Wind Power
in Karnataka and Andhra Pradesh
Potential Assessment, Costs, and Grid Implications

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Wind Power
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Executive Summary

Till recently, the on-shore wind power potential in India was officially estimated to be 49 GW, out of which 17 GW forms part of the country's mainstream energy mix. However, recent studies have indicated this potential to be underestimated. A few studies have estimated wind potential in India to be over 2000 GW and the official wind resource potential was recently revised to 102 GW by the Center for Wind Energy Technology (C-WET), at 80 m hub height. Given that wind power generation technology is already cost-effective, if this revised potential is confirmed to exist, wind can form a significant share of the country's energy mix. It is to this effect that CSTEP undertook the study of reassessment of wind resource potential in the states of Karnataka (KA) and Andhra Pradesh (AP), which account for more than one-fourth of the wind potential in the country according to official estimates. The methodology used, and some of the key findings of this study are discussed briefly below.

Methodology

Weibull characterization of annual wind speed histograms at 80m hub height is used to extrapolate Wind Power Density(WPD) at each location to higher hub heights of 100 and 120m. The WPD, an indicator of the energy generation potential of a site, was intersected with land-use information to spatially estimate state-wide potential across waste and agricultural land. This potential was translated to installable capacity, with a capacity density factor of 6.3 MW/ km^2, assuming a Suzlon 2.1 MW turbine and inter-turbine spacing of a 7D * 5D array configuration.

The cost of realizing the installable potential is estimated in terms of Levelized Cost of Energy (LCOE) at three hub heights, using the power curve of a Suzlon 2.1 MW machine with a rated speed suited for Indian conditions. Baseline capital costs at 80 m are scaled to higher hub heights of 100 and 120 m. Further, wind power generation data for typical seasonal days is analyzed for a discussion on required storage ramp-up times. Finally, storage technology options are evaluated, with a demonstrative case study of the impact of including Na-S storage battery on the system LCOE.

Key Findings

Wind Potential Estimates: Potential estimates are summarized below, for the theoretical maximum available for wasteland and scrub forest land. Estimates for *agricultural land* are presented as *a moderate scenario for a 5% usage* of suitable wind potential sites, keeping in mind practical constraints in realizing the same. For instance, potential on agricultural land in KA has a large outer limit owing to almost 70% coverage of the state. However all wind potential sites are not considered suitable for full exploitation given food security concerns.

Potential estimates, by land type, for Karnataka:

MW Potential			
Hub height (m)	**Wasteland**	**Scrub forests**	**Agricultural land (moderate scenario)**
80	30, 400	18, 900	20, 100
100	43, 200	28, 300	32, 200
120	49, 500	31, 500	38, 400

Potential estimates, by land type, for Andhra Pradesh:

MW Potential		
Hub height (m)	**Wasteland**	**Agricultural land (moderate scenario)**
80	88, 900	12, 000
100	1, 15, 200	18, 200
120	1, 63, 800	30, 800

Wastelands: In KA, districts with good potential from wastelands are Bellary, Chitradurga, Chamrajnagar, Chikballapur and parts of Hassan, Koppal, Bijapur, Chikmagalur and Kolar. In AP, good potential is concentrated in the districts of Ananthpur, Kadapa, Chittoor, Kurnool, Vishakapatnam and parts of Srikakulam.

Scrub Forest Land, KA: Most of the scrub forest land suitable for wind power is concentrated in Bellary with smaller parcels in Chikballapur and Chamrajnagar.

Agricultural Land: In KA, districts with good potential from agricultural lands are Bellary, Chitradurga, Chamrajnagar, Chikmagalur, Kolar, Chikballapur, and parts of Bijapur, Haveri, Tumkur and Hassan. In AP, best potential is found in the districts of Ananthpur, Chittoor, parts of Kadapa and eastern coastline of AP.

Cost of Wind Power Generation: Baseline capital costs were estimated to be Rs. 5.9 Cr. / MW from a median observation of CDM projects. Scaled costs at 100 m and 120 m were estimated to be Rs. 6.5 Cr. / MW and Rs. 7.3 Cr. / MW respectively, for the higher end of the scaling range.

Based on the above capital costs, LCOE values for adding capacity estimated in the previous sections, ranged from Rs. 5.5/ kWh to Rs. 3.8/ kWh, and Rs. 5.9/ kWh to Rs. 3.2/ kWh, for KA and AP, at 80 m and 100 m respectively. This corresponded to net Capacity Utilization Factors (CUFs) ranging from 20% to 32%, and 19% to 39%, for KA and AP, at 80m and 100 m hub height respectively.

Capacity factors increase as a result of increased net energy production (owing to better wind speeds and WPD), across all WPD ranges, from 80 m to 100 m. This contributes to lowered LCOE values for all WPD ranges from 80 m to 100 m. However, in the case of potential LCOE/CUF improvements from 100 m to 120 m, the increased energy generation (and improved CUF), does not necessarily compensate the incremental capital cost expected at 120 m in terms of the LCOE. Since capital cost estimation at 120 m is based on limited field experience and its impact on LCOE is uncertain, results are considered for 80 m to 100 m only.

If the estimated potential is cumulatively added, using best potential sites first, the following capacity is available at the minimum CUF values indicated correspondingly:

Capacity (MW) and corresponding CUF in Karnataka				
Hub height (m)	**Wasteland**	**Scrub forests**	**Agricultural land**	**CUF**
80	5, 000	5, 000	35, 000	25% and above
100	13, 000	9, 500	1, 00, 000	30% and above

Capacity (MW) and corresponding CUF in Andhra Pradesh			
Hub height (m)	**Wasteland**	**Agricultural land**	**CUF**
80	28, 000	60, 000	25% and above
100	44, 000	1,00, 000	30% and above

Grid Integration: Based on analysis of state load demand and generation data, it was observed that in Karnataka, wind power generation is high during the monsoon periods when the load demand is low. There are both diurnal as well as seasonal variations in the wind power generation. While present hydro power generation capacity in Karnataka, at 3, 600 MW is sufficient to offset the variation in the existing wind power generation, future plans to increase wind capacity need to include fast ramping generation and storage options to avoid grid management problems.

Variations in wind power generation, in the form of ramps, for the month of April ’11 and August ’11 which are representative of low-wind and high-wind seasons respectively, were analyzed to assess the requirement of the maximum extent of the ramps that can be expected in the grid, at hourly and sub-hourly levels. It was observed that higher ramp-downs, i.e. events when generation decreases over time, are more frequent in the month of August which is the high windy season. In August 2011, wind power ramp down of 8 - 14% of installed capacity in Karnataka is observed nearly 20 times over 60 minute intervals. For an installed capacity of 20, 000 MW, this variation translates to a 1600 to 2000 MW power loss in 60 minutes. This is indicative of the extent of planning required for adding large-scale wind power to the grid.

Storage options: An illustrative analysis of costs of Na-S battery systems was carried out, with an estimated capital cost of Rs. 1.98 Cr./ MW at 20% (of installed turbine capacity) storage level. With a discharge time of 3 hours, capital cost varied from Rs. 1.98 Cr. / MW to Rs. 4.94 Cr. / MW from 20% to 50% storage levels respectively. At a 20% level, the costs varied from Rs. 1.32 Cr. / MW to Rs. 5.27 Cr. / MW from discharge time of 2 hours to 8 hours respectively. From the per - unit cost perspective, the LCOE of a 1 MW wind farm with 22% CUF that includes Na-S storage for 3 hours once daily is estimated to increase by Rs. 2.54/ kWh. The marginal rate of increase in LCOE is higher for increasing backup duration.

Based on the rate of change of the above values, it is evident that from a total cost perspective, it is more economical to invest in low duration high-power capacity storage i.e. power intensive systems than high duration low power capacity storage i.e. energy intensive systems, keeping the energy capacity of both as same.

Discussion of the above findings, and methodology for analysis, are detailed in the respective sections of the report.

1 Introduction

Until recently, India's wind power potential was estimated to be 49,000 MW. This was based on the assumption of 50 m hub height, 2% land availability in most states and 0.5% in poor windy states. In terms of realized potential, present wind power installed capacity is at 17,350 MW [1]. This places India fifth in the world, after China (~62 GW), USA (~47 GW), Germany (29GW) and Spain (21 GW)[2]. Five states, namely Tamil Nadu, Gujarat, Maharashtra, Rajasthan and Karnataka, account for most of India's installed capacity and estimated potential (Table 1).

Table 1.1: Installed Capacities in major States

State	Installed Capacity (MW)	Estimated potential (MW)
Tamil Nadu	7072	5374
Gujarat	3016	10609
Maharashtra	2772	5439
Rajasthan	2079	5005
Karnataka	2143	8591

However, several recent studies have indicated that the potential is underestimated. A recent study from Lawrence Berkeley National Laboratory (LBNL) estimated wind power potential in India to be 2006 GW at 80 m and 3121 GW at 120 m hub-height[3].[i] The Energy and Resources Institute (TERI) estimates 4250 GW as the outer limit potential for wind power development[4]. Similar re-assessments in US and China have yielded 400% and 800% higher potential respectively[5].

These reassessments reflect technology advancements that allow wind turbine installations at hub heights of 80-120 m. The current global trend is also to install more powerful wind electric generators with name plate capacities of 1-4 MW. Together, these factors enable extraction of more power from wind compared to sub-MW turbine installations at lower hub heights of 50 m based on which earlier assessments were done. Subsequent to these studies, India's official estimates were also revised to 102,788 MW at 80 m based on uniform land availability assumptions of 2% [6].

The above mentioned official estimates assumed uniform land availability across the country. Since wind potential is closely tied to the land where the resource is found, there is a need to delve deeper and integrate land use information at the state level for accurate wind potential assessments. Further, land use policies for different land types vary across states and directly impact the realizable potential. This was the main motivation for State-level reassessment of wind potential.

Scope and Objective

In this study, we focused on Karnataka and Andhra Pradesh (AP), since these two states account for more than one-fourth of the wind potential in the country. The current installed capacity of wind power in Karnataka and AP is 2143 MW and 248 MW respectively. Further, these states have projects planned for an additional 7000 MW and 2000 MW respectively.

However, merely having high potential is not enough. There are several challenges that the developers and system operators face - from land allocation challenges and long gestation periods of projects, to challenges with managing intermittency in wind generation. Wind and other renewable sources add significant operational strains on the grid due to its intermittency, and require complementary sources like hydro, gas or storage options to ensure stable operation of the grid. Since availability of these complementary sources and planning for them vary across states, this analysis is better done at the state level to begin with.

The approach in this study is at a granularity suitable for utility-scale assessment for planning; it is not for investment-grade analysis, which requires much more detailed assessment of wind measurements at turbine installation height. The study excludes offshore wind potential and also excludes analyses for small-wind turbines which are installable on rooftops.

The specific objectives of this study are the following:

1) Estimation of wind power potential in Karnataka and A.P considering :
    a. 3 hub heights – 80 m, 100 m and 120 m
    b. Various land use types suitable for wind power development
2) Costs of wind power generation
3) Analysis of wind intermittency patterns in the region and grid integration challenges
4) Analysis of options to manage intermittency

This report is organised in four sections to mirror the above objectives. First section details wind potential estimation methodology and results. Second section discusses the costs of generating energy from this potential, followed by observations from field visits to validate land characteristics of sites with high potential. Third section deals with wind intermittency patterns observed in existing wind capacity. Finally, the fourth section discusses storage options available to manage the observed intermittency.

