAST	99.95	7.748	8.531	17.296	0.3170
	SODAR	99.23	7.608	8.451	16.330	0.140
80 m	MAST	99.91	8.330	9.258	18.412	0.904
	SODAR	99.93	7.989	8.970	16.180	0.600
100 m	MAST	100	8.456	9.488	18.421	0.731
	SODAR	100	8.351	9.340	23.280	0.300
120 m	MAST	99.93	8.706	9.812	18.453	0.425
	SODAR	99.83	8.361	9.170	23.443	0.100

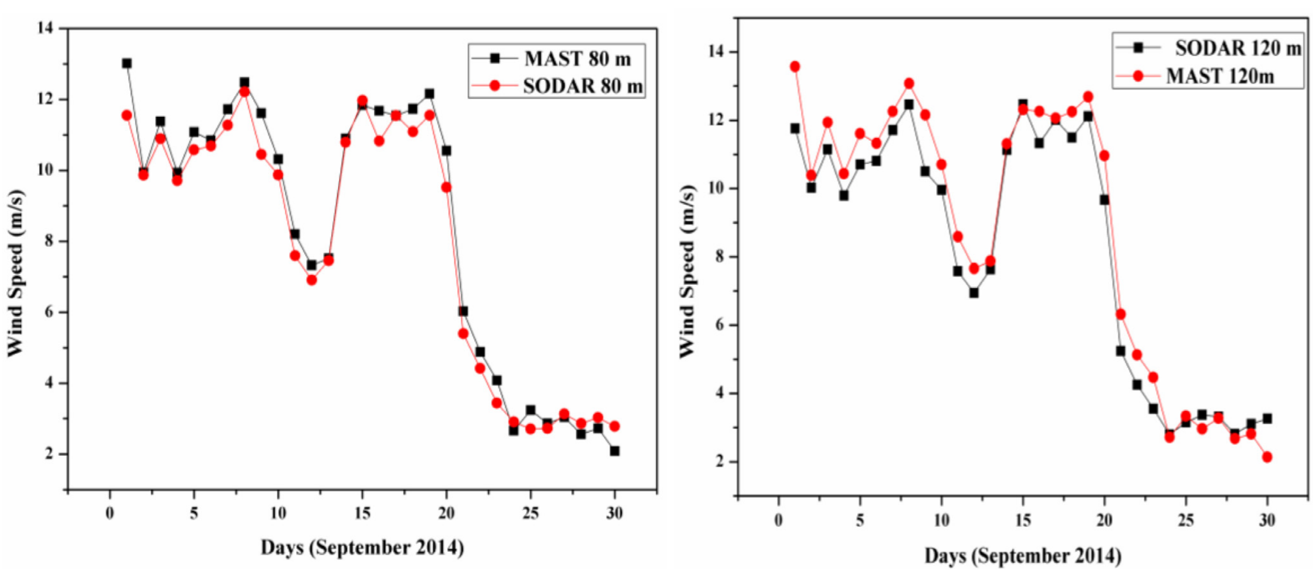

Fig. 5. Comparison of daily mean wind speed profile.

brated mast-mounted cup anemometer installed at Kayathar, Tamil Nadu. The comparison results showed a very good correlation between the data obtained from mast-mounted cup anemometer and SODAR.

The Table 5 tabulates the result of the statistical analysis. The maximum mean absolute percentage error (MAPE) is found to be 1.8 percent, while the minimum R^2 value was found to be 0.9696. The result of statistical analysis shows the variation of Weibull distribution obtained from SODAR measurement against measured from mast. From the above table it can be seen that there is not much discrepancies between the result of Weibull parameters of Mast and SODAR

4. SODAR – based observations of wind characteristics

In this segment, wind characteristics are investigated on the basis of the wind SODAR measurements. The aim of this detailed investigation is to provide useful information for the design of wind resistance structures and accurate assessment of wind resources at

Table 5
Summarization of statistical analysis at overlapping heights.

