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ENHANCE PREDICTION PERFORMANCE THROUGH CONTINUOUS MONITORING OF WIND TURBINE

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Abstract: India lost first place in worldwide ranking on total installed wind capacity to china. Due to some issues like, grid issue, unavailability of infrastructure, monitoring wind turbine, offshore wind related R & D activities in the country, etc. This makes attributed to the slower pace to addition of wind power capacity; due to unavailability of on-shore wind sites with sufficiently high wind velocity is expected to take centre stage in the next few years. Low wind velocity makes the investment unattractive to developers. In current situation, monitoring and R & D is an investment option. Which has already seen favourable response in a country like china Germany, Denmark would begins in India. This analyses the present situation of wind energy farm at District Devas, Madhya Pradesh and investigates the possibilities of monitor the wind turbine to enhance the performance. In this paper, wind speed, peak speed, standard deviation, wind power density is to estimated monthly at different altitude. Monitor capacity factor, energy generated through wind turbine, X-chart and R-chart drawn, maintenance and environmental impact have been analyzed.

Keyword. Wind Velocity; Air Density; Wind Power; Standard Deviation; Monitoring; Prediction Performance; Capacity Factor; etc.

INTRODUCTION

Earth equatorial regions receiving more solar energy than its polar regions and this sets up large scale convection current its result wind generated. It is estimated that about 1% of incoming solar radiation is converted into wind energy which is can fulfil our daily to present world need [1]. Due to rise in fossil fuel cost and pollution in environment has led to the world's interest towards renewable energy sources. Wind is commercially and operationally the most viable renewable energy resource and it is emerging as one of the great renewable energy source. Wind energy can hold the promise of meeting energy demand by the direct grid connected modes as well as it can stand alone and remote applications. India has a good wind potential throughout the country. Winds in India are influenced by the strong south-west summer monsoon, which begins in May–June, Due to cool, humid air from Indian Ocean and Bay of Bengal moves towards the land and the weaker north-east winter monsoon, which begins in October, when cool dry air moves towards the ocean. Winds are uniformly strong in India in the period of March–August, except the eastern coastal area. During the period from November to March winds are relatively weak in India, but in the coastline of the state of Tamil Nadu higher wind speed is available during a part of this period. In our country Ministry of New and Renewable Energy (MNRE) is the ministry of Indian Government for all matters relating to new and renewable energy [2].

WIND ENERGY SCENARIO

WORLD WIDE WIND ENERGY STATICS

According to WWEA the worldwide wind capacity reached 392'927 MW by the end of June 2015, out of which 21'678 MW were added in the first six months of 2015. This increase is substantially higher than in the first half of 2014 and 2013, when 17.6 GW respectively 13.9 GW were added. All wind turbines installed worldwide by mid-2015 can generate 4 % of the world's electricity demand.

The global wind capacity grew by 5.8% within six months (after 5.6 % in the same period in 2014 and 4.9 % in 2013) and by 16.8 % on an annual basis (mid-2015 compared with mid-2014). In comparison, the annual growth rate in 2014 was 16.5 % lower.

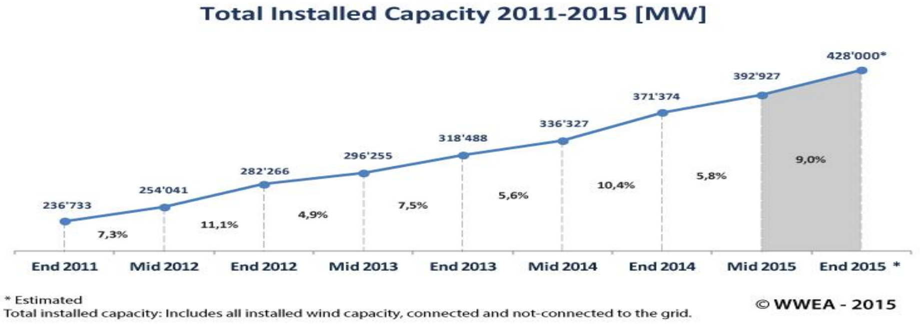
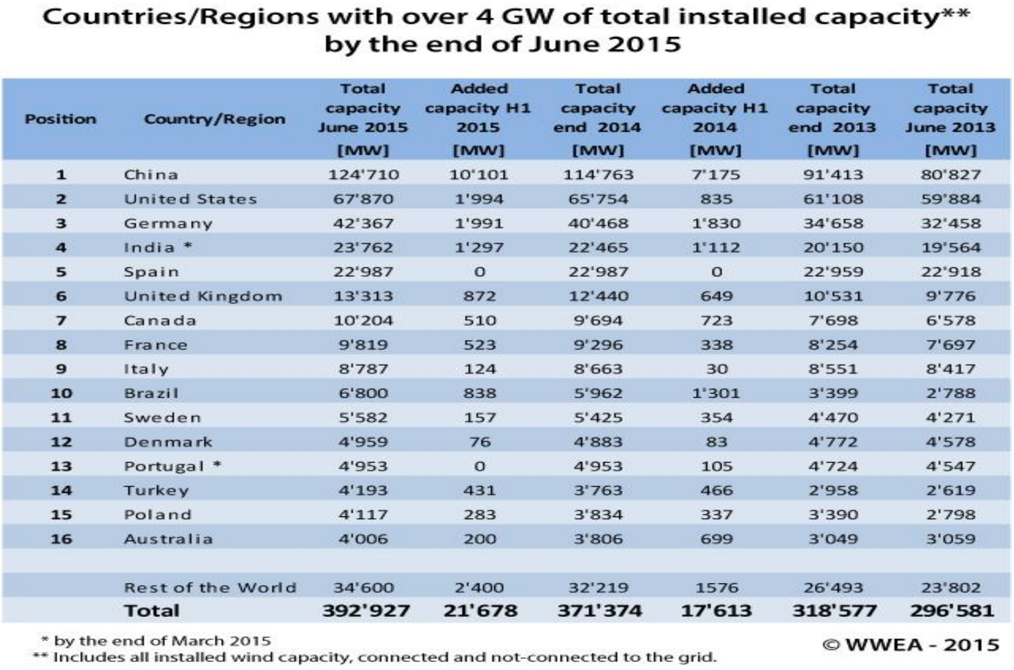