2 Estimation of Wind Power Potential

This study used Geographic Information System (GIS) to overlay wind potential data and land use data to identify sites suitable for wind power development. This section details the data sources used, methodology for calculating potential, and presents results of the analyses for Karnataka and AP. Wind Potential assessment results for each State are presented separately and potential available from different types of land, depending on what portion of land can be dispensed for wind power development, is highlighted.

Data Sources

Wind data

Wind speed and wind power density datasets are obtained from 3Tier at 50 m at 80 m levels. These datasets are part of a global wind dataset derived from Numerical Weather Prediction models (NWP) that combine meso-scale weather models with data on elevation, vegetation etc. to simulate surface processes and jet level dynamics. Since these datasets were obtained from 10- year mesoscale Weather Research and Forecasting (WRF) model runs, they can be considered as indicative of long-term wind resource assessments. However, project-specific analysis will require higher resolution data backed with ground measurements. An analysis at the level of this study is useful for stakeholders to choose the most promising locations.

Following data were obtained from 3Tier at 3.6 km horizontal resolution for the entire state of Karnataka and A.P.

a) Annual average wind speeds and wind speed densities (WPD)[1] at 50 m and 80 m hub heights

b) Monthly average wind speeds and WPD at 50 m and 80 m hub heights

c) Annual wind frequency histograms at 50 m and 80 m hub heights

For example, Fig. 2.1 shows monthly average wind speeds at 50 m for one location in Karnataka. Wind speeds are significantly higher in the monsoon months which is typical of most locations analysed. Such seasonal and daily variations in wind speed are represented using a wind speed histogram which depicts the frequency distribution of wind speeds for the entire year. A sample histogram is provided in Fig. 2.2. Such data was available at a 3.6 km resolution for Karnataka and A.P.

[1] Explained in detail in Section 2.3

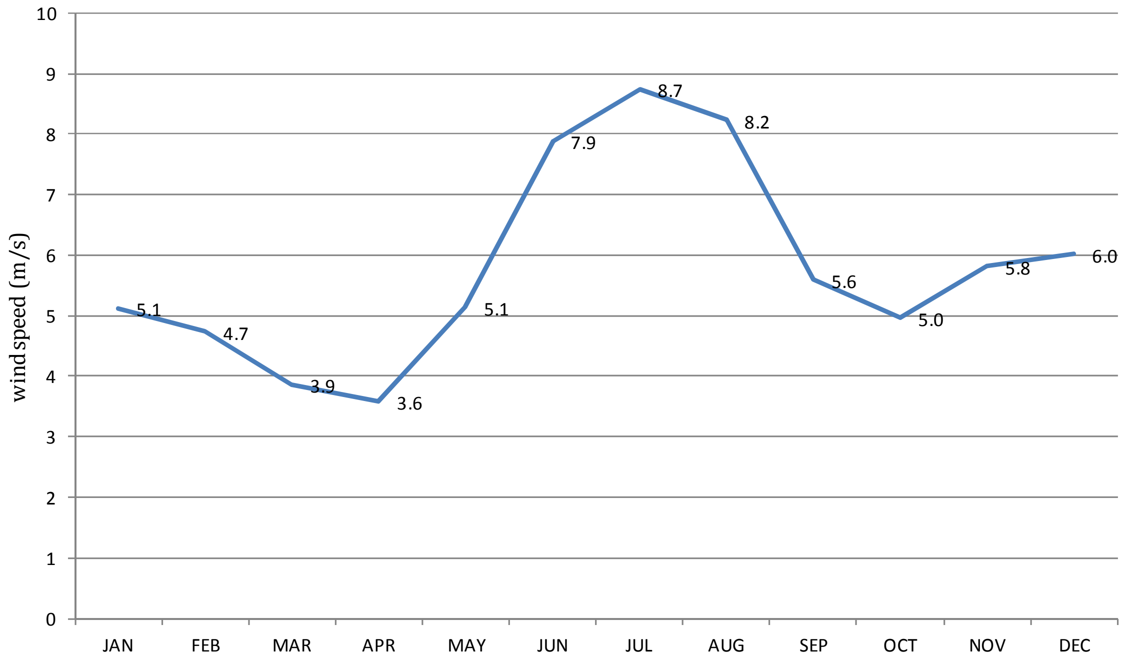

Figure 2.1: Monthly average wind speeds at 50 m for one location in Karnataka

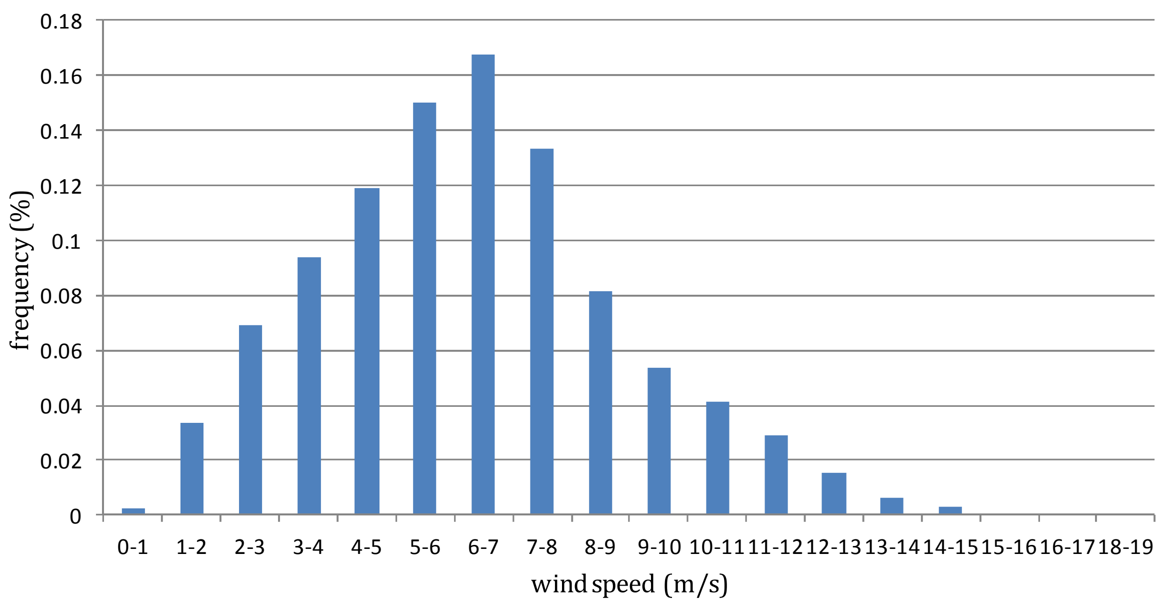

Figure 2.2: Sample wind speed histogram at 50 m

Validation of model data

The above wind speed data are the results of mesoscale weather models. The wind data from the model as described above needs to be validated against actual wind speed measurements. This validation was performed by 3Tier themselves, for the South Asian region against surface observations from the National Centre for Environment Protection (NCEP) dataset, which consisted of data from 24 meteorological stations, 16 of which were in India. The model showed an overall bias of +0.19 m/s and a Root Mean Square Error (RMSE) of 0.69 m/s against the NCEP dataset [7].

Further, we had access to 10-minute interval wind speed data from ten wind monitoring stations in Karnataka, from Karnataka Renewable Energy Development Ltd (KREDL). This was used to compare model data with actual wind measurements at 50 m hub height. The monitoring stations were concentrated in the northern and central regions of Karnataka (Fig 2.3).

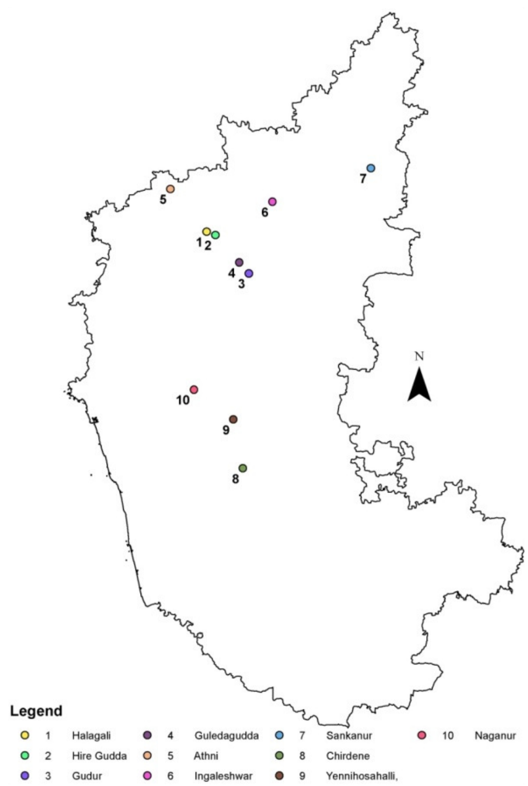

Figure 2.3: Location of wind power monitoring stations in Karnataka at hub height of 50 m

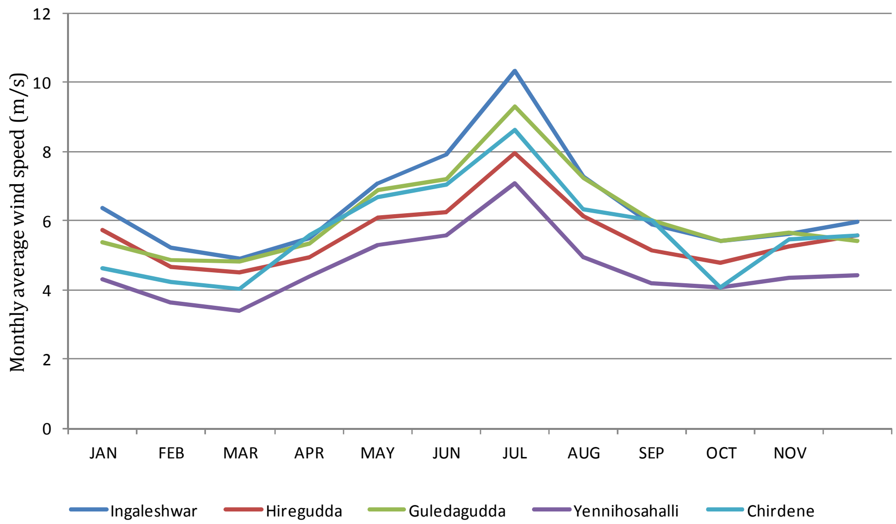

Figure 2.4: Monthly average wind speeds from 5 wind monitoring stations in Karnataka

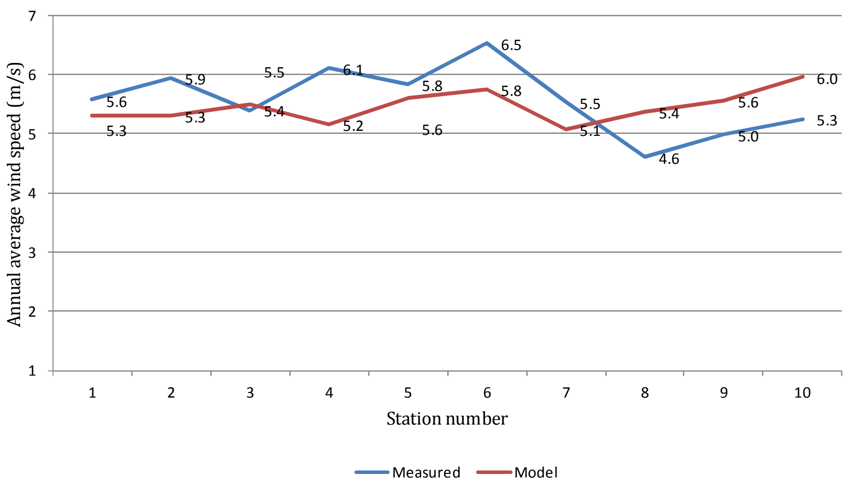

Figure 2.5: Comparison between model and measured data

Fig. 2.4 shows monthly average wind speeds, obtained from 10-minute interval observations of wind speeds, from ten stations in Karnataka. This illustrates the seasonality of wind speeds. Fig. 2.5 compares annual average wind speeds from the model with those from the ten monitoring stations. It is important to note that while measured data were for a 2-year period, the data available from model were based on a 10-year run. Even with this constraint, the model compared well with the observed values with an RMSE of 0.61m/s, acceptable for a scoping study.

