Experimental Investigation, Optimization and Performance Prediction of Wind Turbines for Complex Terrain

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Abstract: This paper presents on investigation of site selection for wind turbine on the basis of wind flow characteristic at RGPV Hill-top. The purpose of this article is to addressing the general aspects of this area of knowledge and contextualizing it to perform an investigation on wind flow characteristics and to determine the Annual Energy Production (AEP) for previously installed wind turbines located at the same site. In this work, the recorded time series wind data fetched by the NRG Symphonie Data logger wind mast installed at Energy Park, RGPV campus. This data analyzed for a period of One year at the height of 20 meter, for studying the observed wind climate (OWC).The wind turbine site selection tool i.e. WAsP, presented in this paper provides insights into the most feasible sites for a given geographic area based on user inputs, and can assist for the further planning. The influences of roughness of the terrain, for the area were also taken into consideration, followed by the vector map of the area. These data were analyzed using WAsP software and regional wind climate of the area was determined, leading to a wind resource map of the whole site, providing vital details which helped in selecting the proposed turbine sites.

Keywords: OWC, Generalized wind climate, Wind Rose, WAsP, AEP, wind power density.

1. Introduction

Wind was one of the first power sources harnessed by civilizations. The earliest known sailing vessels date back to 4000 bc and the earliest known windmills. The growing public awareness of the environmental concerns, limited energy supply, and uncertain energy prices has spearheaded this debate. Wind energy has experienced a remarkable expansion in the past years. The global cumulative capacity of wind power generation has increased 20 times in a ten year period and is expected to grow even faster in the future. Year 2013 saw a global boom for wind energy. Across the globe wind turbines are being installed in cities, homes, farms, Indian reservations, businesses and universities. As a leading renewable energy source, wind power is on the rise [3].

An understanding of the characteristics of the wind (velocity, direction, variation) is critical to all aspects of wind energy generation, from the identification of suitable sites to predictions of the economic viability of wind farm projects to the design of wind turbines themselves, all is dependent on characteristic of wind. The most striking characteristic of the wind is its stochastic nature or randomness. The wind is highly variable, both geographically and temporally. Moreover this variability exists over a very wide range of scales, both in space and time. This variability is due to different climatic conditions in the world also the tilt of earth on its axis and its own spinning results in different wind distributions across the world. Also within any climatic region, there is a great deal of variation on a smaller scale, which is dictated by several factors such as ratio of land and water, presence of mountains etc. The type of vegetation also affects wind distribution through absorption of moisture, temperature moderation and reflection of sun's energy. Generally more wind is witnessed on the tops of hills and mountains than in low level areas. Even more locally, wind velocities are altered by obstacles such as trees or buildings. For any location there is variation of wind pattern, wind speed may vary from year to year; also wind distribution will change from decade to decade. These variations are important to be considered because they can affect production of wind energy [5].

2. Methodology

An overview over the logical sequence of the simulation process, from preparation to simulation is providing in (Fig. 1).

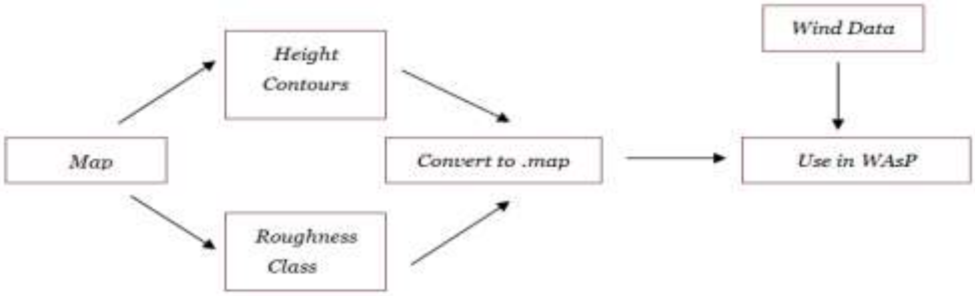

Fig. 1 The Simulation Process

2.1 Map

The map for the selected area is downloaded from Shuttle Radar Topography Mission (SRTM) data, which offers maps of high resolution. SRTM elevation data has now been released for the entire terrestrial surface.