Height	Weibull parameters				Statistical analysis			
	MAST measured value		SODAR		MAPE (%)	R^2	RPE (%)	
	k	c (m/s)	k	c (m/s)			k	c (m/s)
60 m	2.026	8.699	1.967	8.523	0.12	0.9953	2.91	2.02
80 m	2.023	9.354	2.070	8.974	0.73	0.9875	2.47	4.06
100 m	2.027	9.542	1.975	9.012	1.1	0.9735	2.56	5.55
120 m	2.035	9.772	1.974	9.189	1.8	0.9696	2.99	5.96

higher heights along with valuation of economic feasibility of wind turbine project.

4.1. Measured wind speed characteristics

The wind is highly variable and intermittent both spatially and temporally the power extracted from the incident wind by a wind turbine is proportional to the cube of the wind speed, therefore accurate assessment of wind speed is necessary for the estimation of wind energy potential, economic feasibility of the project and design of wind turbine structures. The probability distribution models are usually used for the analysis of the wind speed distribution, in which the two parameters Weibull distribution functions are commonly used for the estimation of the wind speed distribution over the time period. The Weibull probability function and cumulative distribution function is given by [8,19,25]

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \times \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

where f(v) and F(v) are probability and cumulative density function. The dimensionless Weibull k (shape factor) parameter directs the width of the distribution and Weibull c (scale factor) parameter with a unit of m/s controls the average wind speed.

There are various methods to compute Weibull parameter, [8,22,26, and 27]. In 2017, Baseer et al. [26] estimated Weibull parameters using least square-regression method, maximum likelihood method and WAsP algorithm to study the wind characteristics of seven locations in Jubail, Saudi Arabia, similarly in 2015 Baseer et al. [27] determined Weibull parameter using maximum likelihood method to analyze the wind characteristics and resource assessment in Middle East (Jubail Industrial city) using hourly wind speed data at different heights. In this study maximum likelihood method and modified maximum likelihood method have been considered. The maximum likelihood and modified maximum likelihood methods are extensively used method and requires a numerical iteration for the estimation of shape factor. For the maximum likelihood method, the mathematical equation to determine Weibull parameter is given by [8,22]

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln v_i}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln v_i}{n}\right)^{-1} \tag{3}$$

$$c = \left[\frac{1}{n}\sum_{i=1}^{n}(v_i)^k\right]^{\frac{1}{k}} \tag{4}$$

similarly for the modified maximum likelihood method the Weibull parameters are estimated using equation as given below [8]

$$k = \left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i) f(v_i)}{\sum_{i=1}^{n} v_i^k f(v_i)} - \frac{\sum_{i=1}^{n} \ln(v_i) f(v_i)}{f(v \geq 0)}\right]^{-1} \tag{5}$$

$$c = \left[\frac{1}{f(v \geq 0)}\sum_{i=1}^{n}(v_i)^k f(v_i)\right]^{\frac{1}{k}} \tag{6}$$

where n is the number of observations, v_i is the wind speed measured at the interval i, $f(v_i)$ the frequency for wind speed ranging within interval i, and $f(v \geq 0)$ is the probability for wind speed equal to or exceeding zero. From Table 4 above, the average 10-min wind speed measured from meteorological mast increases from 7.748 m/s at 60 m to 8.706 m/s at 120 m, while maximum wind speed increases from 17.296 m/s to 18.453 m/s as the height increases. Whereas for the SODAR instrument the average wind speed increases from 7.608 at 60 m to 8.361 at 120 m and maximum wind speed increases from 16.330 m/s to 23.443 m/s. The Weibull parameters k and c derived from maximum likelihood method and modified maximum likelihood method is shown in Table 6 for all the measured heights.

The Weibull parameters derived shows a good agreement, the shape parameter k was observed to be around 1.96 to 2.16 at all height excluding at 60 m and scale parameter c (m/s) is centerd with a value around 8.5 m/s to 10 m/s. After determining Weibull parameters, they can be used to compute wind power density. Wind power density shows the total available energy at the site for conversion, which can be calculated as [8]:

$$\frac{P}{A} = \frac{1}{2}\rho\, c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{7}$$

The Table 7 below summarizes the calculated wind power densities by both the measuring instrument using different methods at all measurement heights.