Land Use Data

Land Use Land Cover (LULC) data was procured from Karnataka State Remote Sensing Applications Centre (KSRSAC), from a project on Land Use/ Land Cover Mapping on 1:50,000 scale using Linear Imaging Self-scanning Sensor (LISS) –IV (5.8m) satellite image. Bhuvan LULC data was also available in a raster format. However, since the area of each LULC class after combining with wind power density information is easy to obtain accurately in a vector format, the LULC data from KSRSAC were selected for this analysis. This data is current till 2005-06.

In addition to land use classification, the World Database of Protected Areas (WDPA) database was used in this study to eliminate all areas notified as protected areas as these strictly cannot be used for any developmental purpose. This is a worldwide spatial database of protected areas created by the United Nations Environment Programme, World Conservation Monitoring Centre and the International Union of Conservation of Nature's World Commission of Protected Areas. The database is updated and released annually and the 2010 release was used for this analysis.

Elevation Data

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) is a freely downloadable DEM for the entire world with a spatial resolution of 30 m. It is developed jointly by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). ASTER GDEM is in GeoTIFF format with geographic lat/long coordinates and a 1 arcsecond (approximately 30 m) grid that provides elevation information for each pixel. This was used in the analysis to eliminate areas situated at an elevation above 1500 m.

Slope

Slope is an important factor in identifying good wind sites. Generally, wind developers exclude locations which have a slope exceeding 20%. The slope map of Karnataka was also procured from KSRSAC. It was generated from the contour maps of 20 m interval, from the Survey of India (SOI) toposheet.

Methodology

Theoretical Background of Estimation

Wind power generation involves individual turbines converting kinetic energy in wind to electrical energy using a wind electric generator. The instantaneous power extracted from wind by a turbine is expressed by the equation below:

$$P = C_p \frac{1}{2} \rho A v^3 \tag{1}$$

where P is power (Watts), ρ is the air density (kg/m^3), A is the cross-sectional area of the rotor (m^2), v is the wind speed (m/s) and C_p is the efficiency of the wind turbine generator[8]. Since the power produced by the turbine is directly proportional to the swept area of the rotor, which is a function of rotor diameter, wind power is often expressed as power available per square meter of cross sectional area of the turbine rotor, denoted by wind power density WPD (W/m^2).

While Eq. 1 depicts the instantaneous power extracted from the wind, a good indicator of wind energy generation potential of a site is the annual average WPD, which accounts for variations of wind speed and thereby, power produced at any instant. Since wind power is proportional to cube of wind speed, even small increases in wind speeds can lead to dramatic increases in power produced. For e.g., doubling of wind speeds produce eight times more power. Therefore, one cannot determine average WPD at a site by substituting annual average wind speed into the above equation. Therefore, calculation of annual average WPD requires averaging of cubes of wind velocities at 1-min or 10-min intervals throughout the year. Since the wind speed data procured from 3-Tier are available in annual and monthly mean wind speeds for each location and not in time series, it would have been erroneous to use Eq. 1 to calculate annual average WPDs. Therefore, this study used wind speed histograms to calculate WPD at each location.

WPD using Wind Speed Histograms

Wind speed histograms are available from 3Tier at a 3.5 km horizontal resolution. Illustrative line histograms at 80 m for Karnataka and A.P. are displayed in Figures 2.6 and 2.7 respectively for best, median, and lowest WPD. Best WPD locations typically have a more uniform distribution around the mean while lowest WPD locations have exponentially decaying wind speed histograms as illustrated in Fig. 2.6.

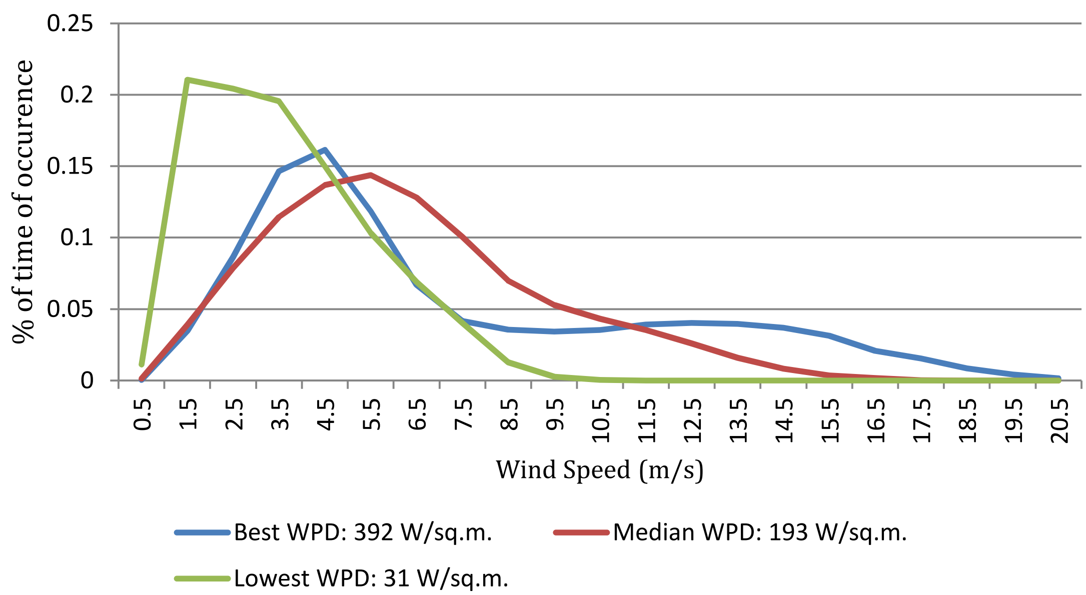

Figure 2.6: Illustrative histogram of the best, median and lowest WPD sites in Karnataka

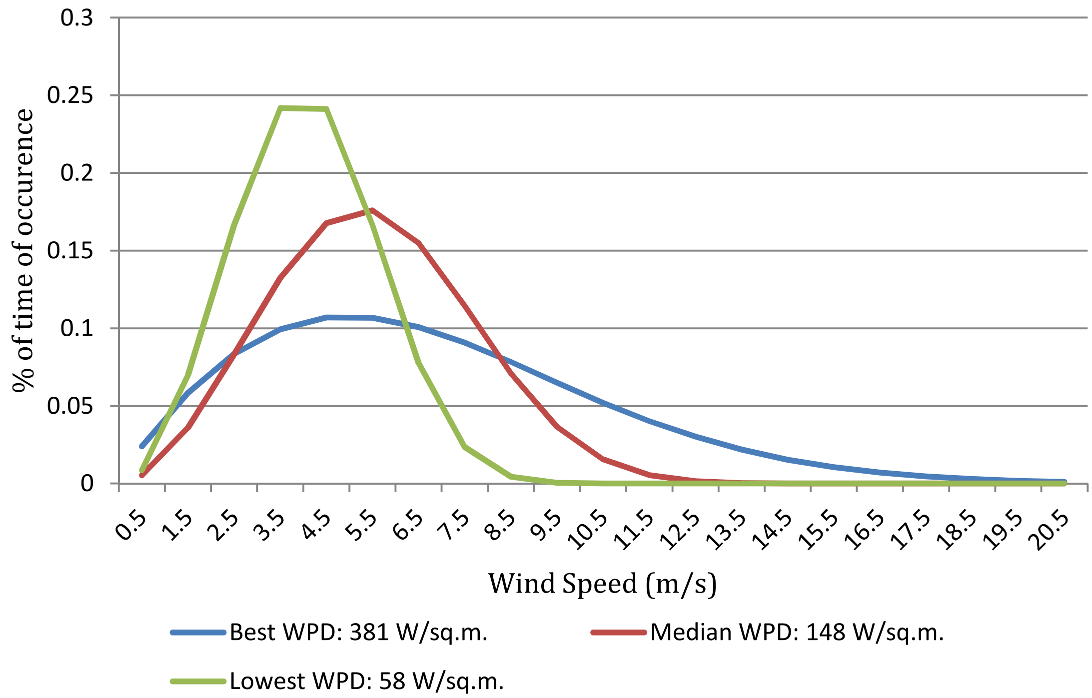

Figure 2.7: Illustrative histogram of the best, median and lowest WPD sites in A.P.

In wind energy calculations, wind speed is considered a random variable that can take any value within a certain range at a given location. Such a wind speed histogram is widely represented in wind climatology literature using a continuous probability distribution function (pdf), specifically the Weibull pdf that is expressed below [9]:

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

Where f(v) is the probability of observing wind speed v, k is the shape parameter (dimensionless) and c is called the scale parameter (m/s). The main feature of representing the wind frequency distribution in such a way is that the area under the curve between any two wind speeds equals the probability that the wind is between those two speeds. Given the wind speed histogram at each location, the cumulative distribution function for any wind speed can then be represented by:

$$F(v) = \{1 - \exp\left[\left(\frac{v}{c}\right)^{k}\right]\} \quad (3)$$

where F (v) is the probability that the observed wind speed is less than v. From Eq. 3, by taking natural logarithm on both sides, we get:

$$\ln\{-\ln[1 - F(v)]\} = k\ln(v) - k\ln(c) \quad (4)$$

A plot of ln { - ln[1- F(v)] } versus ln (v) presents a straight line with a slope of k and y-intercept of -k ln (c) . This is the least square method of finding Weibull parameters [5] and was used in this study to determine k and c. Once the Weibull parameters c and k, at any location are known, WPD can be calculated using:

$$\mathrm{WPD} = \frac{1}{2}\,\rho\,A\,c^3\,\Gamma\left(\frac{k+3}{k}\right) \tag{5}$$

where Γ is the gamma function.

Extrapolation to higher heights

The atmospheric boundary layer extends to the first few 100 m above ground level, and therefore the friction offered by earth's surface affects wind speed. While smooth surfaces like water offer low resistance, irregular surfaces such as forests and buildings offer higher resistance. An expression that takes into account this effect on the wind speed is the power law:

$$\left(\frac{v}{v0}\right) = \left(\frac{H}{H0}\right)^{\alpha} \tag{6}$$

where v is the wind speed at height H, v_0 is the wind speed at height H_0 and α is the friction coefficient [8]. α is a function of the terrain over which wind blows and therefore the impact of height on wind speed varies according to the terrain and is usually approximated to 1/7 for open lands [8].