2.2 Height contours

In WAsP simulations the landscape complexity is described by height contours. These height contours lines are generated by importing Digital Elevation Model (DEM) files of RGPV and surrounding to Global Mapper software, which is to be done by the help of SRTM data.

These files are then exported as a shape file (.shp) which is presented in (Figs. 2 and 3) shows the Roughness lines and contour lines of the area exported using shape files. The height contour lines are essential since change in height influences the turbulence and consequently the wind profile.

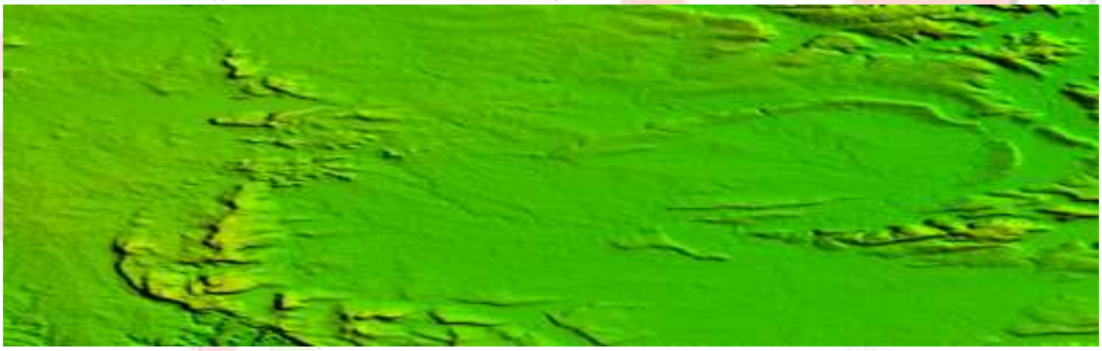

Fig. 2 SRTM map of RGPV energy park, Bhopal (India)

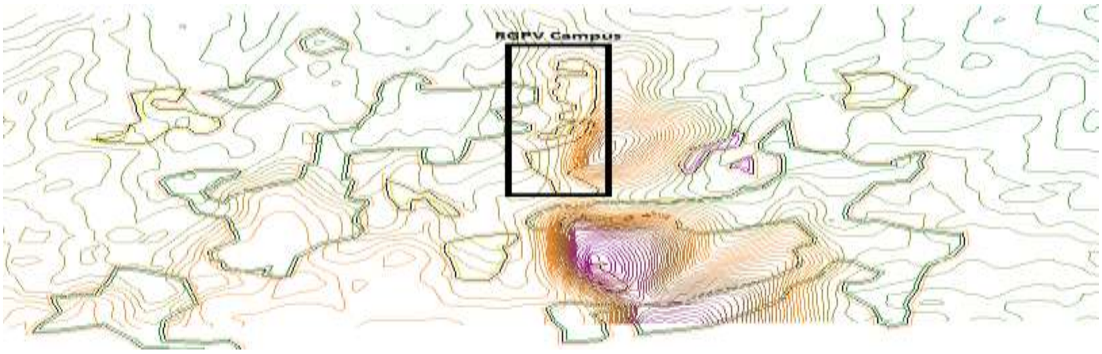

Fig. 3 Combined map with Roughness lines and Contour lines

2.3 Roughness class

The roughness of a particular surface area is determined by the size and distribution of the roughness elements it contains for land surfaces these are typically vegetation, built-up areas and the soil surface.

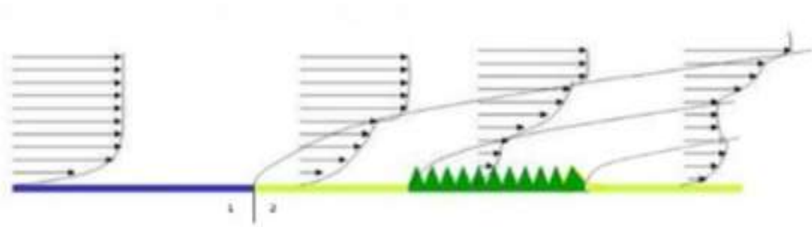

Fig. 4 Effects of change in roughness on boundary layer

Wind profile is dependent on the roughness of the surface. Turbulence increases when there is a change in roughness. This change the height of the internal boundary layer as demonstrated in (Fig. 4). Roughness is classified in different categories and is given certain length. This is presented in the Table 1.