Additionally, Weibull parameter can also be used to calculate characteristics of wind speed namely the most probable wind speed (V_{mp}) and maximum energy carrying wind speed (V_{me}). At a given location the peak of wind speed probability distribution is shown by most probable wind speed, whereas the peak of wind power probability distribution is shown by maximum energy carrying wind speed. The value of V_{mp} and V_{me} can be calculated from the following equations [8]

$$V_{mp} = c\left(1 - \frac{1}{k}\right)^{1/k} \tag{8}$$

$$V_{me} = c\left(1 + \frac{2}{k}\right)^{1/k} \tag{9}$$

The Table 8 below shows the value of V_{mp} and V_{me} at all measurement heights for both the measuring systems. Technically, in order to extract more energy the rated speed of wind turbine should be close to the maximum energy carrying wind speed and the most probable wind speed provides useful information for the structural design of wind turbines.

The values of most probable wind speed (V_{mp}) ranges from 6.217 m/s at 60 m to 7.042 m/s at 120 m for meteorological mast measurement whereas for SODAR measurements it varies from

Table 6
Computed Weibull parameters at all heights.

Height	Measurement technique	Methods					
		Measured value		Maximum likelihood method		Modified maximum likelihood method	
		k	c (m/s)	k	c (m/s)	k	c (m/s)
60 m	MAST	2.026	8.699	3.319	10.151	2.027	8.702
	SODAR	1.967	8.523	3.172	9.978	1.964	8.536
80 m	MAST	2.023	9.354	2.025	9.551	2.034	9.363
	SODAR	2.070	8.974	2.065	8.966	2.070	8.975
100 m	MAST	1.976	9.476	1.976	9.476	1.974	9.477
	SODAR	2.149	9.358	2.144	9.381	2.145	9.387
120 m	MAST	2.035	9.772	2.033	9.716	2.045	9.779
	SODAR	1.974	9.189	1.972	9.185	1.980	9.159

Table 7
Wind power density estimation using Weibull parameters.

Height	Measurement technique	Methods		
		Experimental Value Wind power density (W/m^2)	Maximum likelihood method Wind power density (W/m^2)	Modified maximum likelihood method Wind power density (W/m^2)
60 m	MAST	524	616	529
	SODAR	513	595	516
80 m	MAST	658	700	657
	SODAR	568	568	568
100 m	MAST	702	702	703
	SODAR	622	628	623
120 m	MAST	746	734	744
	SODAR	641	641	632

Table 8
Estimation of characteristics wind speeds.

Height	Measurement technique	Characteristics wind speeds (m/s)					
		Experimental value		Maximum likelihood method		Modified maximum likelihood method	
		V_{mp}	V_{me}	V_{mp}	V_{me}	V_{mp}	V_{me}
60 m	MAST	6.21	12.20	9.11	11.70	6.22	12.20
	SODAR	5.90	12.17	8.85	11.64	5.94	12.20
80 m	MAST	6.67	13.13	6.82	13.40	6.71	13.11
	SODAR	6.52	12.44	6.50	12.44	6.52	12.44
100 m	MAST	6.63	13.49	6.63	13.49	6.62	13.50
	SODAR	6.99	12.70	6.99	12.75	7.00	12.76
120 m	MAST	7.00	13.67	6.96	13.60	7.04	13.65
	SODAR	6.42	13.09	6.41	13.10	6.42	13.03

Table 9
Estimated wind shear coefficients.

Wind shear between	Measurement techniques	Based on all positive value of wind shear coefficient			
		Sample size	Average	Max	Min
α 1- 50 m and 60 m	Mast	4320	0.2680	2.871	0.0003
	SODAR	4320	0.1823	2.801	0.0004
α 2- 60 m and 80 m	MAST	4318	0.2423	2.982	0.0008
	SODAR	4318	0.2217	2.772	0.0002
α 3- 80 m and 100 m	MAST	4317	0.2241	3.143	0.0003
	SODAR	4317	0.2231	3.183	0.0003
α 4- 100 m and 120 m	MAST	4317	0.2121	2.887	0.0004
	SODAR	4317	0.2198	2.964	0.0038

5.904 m/s at 60 m to 7.005 at 100 m, while maximum energy carrying wind speed ranges (V_{me}) from 11.70 m/s 60 m to 13.679 m/s at 120 m for mast measurement and for SODAR measurement it varies between 11.640 at 60 m to 13.100 m/s at 120 m.