In this study, WPD and wind speed histograms at 80 m were known from 3Tier model data. However, this study relied on calculating WPD at higher hub heights rather than average wind speeds. This is possible because Weibull parameters at a new height, and hence the annual average WPD, can be derived if Weibull parameters at any height H_0 are known. Scale parameter at the new height can be determined using [10] :

$$\left(\frac{c}{c0}\right) = \left(\frac{H}{H0}\right)^{n} \tag{7}$$

Where c_0 is the scale parameter at a known height H_0, c is the scale parameter to be found at a new height H and exponent n is [11]:

$$n = \frac{[\,0.37-0.088\ln(c0)]}{[1-0.088\ln\,(\frac{H0}{10})]} \tag{8}$$

Equations 7 and 8 are used to determine the scale parameter at 100 m and 120 m. Shape parameter for the wind frequency distribution is assumed to be the same between 80-120m.

GIS analysis for selection of sites using WPD criteria

GIS is a powerful tool for performing spatial analysis. In this analysis, ArcGIS, the industry standard GIS software was used. The WPD and wind speed histogram data obtained from 3-Tier for 80 m were first extrapolated to higher hub heights of 100 m and 120 m using the above method. This yielded WPD at 3 hub heights of 80, 100, and 120 m at a 3.6 km horizontal resolution. This was used to create a layer (WPD layer) to geospatially locate sites with WPD greater than 200 W/m^2. Figures 2.8 – 2.10 show the wind power density distribution for Karnataka. As wind speeds increase with height and WPD is proportional to cube of velocity, turbine height is a crucial factor. As expected, there are significantly more locations with wind power density greater than 200W/m^2 at 120 m.

Figures 2.8-2.10 illustrate that most of the high wind regions are concentrated in the central and southern parts. In Karnataka, locations with highest wind potential are in the districts of Bellary, Chitradurga, Chamrajnagar and parts of Kolar, Chikballapur, Hassan, Haveri, Gadag, Koppal and Bijapur.

Similarly, Figures 2.11 – 2.13 show the WPD maps for Andhra Pradesh. In Andhra Pradesh, the highest wind power potential sites are located mostly in the north eastern coast, and in the southern districts of Ananthpur and Chittoor.

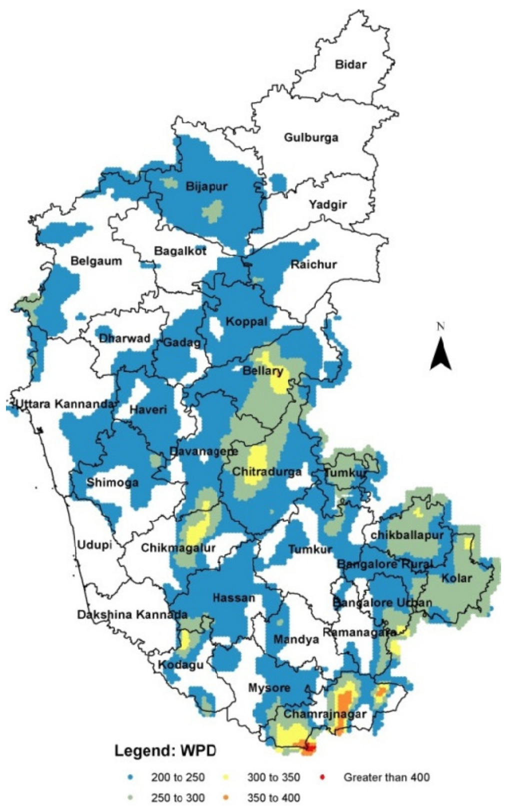

Figure 2.8: Locations with WPD > 200 W/m² at 80m hub height

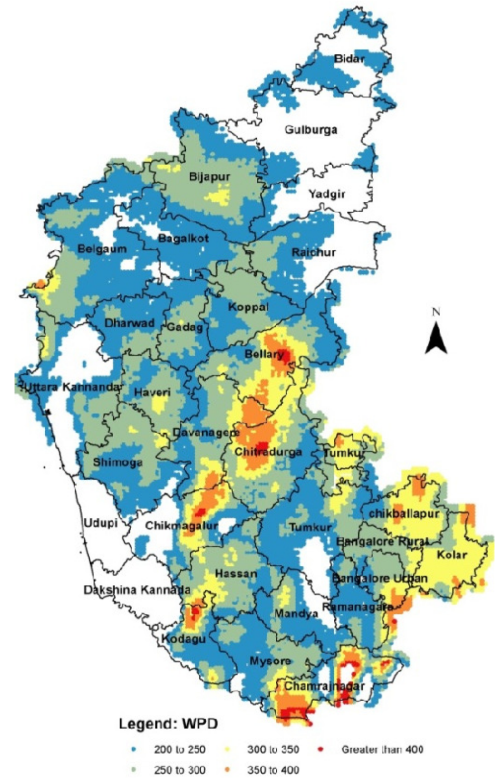

Figure 2.9: Locations with WPD > 200 W/m² at 100m hub height

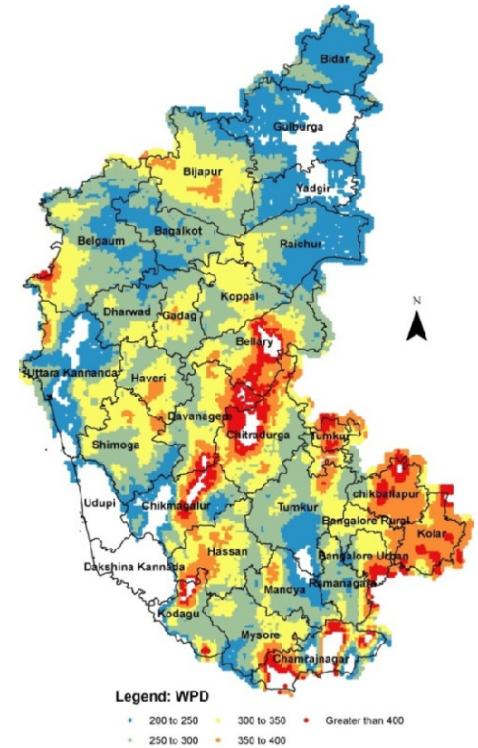

Figure 2.10: Locations with WPD > 200 W/m² at 120m hub height

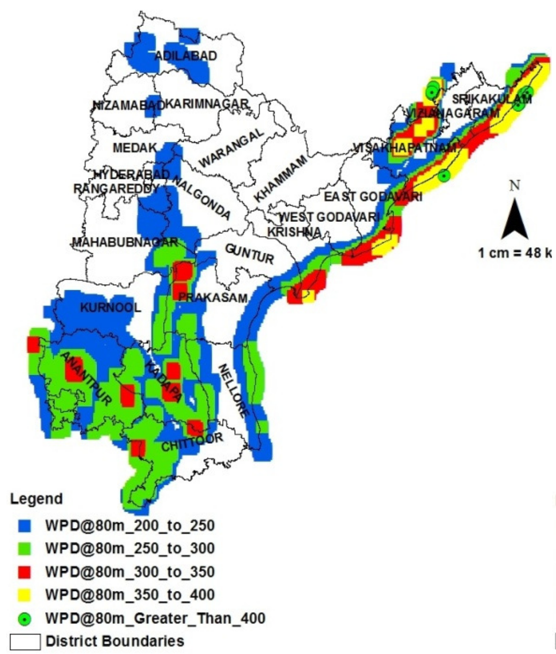

Figure 2.11: Locations with WPD > 200 W/m² at 80m hub height

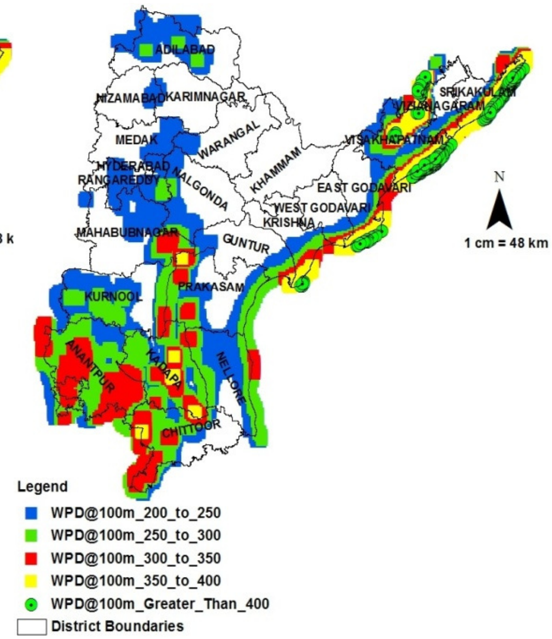

Figure 2.12: Locations with WPD > 200 W/m² at 100m hub height

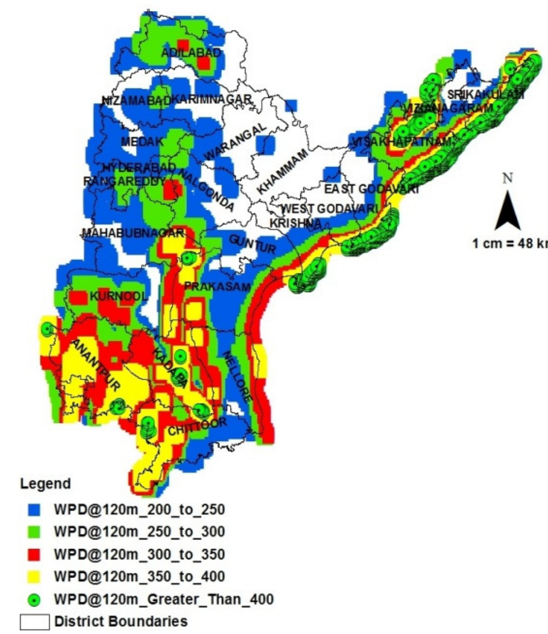

Figure 2.13: Locations with WPD > 200 W/m² at 120m hub height

Applying Land use criteria

In addition to identifying high potential wind sites, it is important to assess if they are available at locations that make it possible to realize the potential. The selection of a good site for installing wind farms depends on several factors as listed below:

1. Elevation of site: This should be preferably lower than 1500 m, as the air density decreases with height
2. Gradient: The gradient should be preferably lower than 15-20% because wind farm construction is difficult in steep terrain
3. Proximity to road network: This is important as the large turbine blades and other equipment have to be transported to the site
4. Proximity to Transmission network: It is preferable for the site to be close to the transmission network so as to minimise cost
5. Type of land: This study gives priority to land classified as wastelands as these land types are not used for anything else, are stony or degraded. Therefore, there is scope for diverting significant portion of these lands for wind power development. The table below shows various categories of wastelands as per National Remote Sensing Centre (NRSC) definition

Table 2.1: Distribution of different types of wasteland

Wasteland Category	Definition
Salt affected	Land that has adverse effects on growth of most plants due to the action or presence of excess soluble salts (saline) or high exchangeable sodium.
Gullied/ Ravenous	Due to erosion of soil, land dissection occurs and finger like processes appear on the surface of the land in isolation
Scrub Land	Land prone to deterioration due to erosion; such lands generally occupy topographically high locations, excluding hilly/mountain terrain.
Sandy area	Areas that have stabilised accumulation of sand, in coastal, riverine or inland areas
Barren rocky/stony waste	Rock exposures of varying lithology, often barren and devoid of soil and vegetation cover

The suitability of different types of wastelands for wind farms depends on the terrain. This study also considers land classified as scrub forests for wind potential analysis. These are commonly in the fringes of notified forest areas, and could be considered for wind power development subject to forest department clearances. We have also included agricultural lands in the analysis because wind power development has a relatively smaller land foot print as compared to area of the total wind farm [12]. This offers an opportunity for simultaneous use for agriculture and wind power. Even a small portion of agricultural land subjected to mixed use holds significant wind power potential. The percentages of these different land types that can be set apart for wind power affect the realizable potential and this is the subject of analyses, detailed later in the Chapter.