Figure 1. Total installed capacity in the world 2011- 2015.

TOP TEN WIND MARKET: CHINA, USA, GERMANY, SPAIN AND INDIA CONTINUE TO LEAD

In 2015 annual installations crossed the 60 GW mark and more than 63 GW of new wind power capacity was brought on line. The last record was set in 2014 when over 51.7 GW of new capacity was installed globally. 2015 figures were up 4% from 2014's investment and beating the previous record set in 2011 by 3%. The new global total for wind power at the end of 2015 was 432.9 GW, representing cumulative market growth of more than 17%. This growth was powered by an astonishing new installations figure of 30,753 MW in China; the global wind power industry installed 63,467 MW in 2015, representing annual market growth of 22%.By the end of June 2015 last ten countries had more than 10,000 MW of installed capacity including China (124,710 MW), the US (67,870 MW), Germany (42,370 MW), India (23,762, MW), Spain (22,987 MW), UK (13,313 MW), Canada (10,204 MW), France (9,819 MW), Italy (8,787MW) and Brazil (6,800MW). [10]

Table1. World wise wind power installed capacity by the end of June 2015



Countries/Regions with over 4 GW of total installed capacity**
by the end of June 2015

Position	Country/Region	Total capacity June 2015 [MW]	Added capacity H1 2015 [MW]	Total capacity end 2014 [MW]	Added capacity H1 2014 [MW]	Total capacity end 2013 [MW]	Total capacity June 2013 [MW]
1	China	124'710	10'101	114'763	7'175	91'413	80'827
2	United States	67'870	1'994	65'754	835	61'108	59'884
3	Germany	42'367	1'991	40'468	1'830	34'658	32'458
4	India *	23'762	1'297	22'465	1'112	20'150	19'564
5	Spain	22'987	0	22'987	0	22'959	22'918
6	United Kingdom	13'313	872	12'440	649	10'531	9'776
7	Canada	10'204	510	9'694	723	7'698	6'578
8	France	9'819	523	9'296	338	8'254	7'697
9	Italy	8'787	124	8'663	30	8'551	8'417
10	Brazil	6'800	838	5'962	1'301	3'399	2'788
11	Sweden	5'582	157	5'425	354	4'470	4'271
12	Denmark	4'959	76	4'883	83	4'772	4'578
13	Portugal *	4'953	0	4'953	105	4'724	4'547
14	Turkey	4'193	431	3'763	466	2'958	2'619
15	Poland	4'117	283	3'834	337	3'390	2'798
16	Australia	4'006	200	3'806	699	3'049	3'059
	Rest of the World	34'600	2'400	32'219	1576	26'493	23'802
	Total	**392'927**	**21'678**	**371'374**	**17'613**	**318'577**	**296'581**

* by the end of March 2015
** Includes all installed wind capacity, connected and not-connected to the grid.

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GENERAL SITUATION SMALL WIND WORLD MARKET

The IEC, defines SWTs in standard IEC 61400-2 as having a rotor swept area of less than 200 m2, rated power of approximately 50 kW generating at a voltage below 1'000 V AC or 1'500 V DC. As of the end of 2014, a cumulative total of at least 945'000 small wind turbines were installed all over the world. This is an increase of 8.3% (7.4% in 2013) compared with the previous year, when 872'000 units were registered.

The recorded small wind capacity installed worldwide has more than 830MW as of the end of 2014. This is a growth of 10.9 % compared with 2013, when 749 MW registered. In 2012, 678 MW were installed. China continues clearly to be the market leader in terms of installed units: 64'000 units were added in 2014, 9'000 more than in 2013, reaching 689'000 units installed by the end of 2014. The booming market of the recent years, Italy, grew by 71% reaching 1'610 units by the end of 2014.