Table 1 Roughness type and length (roughness length is 1/30th of the actual length of the element)

Area Type	Roughness Length (m)
Water areas e.g. lakes, ocean etc.	0.002
Farmland with open-appearance / buildings / trees	0.03
Farmland with closed appearance	0.10
Suburbs, shelter belts, trees & bushes	0.40
Tall forest	1.50

2.4 Convert to .map

Both height contours and roughness lines are converted into .map format. This is done only because WAsP requires this format type in their simulations [1].

3. Wind Data

The wind data was recorded by the NRG Symphonie data logger which is installed at geographical location of East 077' 21.668 and North 23' 18.720 and the elevation of mast base is 591 meters. At the wind measurement mast, a 3 cup type anemometer with measuring height of 20 meter along with two wind vanes at the heights of 20 and 38 meters is assembled as shown in (Fig. 5). It also provides the measurements for relative humidity, atmospheric pressure, temperature and rain gauge.

Fig. 5 Wind masts at energy park, RGPV

Site Information:
Project: New Project
Location:
Elevation: 591

Sensor Information:
1 NRG #40C Anem m/s
2 NRG #40C Anem m/s
3 NRG #40C Anem m/s
4 No SCM Installed
5 No SCM Installed
6 No SCM Installed
7 NRG 200P Vane deg
8 NRG 200P Vane deg
9 NRG 110S Temp C
10 NRG BP20 Baro mb
11 No SCM Installed
12 iPack Voltmeter
13 NRG #40C Anem m/s
14 NRG #40C Anem m/s
15 NRG #40C Anem m/s

9/1/2013 to 8/31/2014
Summary Report
SITE 4444
New Site

Channel	1	2	3				7	8	9	10		12	13	14	15
Height	40 m	40 m	20 m	—	—	—	38 m	20 m	6 m	3 m	—	m	0	0	0
Units	m/s	m/s	m/s	—	—	—	deg	deg	C	mb	—	Volt	m/s	m/s	m/s
Intervals with Valid Data	51924	51924	51924				51924	51924	51924	51924		51924	51924	51924	51924
Average Filtered Data	3.86	3.88	2.63				340.93	323.44	25.58	948.41		13.47	0.4	0.4	0.4
Average for All Data	3.86	3.88	2.63				340.93	323.44	25.58	948.41		13.47	0.4	0.4	0.4
Min Interval Average	0.3	0.4	0.4						8	933.4		13.1	0.4	0.4	0.4
Date of Min Interval	9/9/2013	9/9/2013	9/1/2013						1/12/2014	7/23/2014		4/11/2014	9/1/2013	9/1/2013	9/1/2013
Time of Min Interval	12:00:00 AM	12:00:00 AM	7:20:00 PM						6:50:00 AM	3:10:00 AM		6:30:00 AM	12:00:00 AM	12:00:00 AM	12:00:00 AM
Max Interval Average	17.5	17.5	13.4						45.1	961.1		14.3	0.4	0.4	0.4
Date of Max Interval	4/20/2014	4/20/2014	4/20/2014						6/6/2014	1/19/2014		2/17/2014	9/1/2013	9/1/2013	9/1/2013
Time of Max Interval	9:30:00 PM	9:30:00 PM	9:30:00 PM						2:50:00 PM	10:50:00 AM		8:10:00 AM	12:00:00 AM	12:00:00 AM	12:00:00 AM
Average Interval SD	0.77	0.78	0.79				11.42	17.79	0.11	0.15		0	0	0	0
Min Sample	0.3	0.4	0.4						7.9	933.4		13	0.4	0.4	0.4
Date of Min Sample	9/1/2013	9/1/2013	9/1/2013						1/12/2014	7/23/2014		6/12/2014	9/1/2013	9/1/2013	9/1/2013
Time of Min Sample	2:50:00 PM	10:40:00 PM	12:00:00 AM						6:50:00 AM	2:40:00 AM		6:00:00 AM	12:00:00 AM	12:00:00 AM	12:00:00 AM
Max Sample	38.2	36.7	33.7						45.5	961.5		14.7	0.4	0.4	0.4
Date of Max Sample	4/17/2014	4/17/2014	4/17/2014						6/6/2014	1/19/2014		1/7/2014	9/1/2013	9/1/2013	9/1/2013
Time of Max Sample	6:20:00 PM	6:20:00 PM	6:20:00 PM						2:40:00 PM	10:20:00 AM		9:20:00 AM	12:00:00 AM	12:00:00 AM	12:00:00 AM
Average Interval TI	0.23	0.23	0.34										0	0	0
Wind Speed Direction							W	W							