Fig 2.14 shows the LULC map and Table 2.2 lists the share of each land type in Karnataka.

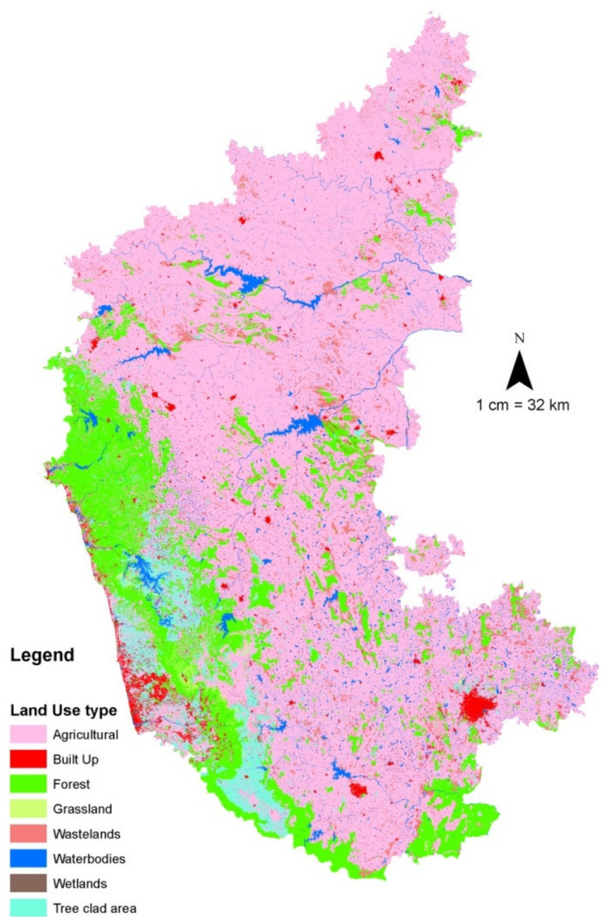

Figure 2.14: LULC map of Karnataka

Table 2.2: Land use statistics of Karnataka

Type of Land	Area (in sq.km)	% of geographical area of the state
Agricultural Lands	1,33,202	69
Wastelands	8,531	4
Forest	29,236	15
Built-Up	5,448	3
Natural & Semi natural grasslands	636	~1
Wetlands	86	~1
Water bodies	7,232	4
Tree Clad Area	7,409	4

It is important to note that KSRSAC dataset classified scrub forests under forest. Interactions with Karnataka Renewable Energy Development Limited (KREDL) indicated that these lands were already allotted for wind power development, subject to Forest Department clearance. Therefore, for Karnataka, this study analyses and presents results for three categories of land: Waste, Scrub forest and Agriculture. Figures 2.15 – 2.16 provide the locations of wasteland and scrub forest land in Karnataka.

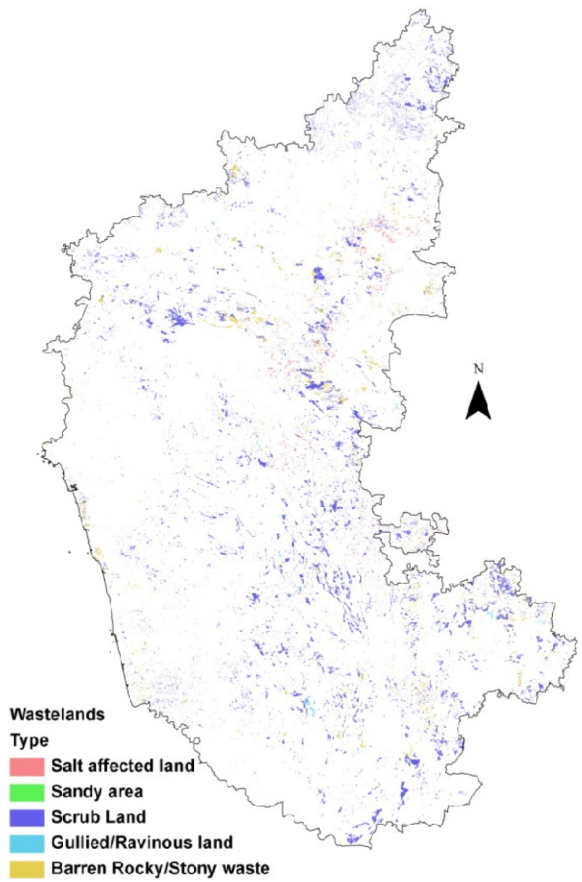

Figure 2.15: Location of wastelands in Karnataka

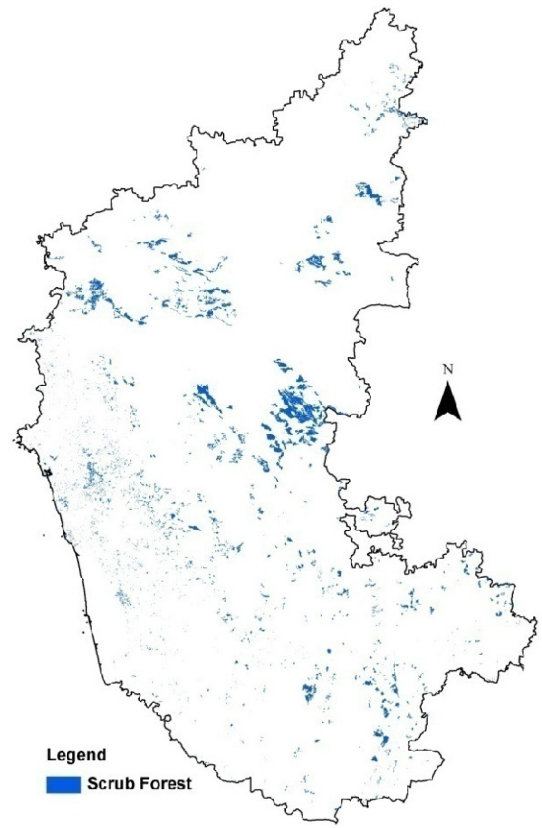

Figure 2.16: Location of scrub forest in Karnataka

We followed a similar procedure for A.P. using Andhra Pradesh State Remote Sensing Applications Centre (APSRAC) data with one exception. For A.P, scrub forests were included under wastelands and not analysed separately. This was because the GIS-based analysis was performed in the APSRAC premises, due to lack of usage permissions. Since the dataset was unavailable in the vector format outside of the premises, it was not possible to separate out scrub forests from wastelands at a later stage. Hence, in case of Andhra Pradesh, we analyse and present results for two categories of lands: wastelands (including scrub forest) and agricultural.

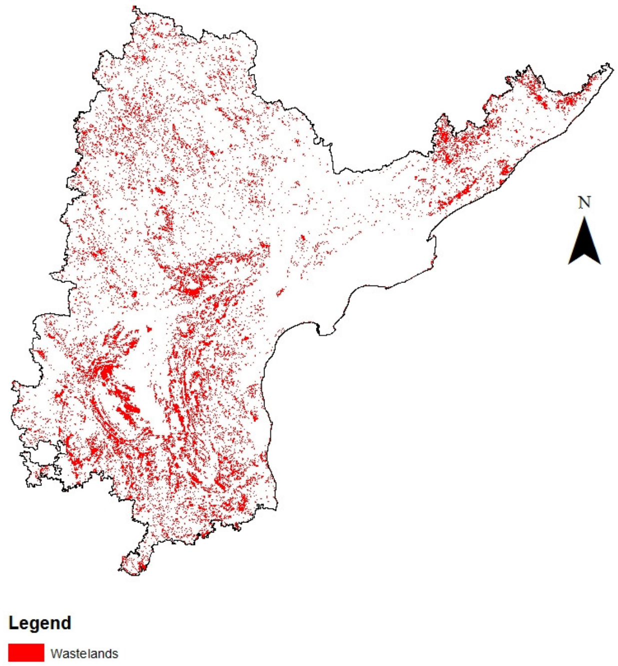

Figure 2.17: Location of wastelands in A.P

Table 2.3: Land use geographical statistics of A.P

Type of Land	Area sq.kms	% of Geographical area of the State
Agricultural Lands	166815	60
Wastelands	36696	13
Forest	48186	17
Built-Up	7887	3
Natural & Semi natural grasslands	136	~1
Wetlands	1188	~1
Waterbodies	15904	6
Others	17	~1

We now explain the procedure used to obtain wind power potential on various categories of lands. Figure 2.18 depicts the flow of the following steps:

1) Convert WPD data for 3 hub heights into GIS compatible format to create a WPD layer of all locations with WPD>200 W/m^2

2) Assign each 3.6 km by 3.6 km vector grid in the WPD layer to a unique wind density bin
   a) 200 to 250
   b) 250 to 300
   c) 300 to 350
   d) 350 to 400
   e) > 400

3) Extract the layer for wastelands, scrub forest and agricultural lands from the LULC layer

4) Intersect each LULC layer obtained in step 3 with the WPD layer obtained in step 2. This generates maps of wastelands, scrub forest and agricultural lands where WPD is > 200W/m^2 at three heights of 80, 100 and 120 m

5) Remove sites identified as protected areas and those at elevation above 1500 m

Several wind assessment studies exclude locations with slope more than 15%. However, we have not applied this exclusion criterion because several existing wind farms in Karnataka were found to be located in places which would have been eliminated on application of this criterion, based on the resolution of the slope data available to this particular study. Proximity to road and transmission network was also not considered as a criterion as it is in the purview of micro-siting studies. However, we undertook field visits to some of the high potential wasteland parcels in the two states to assess their connectivity. This is detailed in Annexure 1.