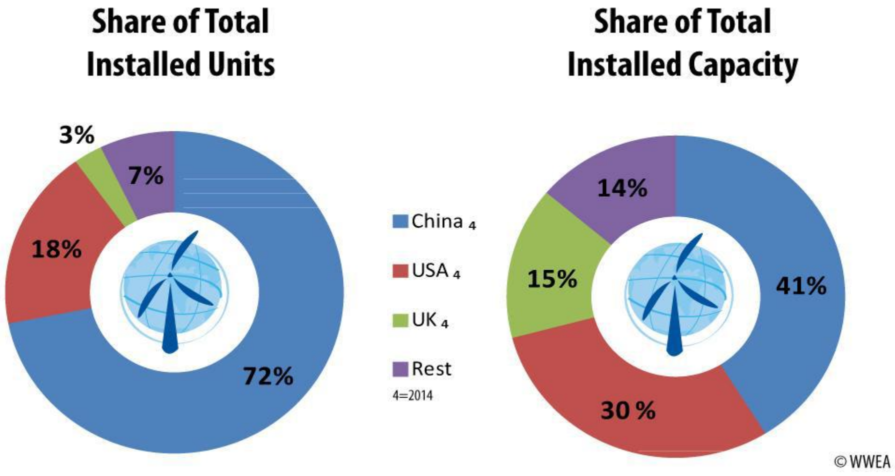

Figure 2. Growth rate small wind world market

NEW WIND WORLD MARKET GROWTH RATES

"The world market for wind power is booming like never before, and we expect new record installations for the total year 2015. The main markets are still China – with an astonishing growth of more than 10 GW within six months – USA, Germany and India. Brazil showed the highest growth rate of all major markets, the country has increased its wind power capacity by 14 % since the beginning of 2015.

The wind industry globally is today driven by a large variety of shareholders and stakeholders, from small and medium sized enterprises, large industries, and energy cooperatives to environmental groups. For the future success, it will be crucial to continue and rather increase this variety."

Table2. New wind world market growth rate

Country	Brazil	Turkey	China	Poland	UK	India
Growth (%)	14.0	11.4	8.6	7.4	7.0	5.7

WIND ENERGY STATISTICS IN INDIA

India continues to be the second largest wind market in Asia, and in 2015 passed Spain to attain 4th place in terms of cumulative installations. The Indian government has committed to a target of 175 GW of renewable by 2022, including 100 GW of solar capacity and 60 GW of cumulative wind power capacity [10].

The Indian wind energy sector has an installed capacity of 23,439.26 MW (as on March 31, 2015). In terms of wind power installed capacity, India is ranked 5th in the World. In 2009-10 India growth rate was highest among other top 4 countries. Tamil Nadu wind power capacity is around 29%, installed capacity 7456 MW, which is nearly 15% capacity utilization factor. As 31 march 2015 the installed capacity of wind power in India as given below in table.

Table3.State-wise Wind Power Installed Capacity In India

State	**Total Capacity (MW) till 31.03.2015**
Andhra Pradesh	1038.15
Gujarat	3642.53
Karnataka	2639.45
Kerala	35.1
Madhya Pradesh	876.7
Maharashtra	4437.9

Rajasthan	3308.15
Tamil Nadu	7456.98
Others	4.3
Total (All India)	23439.26

TECHNOLOGY OPTIONS

Wind energy development has by nature, is a merger of several inter-disciplinary subjects starting with meteorology, environment, mechanical composites, electrical systems and electronic controls along with the civil engineering requirements for the foundation and the tower structure.

Here, the Rotor which converts the kinetic energy in wind to mechanical energy has a possible efficiency level of 45-55%. Theoretically, it can go up to 59% which is known as BETZ's limit and through a system of gears converts the mechanical energy to electrical energy where the high level of efficiency has been established in the industry to the tune of 90-95%. The variable speed rotor is of capable capturing about 15 to 20% more energy from the turbulent wind. The modern machines manufactured in India with foreign collaboration have capacities more than 1 MW and they are highly suited for a tropical Country like India. [8]

THEORETICAL ANALYSIS

The monthly mean of wind speed values and their standard deviations were calculated from the time series data using the following equations:

$$vv_m = \left(\frac{\sum_{i=1}^{N} f_i v_i^n}{\sum_{i=1}^{N} f_i} \right)^{\frac{1}{n}} \left(\frac{\sum_{i=1}^{N} f_i v_i^n}{\sum_{i=1}^{N} f_i} \right)^{\frac{1}{n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The standard deviation of wind speed distributions are calculated from the following equation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} f_i (v_i - v_m)^2}{\sum_{i=1}^{N} f_i}} \sqrt{\frac{\sum_{i=1}^{N} f_i (v_i - v_m)^2}{\sum_{i=1}^{N} f_i}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where:

N is the number of hours in the considered period of time.

'vm' is the mean wind speed (m/s) and the observation values vi.