Generated Saturday, September 20, 2014 NRG Systems SDR Version 7.03

Fig. 6 Device Report

A data logger was connected with all sensors on the mast to collect data in time series, which has a fixed averaging interval of 10 minutes. For each of the 12 channels averages, standard deviations, minimum values and maximum values are calculated from continuous 2 second data samples. Data intervals are calculated every 10 minutes, time stamped with the starting time of each interval and written to the Multi-Media Card at the top of each hour. (Fig. 6) shows the Device Report of NRG system.

4. WAsP

WAsP is software which calculates energy output based on a linear flow model and is reliant on input wind data. This tool is used to estimate and optimize wind farm energy production generate wind resource maps. This software uses the Reynolds-Average Navier-Stokes equation to create a linear model, Wind Atlas, to solve wind flow equations. This Model requires wind data, height contour lines, and Roughness map of the area to calculate energy production of a wind turbine [2].

WAsP can be used for various purposes such as:

- Estimating and optimizing wind farm production and efficiency,
- Mapping of wind resources and
- Digitalizing information on maps, such as height contours.

5. Observed Wind Climate

In the observed wind climate file, the frequencies of occurrence of the wind in a number of sectors (the wind rose) and wind speed bins is represented. This also contains the height of observation above ground level and the geographical coordinates (latitude and longitude) of the wind mast.

Table 2 Sector wise parameters at 20 Meter

Sectors	A	K	U	P	F
0	2.9	1.57	2.58	27	4.4
30	2.4	2.13	2.09	10	7.8
60	2	2.05	1.77	6	13
90	2.2	2.22	1.96	8	12.2
120	2.1	2.17	1.84	7	6.9
150	2	2.12	1.80	6	3.4
180	2.4	1.79	2.12	13	2.2
210	3.1	2.10	2.73	23	6.1
240	3.3	2.08	2.91	28	9.1
270	4.1	2.57	3.67	47	17.7
300	3.8	2.75	3.40	36	11.8
330	3.2	1.82	2.84	30	5.6
All	2.9	1.81	2.59	23	100

The values of Weibull Parameters (A, k), mean wind speed (U), mean power density (P) and frequency of all 12 sector (0° to 359°) is calculated from WAsP OWC Wizard and recorded in Table 2 for 20 meter height respectively.

Table 3 Measured and Emergent Mean Wind Speed and Power Density

	Mean Wind Speed	**Mean Power Density**
Measured at 20 m	2.45 m/s	19 W/m^2
Weibull-fit at 20 m	2.62 m/s	23 W/m^2
Discrepancy at 20 m	1.2 %	2.0 %

The measured discrepancy and the Weibull fitted values of mean wind speed and mean power density for 20 meter height is shown in Table 3.

6. Wind Rose And Weibull Histogram

A wind rose is a diagram that depicts the distribution of wind direction and speed at a location over a period of time on the basis of meteorological observations of wind speeds and wind directions. The length of each spoke on a wind rose indicates how often the wind comes from this direction [7]. The meaning of longer spokes is the wind comes from this direction more often. A

Wind rose is made from dividing the compass into 12 sectors equally, each for 30 degrees of the horizon. (A wind rose can also be drawn for 8 or 16 sectors, but 12 sectors is standard set by the European Wind Atlas) [4].