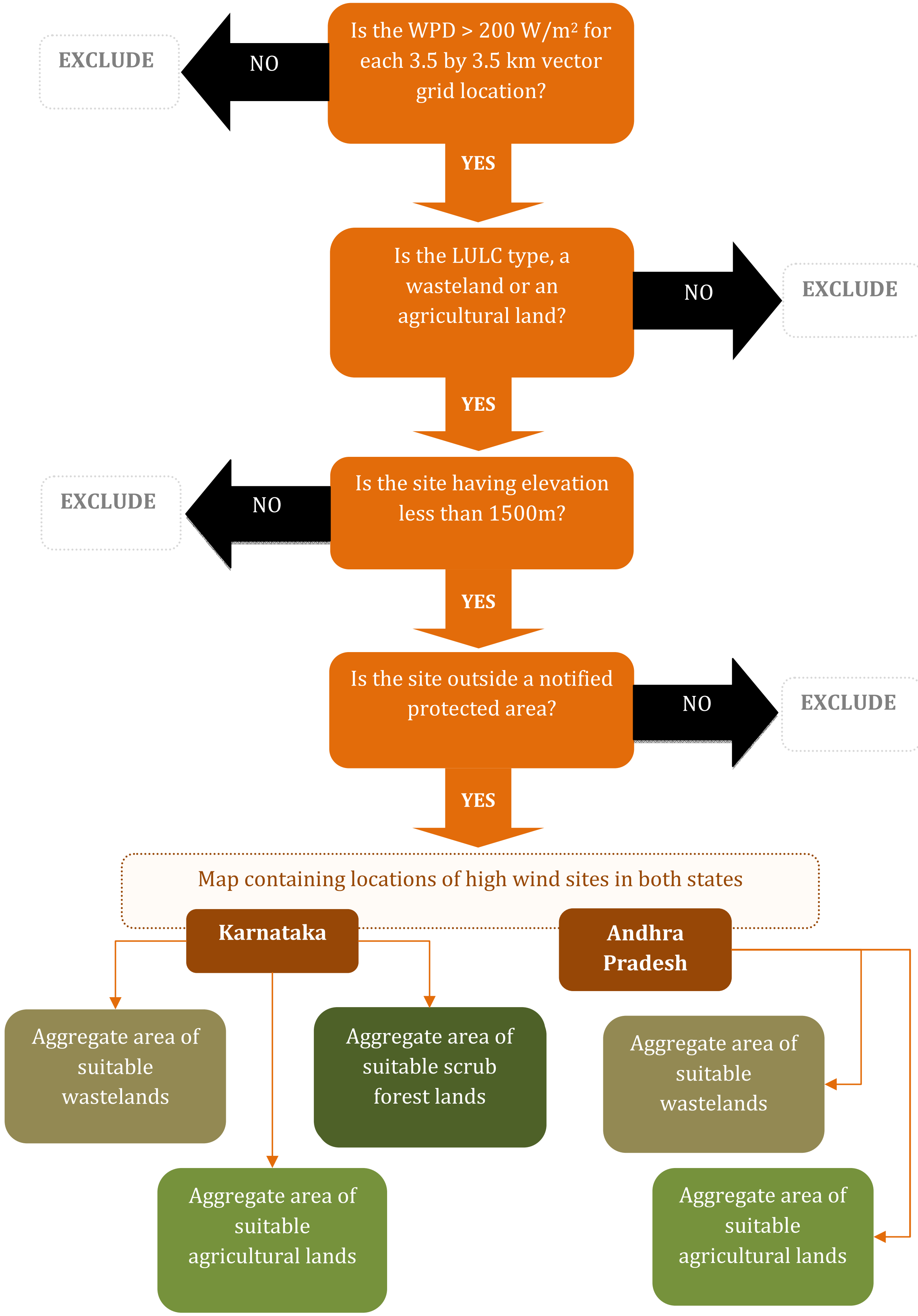

Figure 2.18: Methodology for Wind power potential estimation by land-type

The above methodology is a high level scoping exercise to identify land parcels that are considered suitable for wind power development at hub heights of 80, 100 and 120 m. The next step is to translate this into wind power potential in MW.

Capacity Density

Capacity density represents wind power capacity that can be installed in a given a parcel of land. It depends on choice of turbine as well as the configuration of the wind farm. We considered a representative turbine from several commercially available turbines for the capacity density calculations, i.e. the Suzlon 2.1 MW turbine with 97 m rotor diameter. Inter-turbine spacing is assumed based on a 7D * 5D array configuration, where D denotes rotor diameter of the turbine. Although many other configurations are possible, this was chosen because in Indian wind speed conditions, this configuration is shown to cause the least array losses [13]. The above choice of a representative turbine yields a capacity density of 6.3 MW/ km^2.

Results: Wind Potential Estimates

This section presents the results of wind power potential in Karnataka and Andhra Pradesh for three categories of lands, viz., wastelands, scrub forest and agricultural land for the three hub heights of 80, 100 and 120 m. As discussed previously, In Karnataka, we have segregated wastelands and scrub forests while in Andhra Pradesh, results for wastelands include scrub forests.

It is important to note that it may be practically impossible to use all the wastelands or agricultural lands that are found suitable for wind power to establish wind farms since land is a finite factor with competing uses and opportunity costs associated with it. However, prioritizing between these competing uses of land is outside the scope of this study. Also, it is beyond the scope of this study to evaluate the suitability of different terrain types for wind generation since that is within the purview of micro-siting studies. These studies can be taken up starting at best potential sites, based on scoping results from this study. Therefore, actual realizable potential is based on what portion of each land type may be diverted for wind power development.

From the land found suitable for wind power, we present results assuming the following range of each land use type that may be usable for wind power:

1. Wastelands and scrub forests : availability of 25 – 100%
2. Agricultural land: availability of 1-5 %

Karnataka

Wastelands

Figures 2.19 – 2.21 show the wastelands in Karnataka suitable for wind power at different heights and Table 2.4 summarises the area under each WPD category and potential available from the same at the three hub heights.

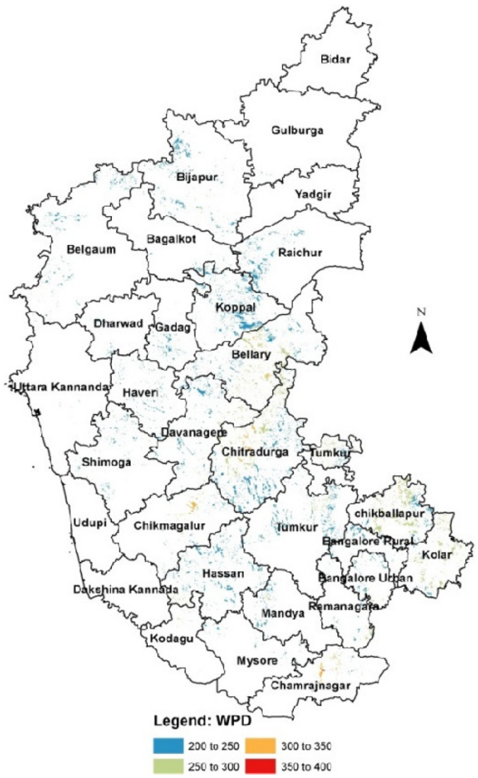

Figure 2.19: Wasteland - 80 m hub height

Figure 2.20: Wasteland - 100 m hub height

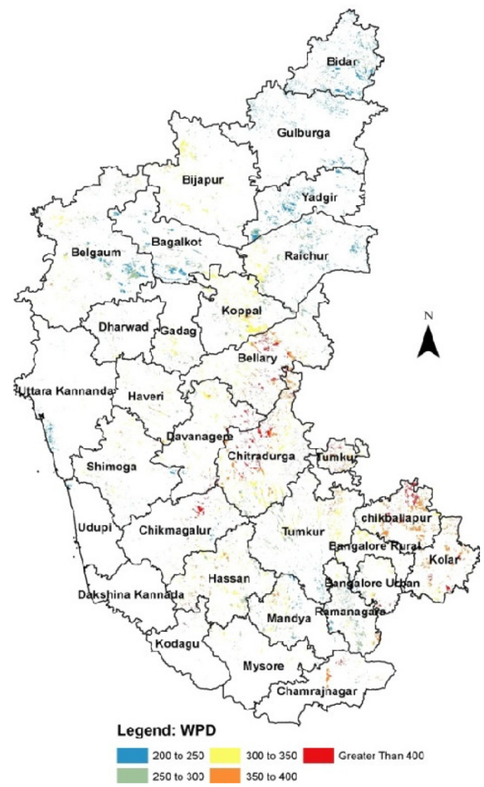

Figure 2.21: Wasteland - 120 m hub height

Table 2.4: Area available from wastelands at different hub heights and WPD

Hub Height (m)	Area of suitable wastelands (sq.km)					Potential from wastelands (MW)
	200-250	250-300	300-350	350-400	>400	
80 m	3,121	1,484	224	5	0	30,400
100 m	2,566	2,405	1,395	448	41	43,200
120 m	1,536	2,201	2,077	1,339	705	49,500

For each hub height, installed capacities at better wind quality sites (with higher WPD) have higher capacity utilization factors and generate more energy, thus bringing down the cost of wind energy. The next chapter details the cost involved in realizing this potential.

The highlights of the results are the following:

- At 80 m hub height, about 5% of the suitable wastelands, are in the WPD category 300-400 W/m^2, while 95% of the suitable wastelands lie in the WPD category 200-300 W/m^2
- At 100 m, more land, about 27% , is available in the WPD category 300-400 W/m^2 while 73% of the suitable land is in the WPD category 200-300 W/m^2
- At 120 m, about 53% of suitable land is in the WPD category 300-400W/m^2
- Districts with good potential from wastelands are Bellary, Chitradurga, Chamrajnagar, Chikballapur and parts of Hassan, Koppal, Bijapur, Chikmagalur and Kolar.

Fig. 2.22 depicts the potential realizable for various percentages of wasteland that may be usable for wind power development.

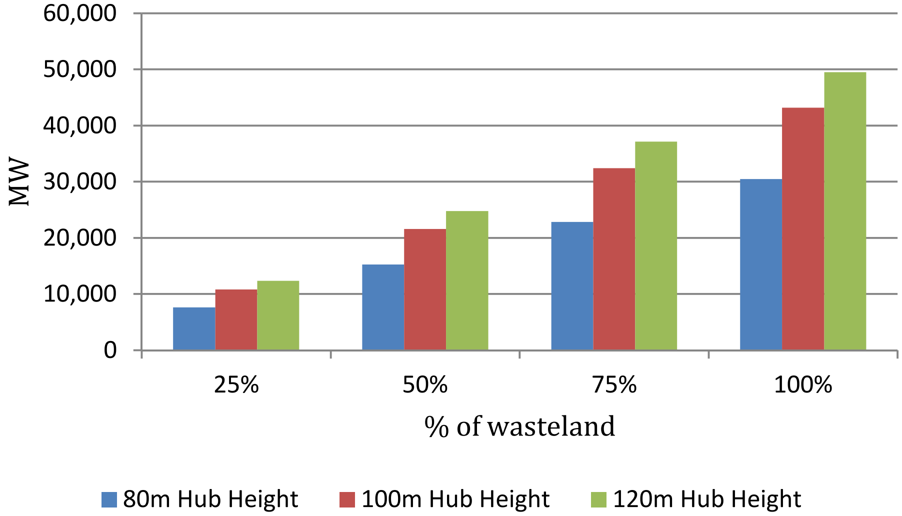

Figure 2.22: Potential based on % of wasteland used

At a conservative estimate, if 25% of best WPD wastelands are used for wind power development, then the potential is 7,600 MW, 10,800 MW, and 12,300 MW at the 3 hub heights of 80 m, 100 m, and 120 m respectively. With increasing height, the MW potential available from higher WPD bins increases. For e.g, at 80 m, only 32 MW is available from sites with WPD greater than 350 W/m^2 but at 120 m, 7,900 MW is above 350W/m^2 WPD.