σ is the standard deviation.

Alternatively, the mean wind speed can be determined from:

$$v_m = \int_0^{\infty} v f(v) dv \, v_m = \int_0^{\infty} v f(v) dv \quad \ldots\ldots\ldots\ldots (3)$$

if the probability density function of the Weibull distribution is known.

POWER DENSITY DISTRIBUTIONS AND MEAN POWER DENSITY

It is well known that the power of the wind that flows at speed () through a blade sweep area (A) increases as the cube of its velocity and is given by v.

$$P = \frac{1}{2} \times \rho A v^3 P = \frac{1}{2} \times \rho A v^3 \quad \ldots\ldots\ldots (4)$$

Where: ρ is the standard air density. A typical value used in all the literature consulted is average air density (1.225 kg/m3), corresponding to standard conditions (sea level, 150 C).

The mean wind power density can be calculated directly from the following equation if the mean value of (v3) m, is already known

$$Pm\,(V) = \frac{1}{2} \rho A (v^3)_m \frac{1}{2} \rho A (v^3)_m \quad \ldots\ldots (5)$$

From Eq. (3), the mean value of v3m, can be determined as

$$(v^3)_m = \int_0^{\infty} v^3 f(v) dv \, (v^3)_m = \int_0^{\infty} v^3 f(v) dv \quad \ldots\ldots\ldots (6)$$

Integrating Eq.(6) the following is obtained for the Weibull function:

$$(v^3)_m = \frac{\Gamma\left(1+\frac{3}{k}\right)}{\Gamma\left(1+\frac{1}{k}\right)}(v_m)^3 (v^3)_m = \frac{\Gamma\left(1+\frac{3}{k}\right)}{\Gamma\left(1+\frac{1}{k}\right)}(v_m)^3 \quad \text{………} \ (7)$$

Where:

k is the Weibull shape factor,

Γ is the gamma function.

The monthly or annual wind power density per unit area of a site based on a Weibull

$$P_w = \frac{1}{2}\rho c^3 \Gamma(1+\frac{3}{k}) P_w = \frac{1}{2}\rho c^3 \Gamma(1+\frac{3}{k}) \quad \text{……….} \ (8)$$

Where:

c is the Weibull scale factor (m/s).

The two significant parameters k and c are closely related to the mean value of the wind speed $v_m v_m$.

$$v_m = c\Gamma(1+\frac{1}{k}) v_m = c\Gamma(1+\frac{1}{k}) \quad \text{….} \ (9)$$

Wind power density.

It is well known that the power of the wind that flows at speed V through a blade sweep area A increases as the cubic of its velocity and is given below

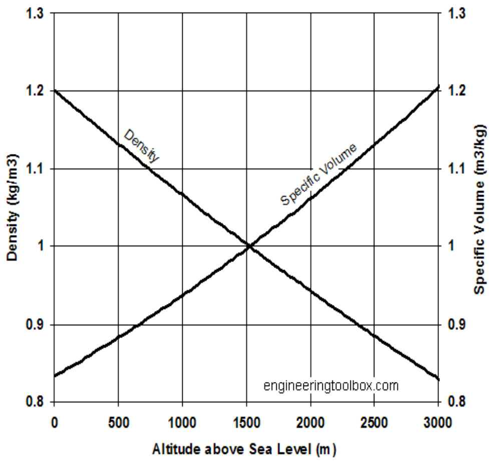

Figure 3.Variation of Air Density and Specific Volume with Altitude

ANALYSIS OF WIND POWER DENSITY

CALCULATION OF WIND ENERGY AND WIND POWER DENSITY

Calculating the energy (and later power) available in the wind relies on knowledge of basic and the physics behind kinetic energy. The kinetic energy (KE) of an object (or collection of objects) with total mass M and velocity V is given by the expression:

KE = ½ × M × V2 ………. (10)

Now, for purposes of finding the kinetic energy of moving air molecules (i.e.: wind), one has a large air parcel with the shape of a huge hockey puck, it has the geometry of a collection of air molecules passing though the plane of a wind turbine blades (which sweep out a cross sectional area A), with thickness (D) passing through the plane over a given time. The volume (Vol) of this parcel is determined by the parcel's area multiplied by its thickness:

Vol = A × D….. (11)

Let ρ represent the density of the air in this parcel. Note that density is mass per volume and is expressed as: ρ= M / Vol …….. (12)

and a little algebra gives: M = ρ × Vol

If a time T is required for this parcel (of thickness D) to move through the plane of the wind turbine blades, then the parcel's velocity can be expressed as V = D / T, and a little algebra gives D = V × T.

Let's make some substitutions in expression no. 1 (KE = ½ × M × V2)

Substitute value for M (= ρ × Vol) to obtain: KE = ½ × (ρ × Vol) × V2

And Vol can be replaced by A × D to give: KE = ½ × (ρ × A × D) × V2

And D can be replaced by V × T to give: KE = ½× (ρ × A × V × T) × V2

Now, power is just energy divided by time, so the power available from our air parcel can be expressed as:

P = KE / T = (½ ρ × ^{vv}m 3× A × T) / T = ½ × ρ× $^{v\ v}$m 3 × A.