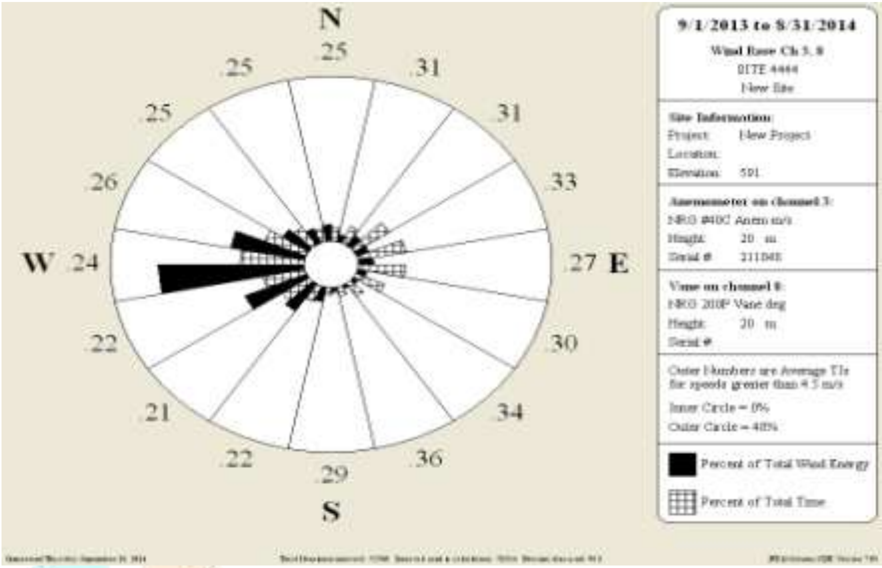

Fig.7 Wind rose generated by Symphonie software

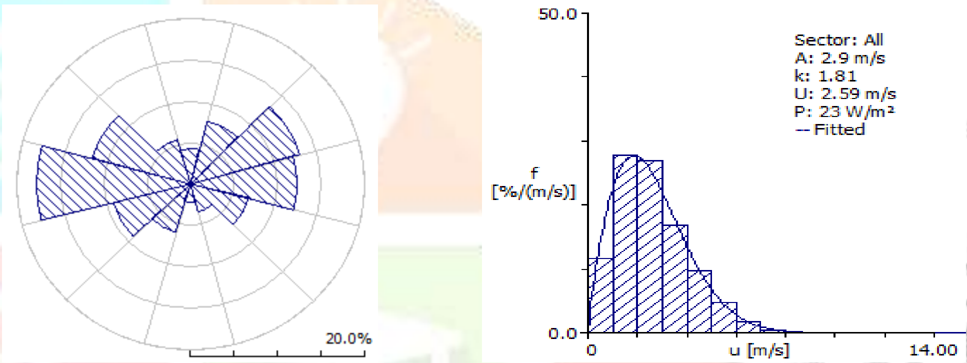

Fig. 8 Wind Rose and Spectrum of Energy Park Mast, RGPV

In (Figs. 7 and 8) the wind rose, wind speed histograms and Weibull approximation is shown for 20 meter meteorological height respectively.

7. Generalized Wind Climate

The observed wind data is converted into a generalized wind climate (GWC). The wind observations have been cleaned in terms of site specific conditions such as: surface roughness, shelter (buildings etc.) and orography. This information was then converted into a map format. When the data has been converted into standard conditions, for four standard roughnesses, five standard heights above ground and 12 azimuth sectors, it can then create a general wind atlas. When the wind atlas data has been generated, WAsP can estimate the wind climate at any particular point by performing the inverse calculation as is used to generate the wind atlas [6].

The wind atlas containing 5 standard heights and 5 standard roughness classes are shown in the Table 4 for 20 meter height respectively.