Scrub Forest Lands

Scrub forest lands occupy fringes of classified forests. This category of land could potentially be used for wind farms subject to environmental and forest department clearance. Fig. 2.23- 2.25 show the location of suitable scrub forest land at 80 m, 100 m and 120 m respectively. Table 2.5 summarises the potential available from all scrub forest land suitable for wind power.

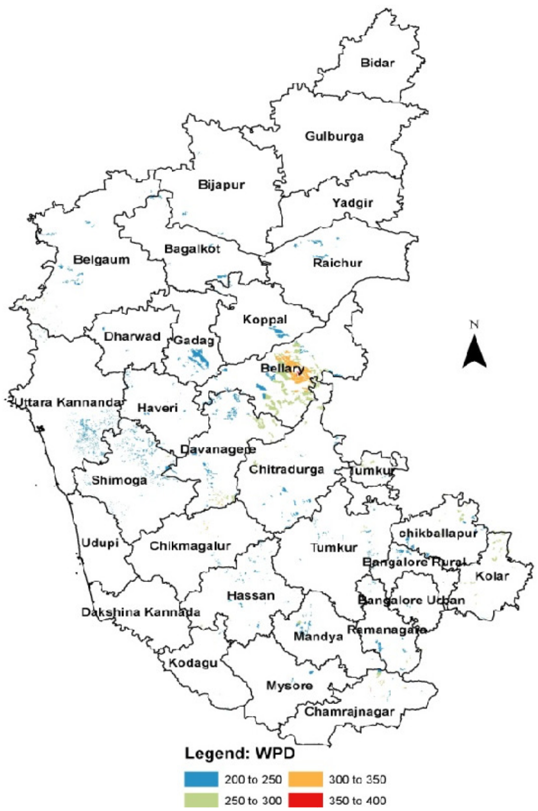

Figure 2.23: Scrub forests - 80 m hub height

Figure 2.24: Scrub forests – 100 m hub height

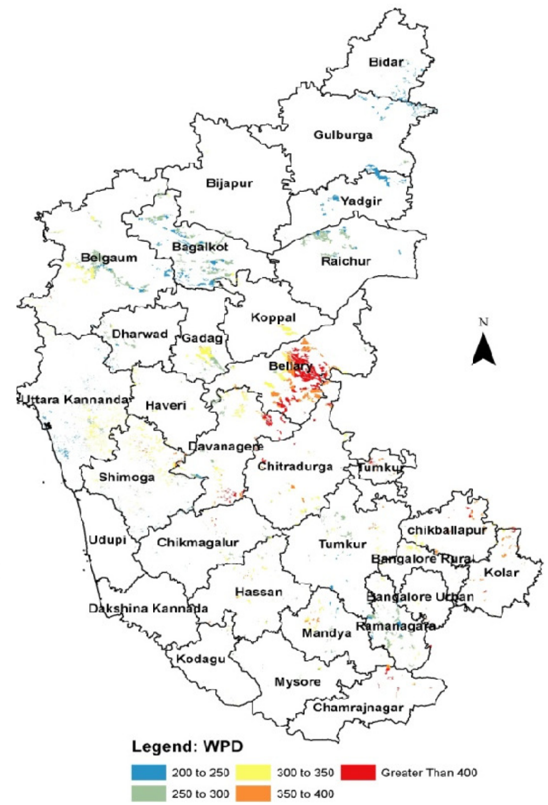

Figure 2.25: Scrub forests – 120 m hub height

Table 2.5: Suitable area and potential from scrub forest land at different hub heights

Hub Height (m)	Area of suitable scrub forest lands (sq.kms)					Potential from scrub forests (MW)
	200-250	250-300	300-350	350-400	>400	
80 m	1,631	995	363	11	0	18,900
100 m	1,730	1,353	858	462	95	28,300
120 m	832	1,484	1,200	746	747	31,500

At 80 m hub height, about 374 km^2 of scrub forests with 69 MW potential is available in the above 300 W/m^2 WPD category. This increases to 4,700 MW at 120m hub height in the same WPD category. Most of the scrub forest land suitable for wind power are concentrated in Bellary with smaller parcels in Chikballapur and Chamrajnagar.

Fig.2.26 depicts the potential realizable for various percentages of scrub forest that may be set apart for wind power development.

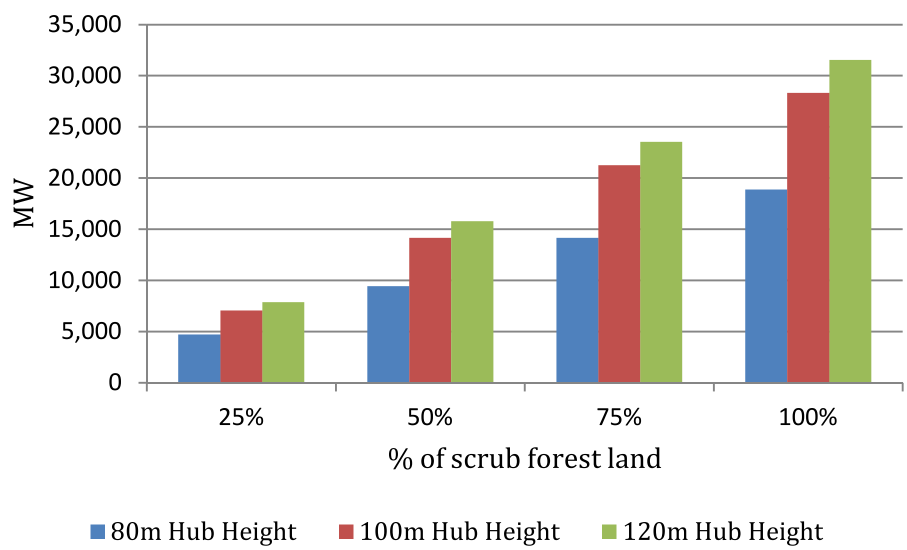

Figure 2.26: Potential based on % of scrub forest land used

At a conservative estimate, if we are able to set apart only 25% of best potential scrub forest lands for wind power development, the potential is 4,700 MW, 7,100 MW and 7,900 MW for the 3 hub heights 80 m, 100 m, 120 m respectively. However, at 80 m only 69 MW is available from the highest quality wind resource sites of greater than 350 W/m^2 while at 100 and 120 m, 3509 MW and 9406 MW are available from the highest quality sites.

Agricultural Lands

Since 70% of the total area is covered by agriculture land, the outer limit of potential from agricultural land is very high. Even though wind has a small foot print, given the concerns about food security, it is not feasible to use all suitable agricultural lands for establishing wind farms. However, there is a scope for considering some of the highest potential agriculture lands for mixed land use between agriculture activities and wind power development. For the same reason a conservative estimate of 2-5% land availability is assumed from agricultural land.

Fig. 2.27- 2.29 show the location of suitable agricultural lands at 80 m, 100 m and 120 m respectively and Table 2.6 summarises land availability in different WPD categories and total potential available.

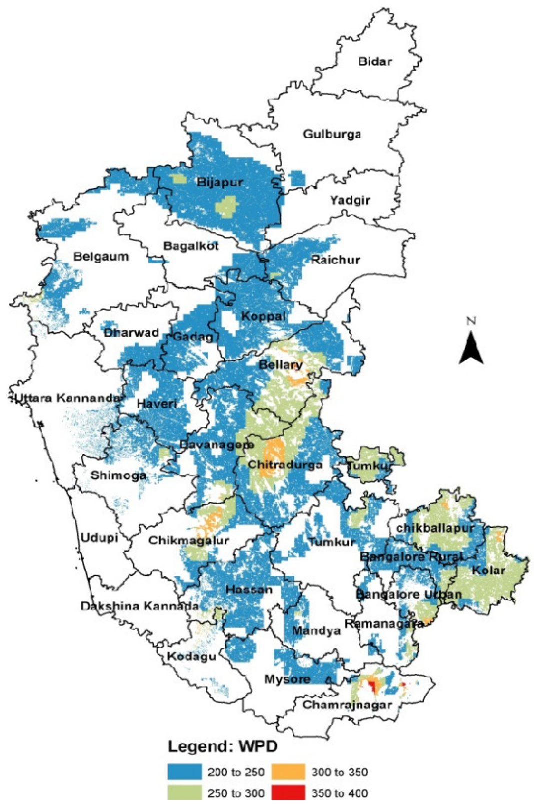

Figure 2.27: Agricultural - 80 m hub height

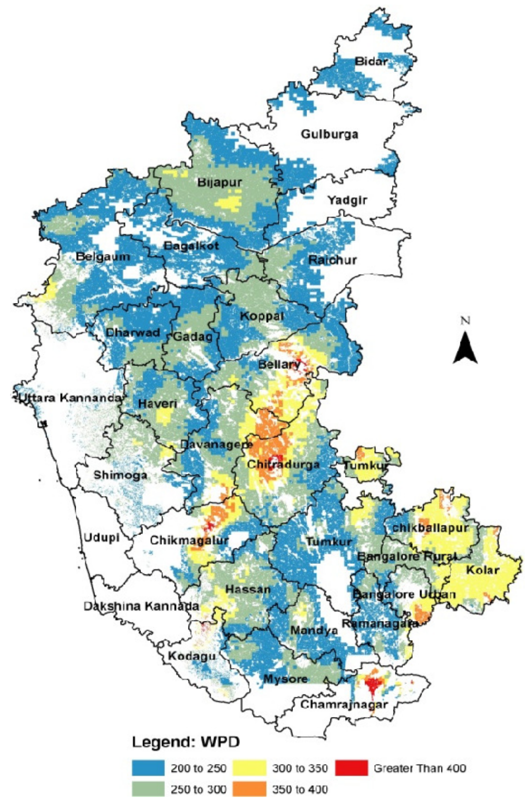

Figure 2.28: Agricultural – 100 m hub height

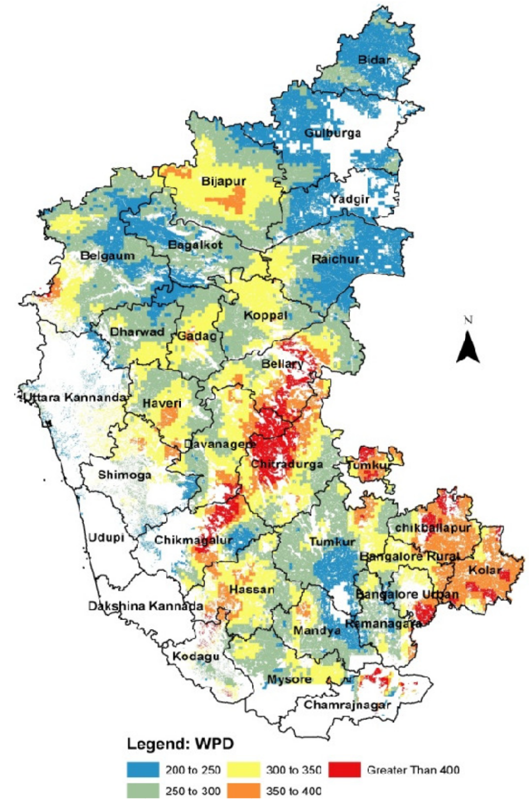

Figure 2.29: Agricultural – 120 m hub height

Table 2.6: Area of suitable agricultural lands at different hub heights

Hub Height (Metres)	Area of suitable agricultural lands (sq.kms)					Potential from agriculture land (MW)
	200-250	250-300	300-350	350-400	>400	
80 m	49,982	12,451	1,303	63	0	4, 01,900
100 m	49,986	36,356	12,394	3,221	368	6, 44,600
120 m	27,614	44,609	31,723	12,477	5,486	7, 68,000

- At 80 m hub height, 63,800 sq. km of agricultural land in Karnataka are suitable for wind power offering a potential of about 402,000 MW. But, only 2% of the land is in the WPD category greater than 300 W/m^2. At 100 m, 16% of the suitable agricultural lands have a WPD greater than 300 W/m^2 and at 120 m, 40% of the suitable agricultural lands have a WPD greater than 300 W/m^2.
- Districts with good potential from agricultural lands are Bellary, Chitradurga, Chamrajnagar, Chikmagalur, Kolar, Chikballapur, And parts of Bijapur, Haveri, Tumkur and Hassan.