And if we divide P by the cross-sectional area (A) of the parcel, then we are get with the expression:

P / A = ½ × ρ × ^{vv}m3 ……. (13)

Note two important things about this expression: one is that the power is proportional to the cube of the wind speed. The other is that by dividing power by the area, we have an expression on the right that is independent of the size of a wind turbine rotor. In other words, P/A only depends on (1) the density of the air and (2) the wind speed. In fact, there is no dependence on size, efficiency or other characteristics of wind turbines when determining P/A. We find the term P/A is called the "Wind Power Density" (WPD)

VARIATION OF WIND SPEED AND AIR DENSITY WITH ALTITUDE

In real measurement, the wind speed tends to increase with height in most locations and depends on atmospheric mixing and terrain roughness. Therefore, to determine the total wind energy potential, the measured surface wind speed must be modified for an height different from the normalized height (i.e. 10 m) for this reason the following equation was used.

$$v = v_i \left(\frac{z}{z_i}\right)^m v = v_i \left(\frac{z}{z_i}\right)^m \quad \text{……… (14)}$$

Where:

vi is the wind speed at normalized height, (m/s)

zi is the normalized height, m

Z is the turbine height, m

The exponent m depends on factors as surface roughness and atmospheric stability. Numerically, generally it lies in the range of 0.05–0.5, with the most frequently adopted value being 0.14 (widely applicable to low surfaces and well exposed sites).

$$m = \frac{\ln(v_i/v_r)\ln(v_i/v_r)}{\ln(z_i/z_r)\ln(z_i/z_r)} \quad \text{………… (15)}$$

Average air density at mean sea level is 1.225kg/m3 density of air above mean sea level can be determine by following exponential equation:

ρ =ρ0exp(-0.297h/3048) ……..(16)

Where

ρ is density of air at h meter height from mean sea level & ρ0 is the air density at mean sea level.

RESULT AND DISCUSSION

Table4.Summary Of Wind Data Jamgodrani Hills (2011)

Month	Monthly mean wind	Monthly standard	Hourly max wind speed	Peak speed (Km/h)

	speed (Km/h)		**deviation (Km/h)**		**(Km/h)**			
Altitudes	10 m	20 m	10m	20 m	10 m	20 m	10 m	20 m
Jan	11.52	13.25	1.16	1.56	31.38	33.79	48.27	55.51
Feb	13.42	15.52	1.70	1.60	35.00	39.82	50.68	89.30
Mar	15.05	17.50	1.05	2.14	41.83	45.05	92.52	100.56
Apr	17.30	20.36	1.86	2.76	35.40	44.25	66.77	89.30
May	21.19	24.49	2.31	2.76	48.67	54.30	78.84	80.45
Jun	21.37	24.79	1.11	1.59	50.28	62.75	95.74	141.59
Jul	21.29	24.56	1.66	1.60	41.43	44.64	61.14	74.82
Aug	18.32	21.73	2.05	2.09	37.01	43.85	55.51	62.75
Sep	15.02	18.24	1.09	1.36	31.38	37.41	69.99	74.01
Oct	11.50	13.17	1.03	0.68	30.57	32.18	55.51	65.16
Nov	11.21	12.79	0.87	1.47	35.00	39.82	41.03	61.14
Dec	9.79	11.34	1.16	1.87	24.94	28.16	37.01	41.03
Annual	15.75	17.98	4.09	4.58	50.28	62.75	95.74	141.59

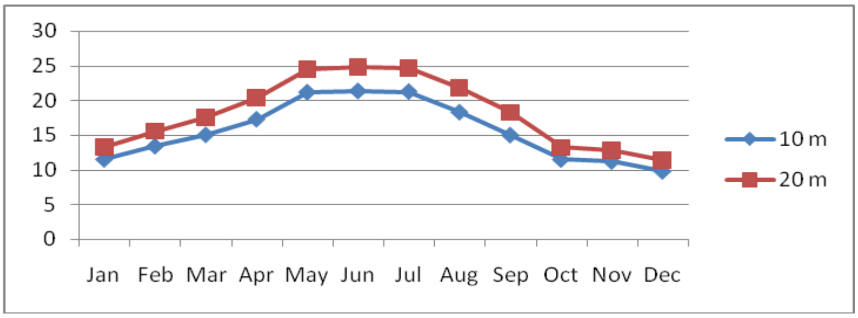

Figure 4. Monthly mean wind speed (Km/h)