Table 4
Wind atlas at 20 meter

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull A [m/s] Weibull k Mean speed [m/s] Power density [W/m²]	3.4 1.87 2.99 34	2.5 1.73 2.19 15	2.1 1.73 1.91 10	1.7 1.72 1.51 5	1.1 1.65 1.00 1
15.0 m	Weibull A [m/s] Weibull k Mean speed [m/s] Power density [W/m²]	3.5 1.88 3.11 38	2.7 1.76 2.37 18	2.4 1.76 2.10 12	1.9 1.75 1.72 7	1.4 1.67 1.23 3
20.0 m	Weibull A [m/s] Weibull k Mean speed [m/s] Power density [W/m²]	3.6 1.89 3.20 41	2.8 1.80 2.51 21	2.5 1.79 2.24 15	2.1 1.78 1.87 9	1.6 1.69 1.39 4
25.0 m	Weibull A [m/s] Weibull k Mean speed [m/s] Power density [W/m²]	3.7 1.90 3.27 43	3.0 1.83 2.62 23	2.7 1.82 2.36 17	2.2 1.80 1.99 10	1.7 1.71 1.52 5
30.0 m	Weibull A [m/s] Weibull k Mean speed [m/s] Power density [W/m²]	3.8 1.92 3.33 45	3.1 1.86 2.72 25	2.8 1.85 2.46 19	2.4 1.83 2.09 12	1.8 1.73 1.63 6

8. Estimation of Power Production of Turbine

The frequency of occurrence of a given wind speed is determine by the probability density function or distribution function. Estimating the relevant probability density function or Weibull distribution is the key purpose of the wind atlas methodology.

Hence, to calculate the power production of a wind turbine or wind farm, we need the predicted wind climate for the site and the following turbine characteristics.

8.1 The wind turbine hub height [m]
8.2 The power curve [ms^{-1} and kW]
8.3 The thrust coefficient curve

8.1 The wind turbine hub height

In general, the hub height is the nominal hub height given by the wind turbine manufacturer. This is the height provided in the wind turbine data files. However, in certain situations the precise meaning of height above the ground is not evident.

8.2 The power curve

Once the power curve $P(u)$ is measured for a wind turbine, the mean power production can be estimated provided the probability density function of the wind speed at hub height is determined by a siting procedure.

$$P = \int_0^{\infty} Pr(u)P(u)d(u)$$

The power production by a wind turbine varies with the wind that strikes the rotor. The power produced as function of the wind speed at hub height is called the *power curve*. The (Fig. 9) shows a power curve of 10 kW Machinocraft wind turbine generator.

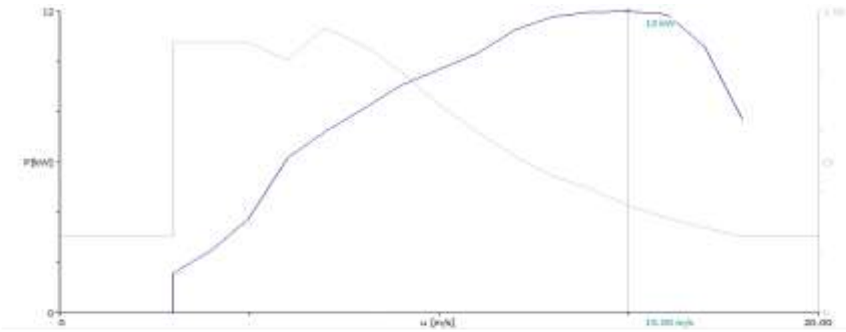

Fig. 9 Power curve of 10 kW Machinocraft wind turbine generator

When the wind speed is less than the *cut-in* wind speed, the turbine will not be able to produce power. When the wind speed exceeds the cut-in speed, the power output $P(u)$ increases with increasing wind speed to a maximum value, the *rated power*; thereafter the output is almost constant. At wind speeds higher than the *cut-out* speed the wind turbine is stopped to prevent structural failures.

8.3 Thrust coefficient curve

The thrust coefficient must be specified in order to calculate wind farm wake effects and wind farm efficiency. WAsP can estimate the wake losses for each turbine in a farm by giving the power and thrust coefficient curves of the wind turbine and the wind farm layout and thereby the net annual energy production (AEP) of each wind turbine and of the entire farm.