4.2. Wind shear coefficient and vertical wind speed profiles

As discussed earlier, the modern machines are getting bigger in size that aims to extract more quantity of wind energy. The wind characteristic at hub height of wind turbine plays a significant role in the assessment of economic feasibility and design of

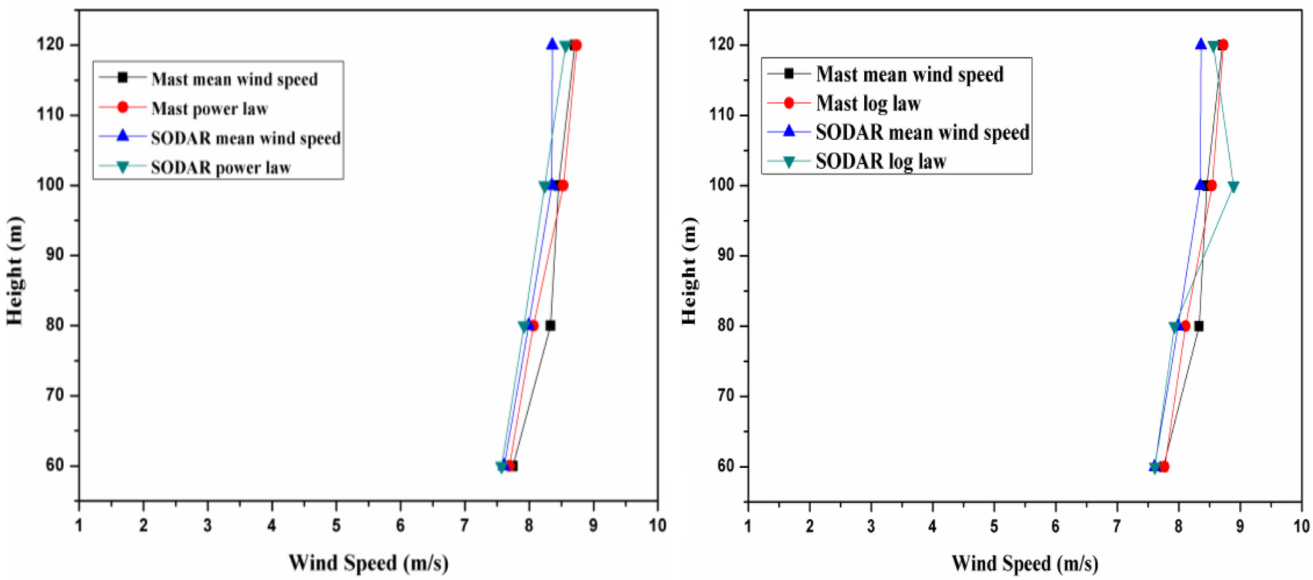

Fig. 6. Comparison of vertical wind speed profile (a) power law (b) log law.

wind turbines. The vertical wind speed models are used to extrapolate wind speed at higher heights. In this study the comparison of the vertical wind speed profile measured from SODAR are compared with power law [28] and the log law [28] along with mast measurements. The power law model is commonly used for defining vertical profile in wind energy and mathematically represented as:

$$U(z) = U(Z_r)\left(\frac{Z}{Z_r}\right)^{\alpha} \tag{10}$$

where U (z) is wind velocity at elevation z, $U(Z_r)$ is wind velocity at higher elevation and α is the power exponent or wind shear exponent.