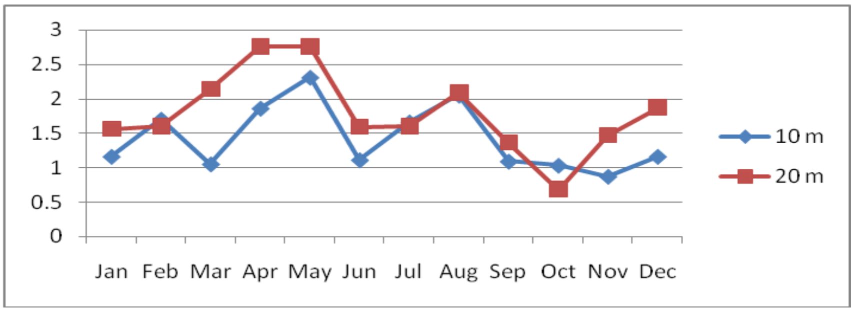

Figure 5. Monthly standard deviation (Km/h)

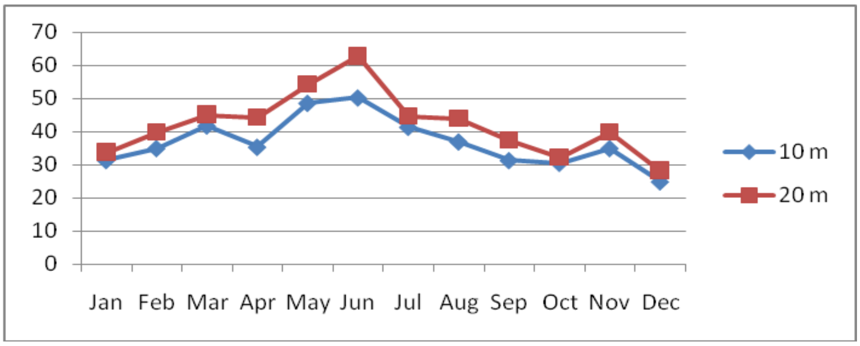

Figure 6. Hourly max wind speed (Km/h)

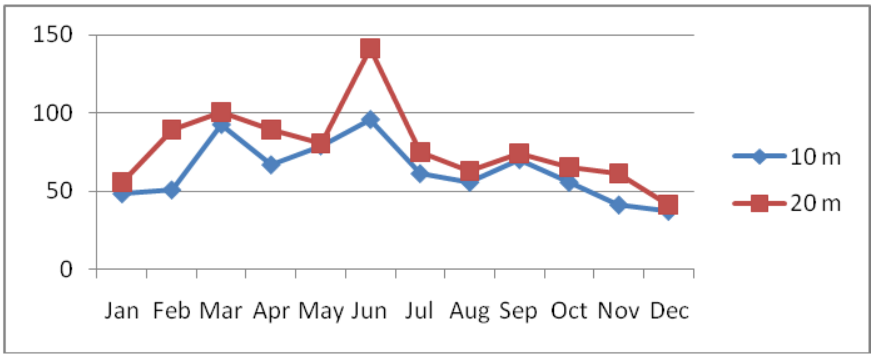

Figure 7. Monthly Peak speed (Km/h)

WIND POWER DENSITY AT JAMGODRANI HILLS AT DIFFERENT ALTITUDE

Table5.Wind Power density at 25 m hub height ρ=1.1566kg/m^3

Month	Velocity m/s	Power density in W/m^2
Jan	3.86022	32.946878
Feb	4.52155	52.936109
Mar	5.0984	75.950101
Apr	5.9316	119.91294
May	7.1348	210.03845
Jun	7.2223	217.85569
Jul	7.1552	211.84545
Aug	6.3307	140.73272
Sep	5.314	86.012059
Oct	3.837	32.363251
Nov	3.726	31.336291
Dec	3.3034	20.662648

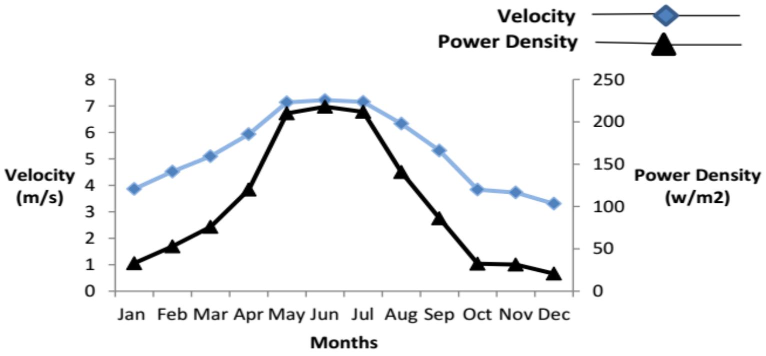

Figure 8.Wind Power density in W/m^2 versus month at 25 m height

Table6.Power density output at 80 m hub height density=1.151 kg/m^3

Month	Velocity m/s	Power density in W/m^2
Jan	4.928401	68.891174
Feb	5.772533	110.69923
Mar	6.508537	158.67026
Apr	7.57261	249.9091
May	9.108512	434.89822

Jun	9.220325	451.11173
Jul	9.13493	438.69327
Aug	8.082529	303.86951
Sep	6.783771	179.66307
Oct	4.898912	67.661911
Nov	4.757609	61.974308
Dec	4.217832	43.183022