9. Resource Grid Maps

Resource grids provide a rectangular set of points for which summary predicted wind climate data are calculated. The points are regularly spaced and are arranged into rows and columns, which shows a pattern of wind climate or wind resources for an area.

Each point in the grid is like a simpler version of a normal turbine site. All the points have the same height a.g.l. If a wind turbine generator is associated with the grid, then that specification is used for all of the points in the grid. The resource grid always shows the gross annual energy production without taking into account the occurrence of any turbines in the area (hierarchy). Likewise, the wind speeds and power densities are 'unobstructed', i.e. no wake effects from any turbines affect these values [4].

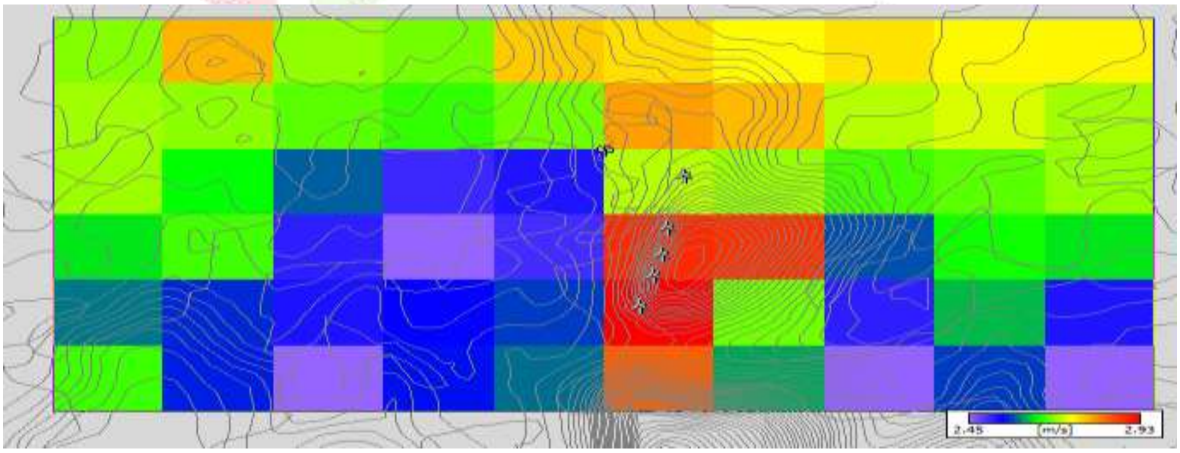

Fig. 10(a) Mean wind speed of resource grid at 20m

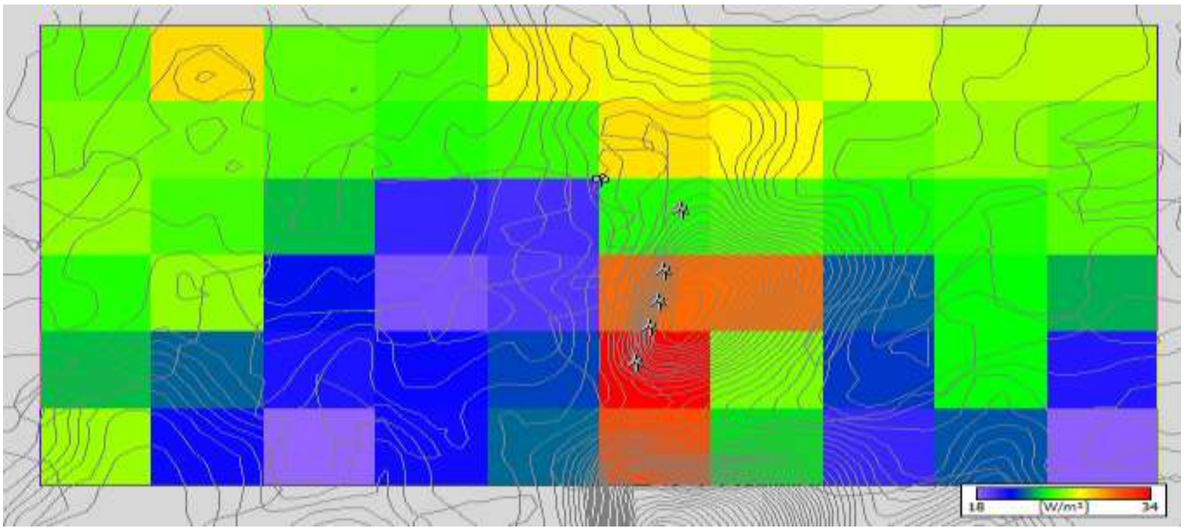

Fig. 10(b) Power density of resource grid at 20m

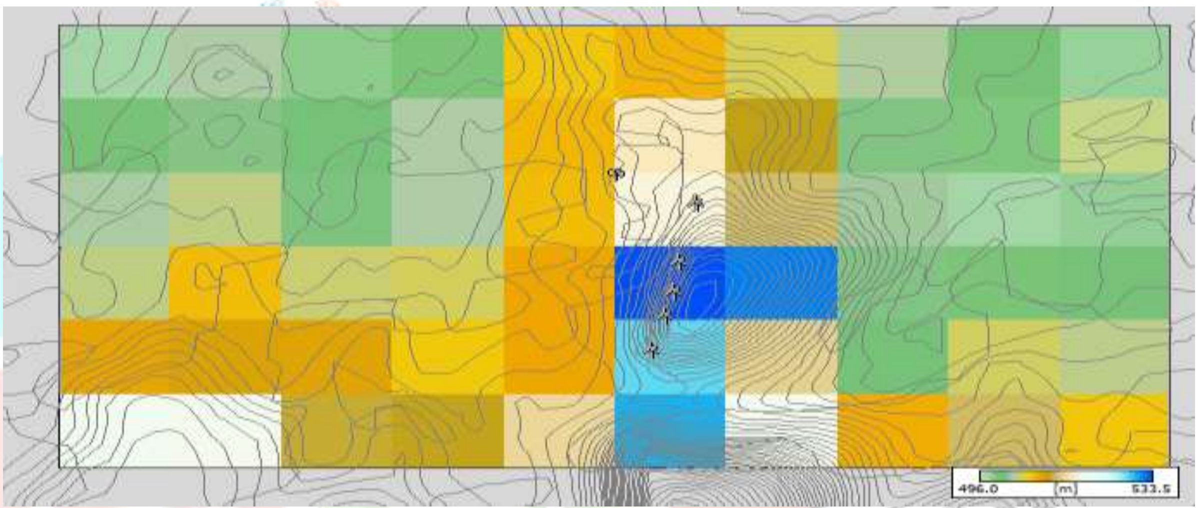

Fig. 10(c) Elevation Profile of Resource Grid

Fig. 10 Resource Grid Maps for RGPV Hill Top

For each point in the grid, WAsP calculates the following data which can be displayed in the resource grid, as shown in (Fig 10).

- The elevation
- The mean wind speed
- The mean power density

10. Conclusions

To study the effects of roughness on the wind flow, the roughness of the whole area surrounding the site was put into consideration and the area was divided into various roughness classes and as a result it was observed that roughness is a crucial factor in predicting the wind flow. In order to study the prevailing wind climate at the site, wind data was recorded at Energy park wind mast of Location East 077' 21.668 and North 23' 18.720 for the duration of One year from 04 July 2016 to 04 July 2017. It was observed from the wind roses that wind flows predominantly in 10 and 11 sectors from the West-North, West(270°-300°) taking North as reference at 0° indicating a strong influence of the rainy season in the Indian subcontinent. It was found out that mean wind speed and mean power density at 20 meter height was 2.59 m/s and 23 W/m^2 respectively, with minimum and maximum wind speed 0.40 m/s and 13.40 m/s respectively.

In order to calculate an estimate for the annual power production by installed wind turbines, Turbine Editor utility tool is used to calculate the power curve for the 10 kW wind turbine and the net AEP calculated for the turbines at turbine site 01 location (741581.7, 2579109.0) m and 05 location (741742.1, 2579906.0) m was 11.240 MWh and 11.647 MWh respectively.

Acknowledgement

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