The logarithmic model is another approach which accounts both the thermal and roughness effect to derive the variation of wind speed with height, which is mathematically expressed as [30]:

$$U(Z) = \frac{u_*}{k} \ln\left(\frac{Z}{Z_0}\right) \tag{11}$$

Where k is von Karman constant (0.4), u_* is the frictional velocity ($u_* = (\tau_0/\ \rho)$) and τ_0 is the surface shear stress. The values of u_* was calculated depending on the wind speed measured at each elevation by two techniques and Z_0 is aerodynamics roughness length (0.3) [22].

The Fig. 6 illustrates the comparison of SODAR-derived vertical profile with mast measurement, assuming a power exponent of 0.14 suggested by International Electro-technical Commission. It is observed that the SODAR-derived mean wind speed profile fits well with both power law and log law. The little variation can be seen mainly due to the influence of wind-driven wave. In this case the standard wind profile measured by SODAR measurement tends to predict higher wind speed in comparison to mast measurement at higher altitudes, which provides useful information in terms of safe-design of turbines structures and tall meteorological mast structures. However, it might also result in overestimation of wind energy potential which may affect the structural design and economic feasibility of the project. It is also observed that the deviation between the SODAR measurement and standard vertical wind profile is dependent on mean wind speed, higher mean wind speed results in higher deviations.

The questionable aspects identified that the 1/7 power law model is generally adopted to find wind speed at hub height of wind turbines due to lack of wind speed measurements data at higher level, however, the value of wind shear coefficient changes under different conditions. Touma [28] suggested that power law is generally satisfactory for neutral conditions and highly dependent on and varies with atmospheric stability, whereas Rehman et al. [29] stated that wind shear coefficient is highly dependent on surface roughness and topographic conditions. In practice Firtin et al. [29] found that the real value of wind shear coefficient is much higher than value of 1/7. In this study, the characteristic of wind shear coefficient is determined on multi-height. The wind shear coefficient is calculated as:

$$\alpha = \frac{\ln(V_2) \ - \ln(V_1)}{\ln(Z_2) - \ln(Z_1)} \tag{12}$$

where V_2 and V_1 are wind speed at height Z_1 and Z_2 . The Table 9 below shows the statistical results of wind shear coefficients. It is seen that the unconditional use of power law may lead in misleading estimation of wind speed at hub height.

4.3. Turbulence

Turbulence structure of wind is another important parameters which plays an important role in wind energy development. The design of wind turbines supporting structures depends on the variation of turbulence intensity [8]. Turbulence depends on thermal instability and mechanical friction of surface roughness in the atmospheric boundary layer. The surface roughness can be considered as invariant for specific site. Under such situation, because of thermal instability the turbulence intensity will increase as mean wind speed decreases. Turk and Emeis [31] mentioned that at lower wind speed the thermal production of turbulence is dominative however, at higher wind speed the wind driven waves produces the mechanical friction which reduces the effect of thermal instability which result in increase of turbulence intensity as a function of increasing mean wind speed. In Fig. 7, it is observed that in lower wind speed range of 2 m/s to 5 m/s the variation of turbulence intensity is maximum at all measured heights but beyond 5 m/s and upto 15 m/s at different elevation as per SODAR observation the turbulence intensity variation is very close in range