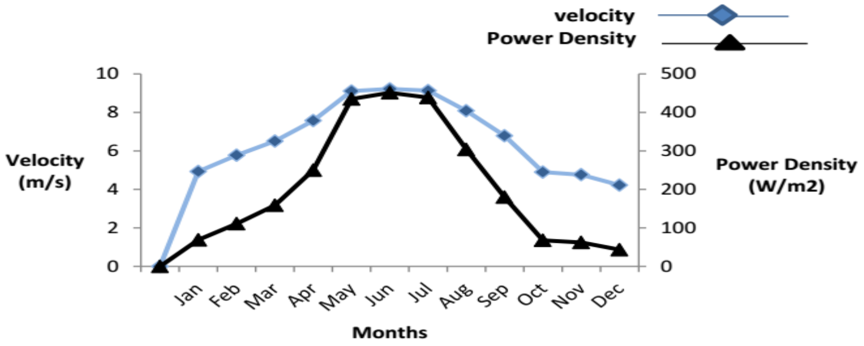

Figure 9.Wind Power density in W/m^2 versus month at 80m height

Figure (8 & 9); Shows that wind power density, increases with altitude. It is maximum in June and minimum in December. In May, June and July wind speed is very high. The season from April to September wind speed is comparatively high so this is called high wind season. The season from October to march when wind speed is low, so that is called low wind season.

MONITORING POWER OUTPUT BY 225 KW NEPC WIND TURBINE INSTALLED AT JAMGODRANI HILLS

Table7.Specifications of M.P. Wind Farms 225kW NEPC Wind Turbines Installed In Jamgodrani Hills

TECHNICAL SPECIFICATION

Rated Power	Hub height	Number of blades	Blade length	Rotor speed	Cut out speed	Rated Speed	Cut in speed	Gear ratio	Generator rpm
225 kW	30 m	3	13 m	40 rev/min	14 m/s	13 m/s	3 m/s	1:40	1600

SPECIAL FEATURES

Type	3 blade upwind horizontal
Braking System	Hydraulic Brake
Control	Microprocessor Control
Gear Type	Helical Gear
Coupling between Generator and Turbine	Flexible Coupling
Generator	Permanent Magnet Alternator
Output	415 VAC Nominal
Power regulation	Stall Regulated
Frequency	50 Hz
Cooling system	Air cooled

Source:M.P.wind farm Jamgodrani hills

The identified power output control limits were obtained 10 turbine 225KW NEPC monthly data. Figure 10 (a-b)represents the X-Chart and R-Chart is obtained from monthly power curve. It can be seen that the identified control limits are well established.

Next the monthly X-Chart and R-Chart is analysed on individual wind turbine. In the average power generation September month is poorly performed. However, other turbines were also poorly performed in the month of September.

For X-Chart; Average= 21.60, UCL= 29.28, LCL= 13.91, A2=0.308, Sub group =10

For the R-Chart; Average= 25.04, UCL= 44.496, LCL= 5.58, D4 = 1.777, D3 =0.223, Sub group= 10