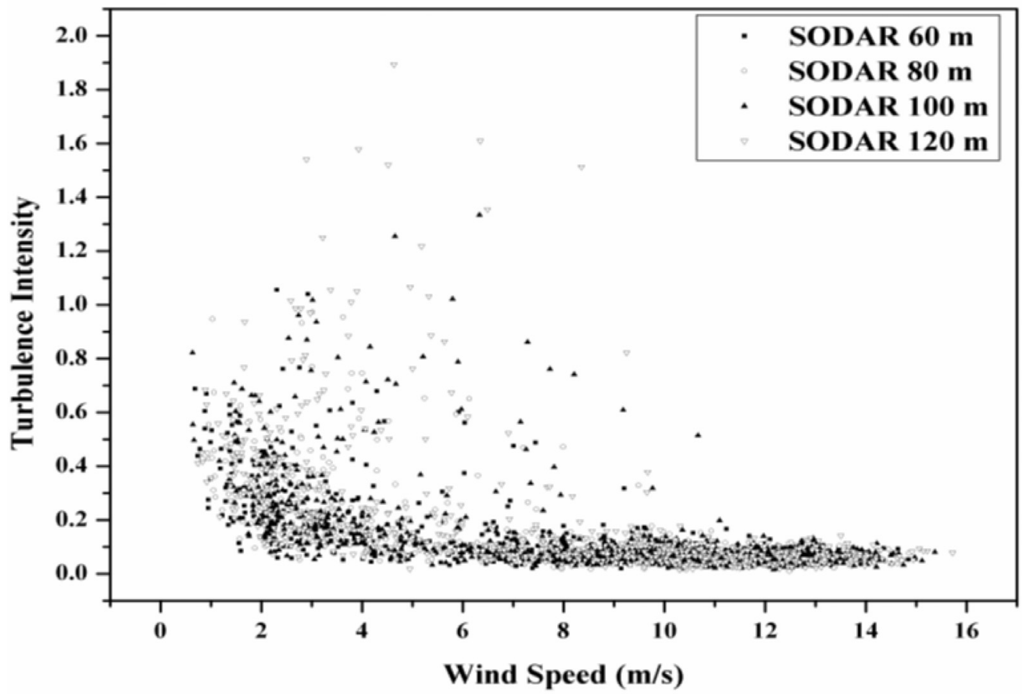

Fig. 7. Variation of turbulence intensity with mean wind speed.

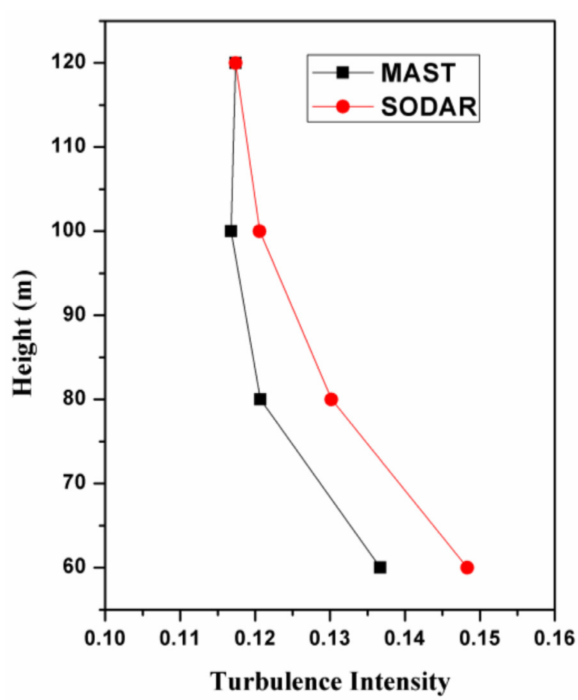

Fig. 8. Vertical profile of turbulence intensity.

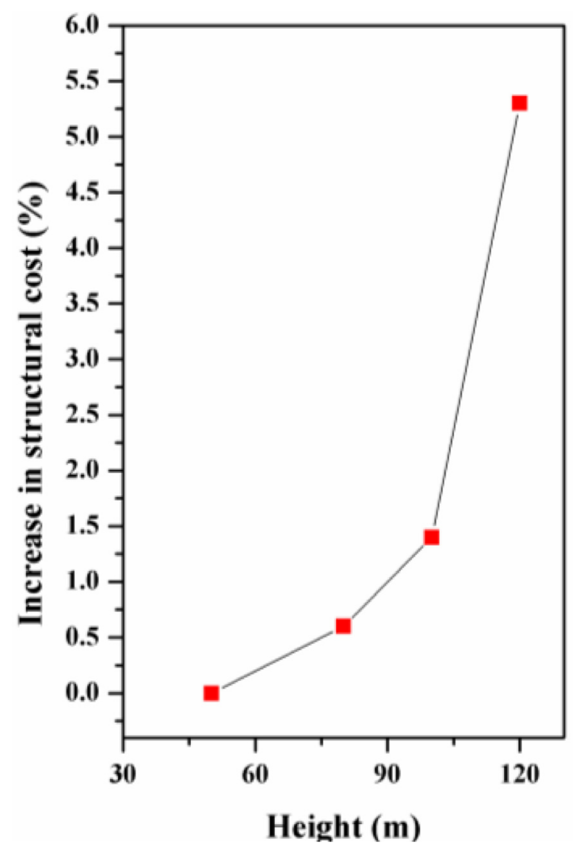

Fig. 9. Percentage increase in cost of meteorological mast.

of 0.05 to 0.15. In this study the atmosphere was thermally stable, the temperature variation has a deviation of less than 0.5 percent.