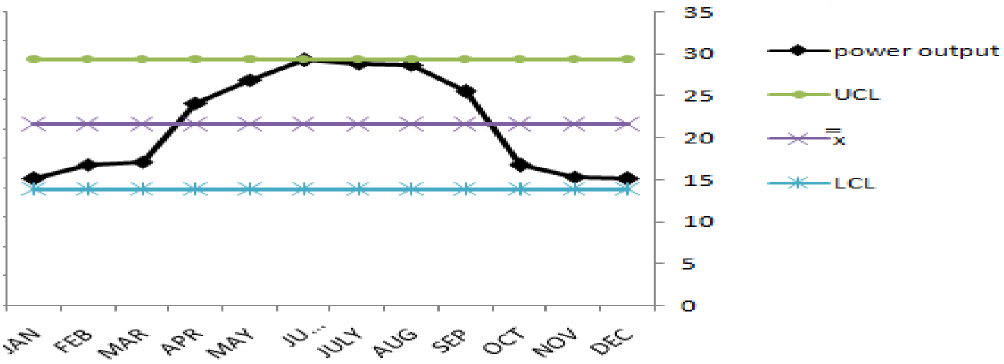

Figure 10. Establish control chart on testing data; (a) X-Chart

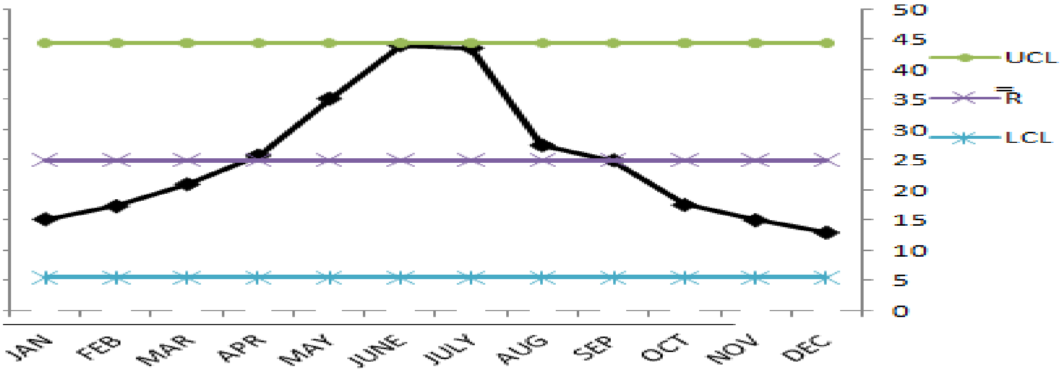

Figure 10. Establish control chart on testing data (b) R-Chart

Based on monthly production data namely capacity factor and effective capacity of wind turbines are observed. While capacity factor mainly depends upon total production output, the effective capacity represents the total energy produce by the wind turbine when it was operational.

$$\mathrm{CF} = \frac{\mathrm{Production(KWh)}}{\mathrm{no.\ of\ days} \times \mathrm{no.\ of} \frac{\mathrm{hours}}{\mathrm{day}} \times \mathrm{rated\ capacity(KWh)}}$$

$$\mathrm{EC} = \frac{\mathrm{Production(KWh)}}{\mathrm{Operation\ period(hr)} \times \mathrm{rated\ capacity(KWh)}}$$

Figure (11& 12) result shows that effective capacity and capacity factor almost similar when in case when all the turbines were found to be within the specified control limit. Whereas, capacity factor and effective capacity for the case with one turbine faults has the lower value for one out of control wind turbine.

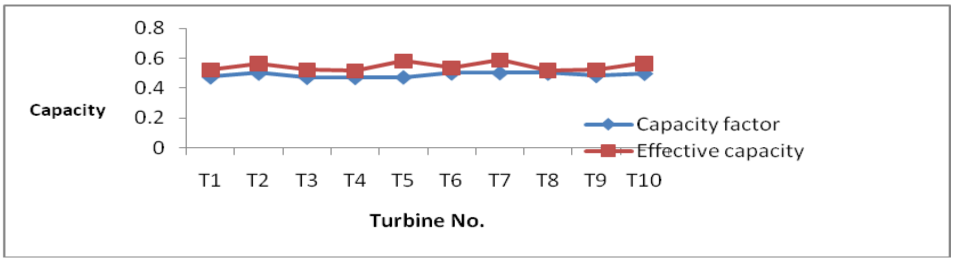

Figure 11. Capacity Curve Of May 2011

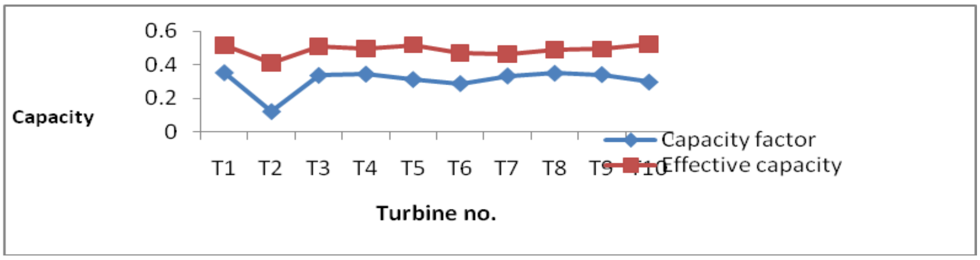

Figure 12. Capacity Curve Of Jan 2011

The result obtained by analysing the production data validates the applicability for X-Chart and R-Chart in performance monitoring and evaluation of overall wind farm.

In above three performance curves, power density, wind velocity curves were used. The X-bar Chart, together with the R-Chart, is a sensitive control chart for identifying assignable causes of power and process variation, and used for continuous monitoring of the data point in time. Finally capacity factor will be investigated.

CONCLUSION & FUTURE SCOPE

This research conducted in the dissertation was divided in two parts: Monitoring the performance of overall wind farm. Within the first part, wind velocity monthly, hourly, standard deviation, peak speed, power density of farm has been validated on the testing instances. Annul average wind speed at 30m height is 5.43 m/s and at 75 m height Annul average wind speed is 6.586m/s. Mean yearly wind power density at 30m height is 92.72 kW/ m2 and at75 m height mean yearly wind power density is 164.52kW/m2.Second part of the paper focused on the monitoring of the overall wind farm using X-bar Chart, together with the R-Chart. Monitoring of overall wind farm based on the operational data only. Also the relationship between the underperforming wind turbines with their capacity factor will be investigated.

A further study can be carried out to increase output power through installing more efficient turbine, increasing hub height, using higher value of swept area, fluctuating power future challenge. Life cycle analysis tool can be applied to precisely estimate the actual economic benefit from installed wind turbine. Condition monitoring instrument like strain analyzer, vibration analyzer can be mounted on tower to ensure reliability that will give the information before breakdown.

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