The statistical characteristic of turbulence intensity is presented in Table 10 and vertical variation is shown in Fig. 8.

The turbulence intensity measured by SODAR was poorly correlated with meteorological mast, the correlation were reasonable. Further study is required to facilitate accurate measurement of turbulence intensity using SODAR. The Fig. 8 shows that there is exponential increase in turbulence intensity with decrease in height measured from both the instruments.

Table 10
Statistic parameters of turbulence intensity at different heights.

Height	Measurement technique	Turbulence intensity		
		Mean	Minimum	Maximum
60 m	MAST	0.1367	0.01728	1.1826
	SODAR	0.1483	0.0199	1.0553
80 m	MAST	0.1207	0.0099	1.1820
	SODAR	0.1302	0.0101	0.9727
100 m	MAST	0.1168	0.0098	1.1827
	SODAR	0.1206	0.0110	0.9523
120 m	MAST	0.1074	0.0063	1.1923
	SODAR	0.1174	0.0155	1.8935

5. Economic assessment – a case study

The Economic appraisal of wind energy depends on several utilities such as annual energy production from wind turbine installation, capital cost of installation, length of contract, operation and maintenance cost, country of origin and market place condition [24]. The wind resource monitoring cost is also a one of an important factor which plays an important role in assessing wind energy economics particularly at higher heights and can affect the economic feasibility of wind farm project. Neglecting the cost of wind resource monitoring effect the value of unit generation of electricity. It is difficult to understand the correlation between turbine price, payback period and cost of electricity with too many factors at a same time. This economic evaluation shows the comparison of the approximate cost of wind resource monitoring done through traditional meteorological mast and SODAR at 80 m and 120 m height. This economic calculation assumes no incentive or loan, grant, discount rate and wind farm land rate. The installed cost per kW for Kenersys 2.0 MW is $ 1103 at 80 m height. The operation and maintenance cost is assumed to be 2.5 percent of turbine installation [32]. The capacity factor is assumed to be 20 percent at both the heights due to better windy season. The current tariff rate in Tamil Nadu, India is $ 0.05 per kWh (fixed for 20 years) [33].

The cost of a typical SecondWind Triton SODAR is approximately $ 51,470 (maintenance cost is negligible) while a 50 m mast of 300 mm x 300 mm with a first class sensor cost approx $ 13,236. The Table 11 shows the approximate cost of meteorological mast with installed sensor. The Table 12 shows the basic tabulation to calculate some techno-economic parameters. The SODAR measurement shows the less unit cost of generation relatively to mast at 120 m height and the expected payback period for the mast at 120 m is longer than SODAR measurement. Hence, on increasing height i.e. above 120 m the total cost decreases for SODAR measurement as compared to mast measurement because on increasing height the structural material of lattice mast increases which results in addition of extra cost to long lattice mast whereas for SODAR measurement the cost remains constant on increasing height.

The cost of erecting a 50 m meteorological mast is approximately $ 13,236, whereas the cost increases by 5.3 times for 120 m meteorological mast.

The percentage increase in the structural cost of meteorological mast varies from 0.60 times at 80 m to 1.40 times at 100 m (cost at 50 m is taken as reference cost). At higher heights i.e. more than 100 m the cost of meteorological mast increases unexpectedly as shown in Fig. 9. From Table 12 it is observed that the approximate cost of wind monitoring and maintenance can be recovered from the project by adopting SODAR for wind measurement at higher heights.

6. Conclusion

In this study fidelity of wind SODAR measurements was examined and nearly similar trend were observed in regard to the comparison of daily mean wind speed profile, whereas good agreement was found in comparison of wind direction with a correlation coefficient above 0.99 and regression slope in the range of nearly 1.0.

Two different methods namely maximum likelihood method and modified maximum likelihood method were applied to estimate the Weibull parameter and no significant difference was found in the values of Weibull parameters. Meanwhile the result presented for wind power density and two useful characteristics wind speeds, namely most probable wind speed and maximum energy carrying wind speed are expected to provide useful information for the assessment of economic feasibility of wind turbine project in this region in near future. The wind shear coefficient was evaluated with a mean value in the range of 0.1 to 0.26. This result can add significant understanding of the vertical variation of wind speed at a particular region, and may also add qualitative information in regard to the structural design of wind turbine. In addition, SODAR-derived wind profile and mast derived wind profile were compared with the existing power-law and log law and results suggested that wind profile fit well for both the measurement technique.

Moreover, the turbulence properties were also compared and investigated and the magnitude of turbulence intensity with height and mean wind speed were determined. Initially the turbulence intensity decreased with the increasing mean wind speed, but once the wind speed reached a certain value, turbulence intensity became constant because of wind driven wave. Further, it was found that the turbulence intensity decreased exponentially on decreasing height. These results would be helpful to assess the fatigue loads, the operation efficacy of wind turbine at this particular region and future development of offshore sites in India.

By employing SOADR system the unit cost of electricity generation decreases to 2.14 percent and payback period to 2.12 percent compared to mast measurement. Hence, by adopting SODAR system for wind resource assessment it is possible to decrease the

Table 11
Approximate cost of meteorological mast installed at site.

Mast Height (m)	Dimension (mm)	Cost of first class sensor (US$)			
		Cup anemometer (Approx)	Wind vane (Approx)	Temperature sensor (Approx)	Pressure sensor (Approx)
50	300 × 300	4 × 1029	2 × 588	1 × 368	1 × 221
80	300 × 300	5 × 1029	3 × 588	1 × 368	1 × 221
100	300 × 300	5 × 1029	3 × 588	1 × 368	1 × 221
120	800 × 800	6 × 1029	4 × 588	2 × 368	1 × 221

Table 12
Comparative payback period and AEP.

Parameters	Formula	Heights				Unit
		80 m		120 m		
		MAST	SODAR	MAST	SODAR	
Turbine capacity	TC	2000	2000	2300	2300	kW
Capacity factor	CF	20	20	20	20	percent
Annual energy production (Y)	Y = TC .CF.8760 h/year	3,504,000	3,504,000	4,029,600	4,029,600	kWh/year
Total electricity generation(20 year)	V_{tog}= Y*20	70,080,000	70,080,000	80,592,000	80,592,000	kWh
Export fraction	F	100	100	100	100	percent
Unit price of exported electricity	P_{exp}	0.05	0.05	0.05	0.05	US$
Annual value of exported electricity	A_{exp}= Y* P_{exp}	174,685	174,685	200,887	174,685	US$/Year
Value of exported electricity (20 years)	$V_{exp} = V_{tog}$ *P_{exp}	3,493,694	3,493,694	4,017,748	4,017,748	US$
Total value of electricity	V_{tot}	3,493,694	3,493,694	4,017,748	4,017,748	US$
Total cost of turbine installation	T_c	2,058,824	2,058,824	2,500,000	2,500,000	US$
Annual operating cost	O_c	25,735	25,735	31,250	31,250	US$
Wind monitoring cost & maintenance cost	W_c+W_m	26,618	58,824	115,368	58,824	US$
Total cost (V_{tot})	$V_{tot} = (T_c + O_c + W_c + W_m)$	2,111,176	2,143,382	2,646,618	2,590,074	US$
Unit cost of electricity generation	G_c= V_{tot}/ V_{tog}	0.0301	0.0305	0.0328	0.0321	US$
Payback period	P_b= V_{tot}/ A_{exp}	12.08	12.27	13.17	12.89	Years
Total saving	S	–	–	–	56,888	US$

total cost without degrading the quality and performance of wind turbines and it is also possible to achieve a payback period of less than 20 years.

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