Fig.2.30 depicts the potential realizable if 2-5% percentage of best potential agricultural land can be set apart for wind power development.

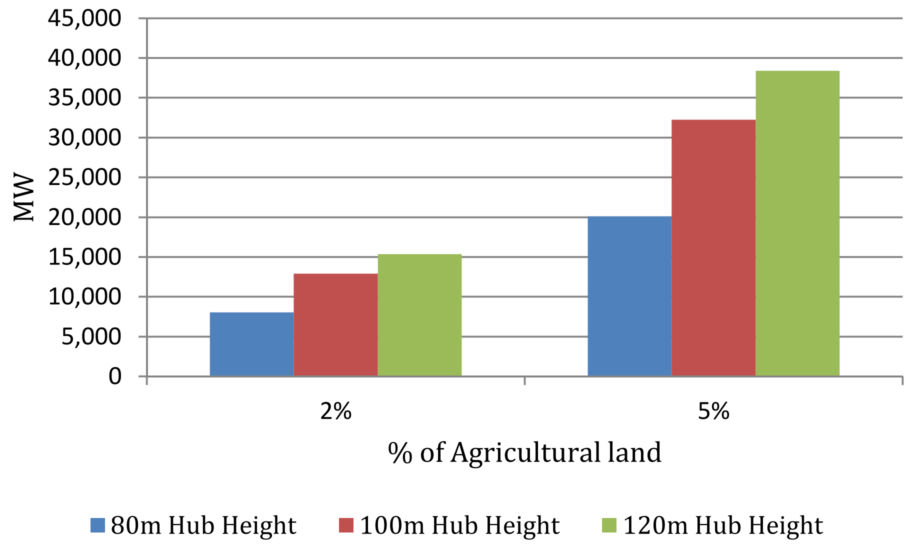

Figure 2.30: Potential based on % of agricultural land used

At a conservative estimate, if 2% of agricultural land suitable for wind power is assumed to be available, then the potential is 8000 MW, 12,900 MW and 15,400 MW for the 3 hub heights 80 m, 100 m and 120 m respectively.

Since realizable wind power potential is directly dependent on the land that can be utilized and there are alternate uses for the same land for other development activities, total wind power potential for Karnataka is summarized in Table 2.7 for the following scenarios of land use assumptions:

1) *Conservative*: A scenario where the State is able to set apart 25% of wasteland and scrub forest land as well as 2% of agriculture land suitable for wind power development at each height

2) *Moderate*: A scenario where the State is able to set apart 50% of wasteland and scrub forest land as well as 5% of agriculture land suitable for wind power development at each height

3) *Theoretical Maximum*: A scenario where all land suitable for wind power at each hub height development are utilized

Table 2.7: Total Potential in Karnataka

Hub Height (Metres)	Conservative (MW)	Moderate (MW)	Theoretical maximum (MW)
80m	20,400	44,780	4,51,300
100m	30,800	68,000	7,16,200
120m	35,600	79,000	8,49,000

Andhra Pradesh

Wastelands

Figures 2.31-2.33 show wastelands in A.P. suitable for wind power at hub heights of 80-120 m and Table 2.8 summarizes wasteland area available in each WPD category and potential available from them at all three hub heights.

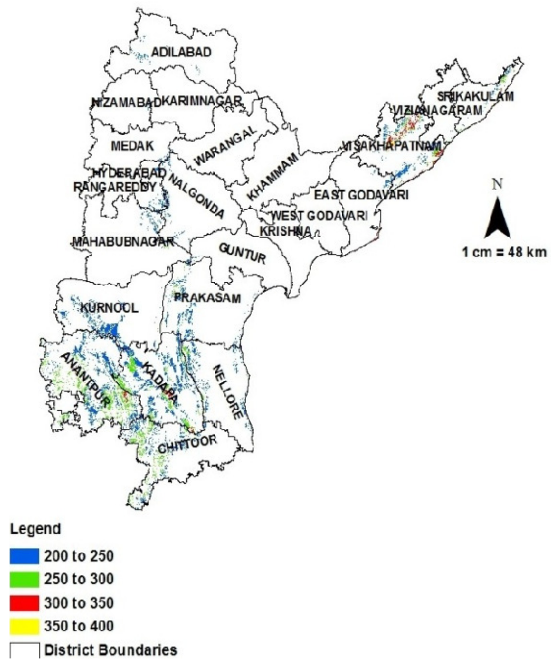

Figure 2.31: Wasteland - 80 m hub height

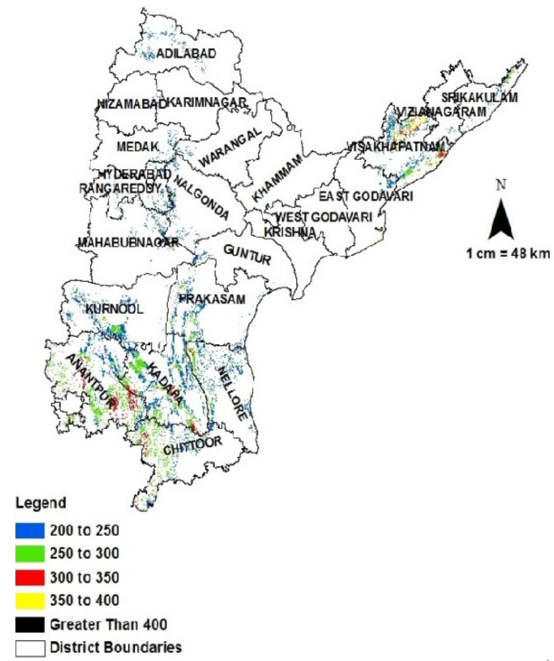

Figure 2.32: Wasteland – 100 m hub height

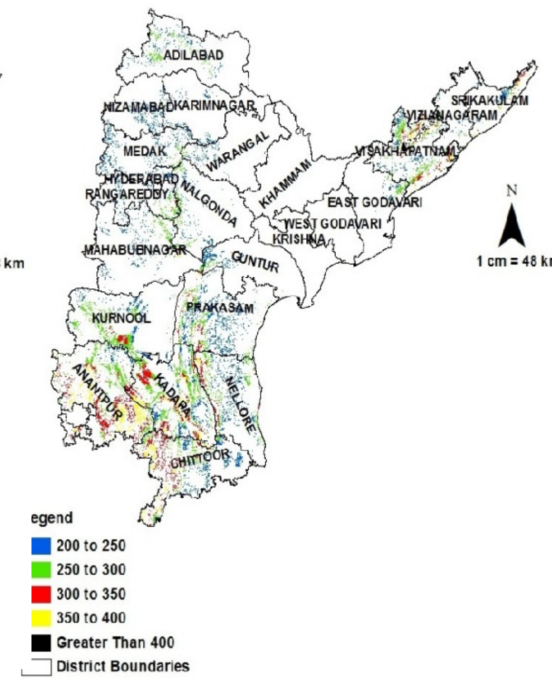

Figure 2.33: Wasteland – 120 m hub height

Table 2.8: Wastelands at different hub heights and WPD classes

Hub Height (Metres)	Area of suitable wasteland (sq.kms)					Potential from wastelands (MW)
	200-250	250-300	300-350	350-400	>400	
80 m	9,469	3,882	688	75	0	88,900
100 m	10,125	5,810	1,854	415	78	1, 15,200
120 m	10,059	8,209	4,993	2,073	664	1,63,800

1) At 80 m hub height, about 5% of wastelands that are suitable are in the WPD range of 300-350 W/m^2 , while 95% of the wastelands are in the WPD category below 300 W/m^2
2) At 100 m, area of wastelands which are suitable has increased. About 13% the wastelands suitable, are in the WPD category 300-400 W/m^2
3) At 120 m, about 30% of suitable wastelands, are, present in the WPD category greater than 300-400 W/m^2
4) Districts with good potential from wastelands are Ananthpur, Kadapa,Chittoor, Kurnool, Vishakapatnam and parts of Srikakulam.

Fig. 2.34 depicts wind power potential based on assumption of 25-100% of wasteland at each height made available for wind power development.

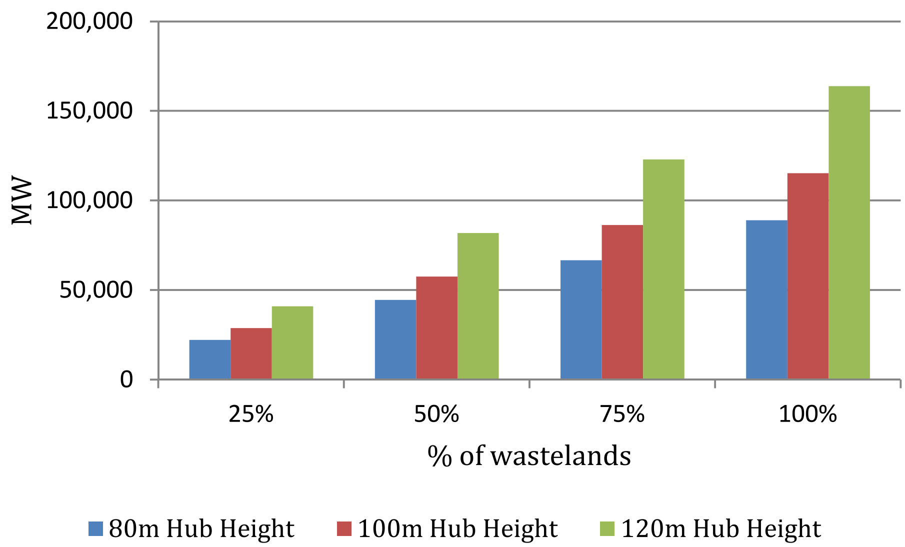

Figure 2.34: Potential based on % of wasteland used

At a conservative estimate, if 25% of the best potential wastelands at each height are used, then the estimated potential is 22,200 MW, 28,800 MW and 40,940 MW for the hub heights 80, 100, and 120 m respectively.

Agricultural Land

Figures 2.35-2.37 show agricultural land in A.P. suitable for wind power at hub heights of 80-120 m. Table 2.9 summarizes area available from each WPD category and total potential available at all three hub heights.

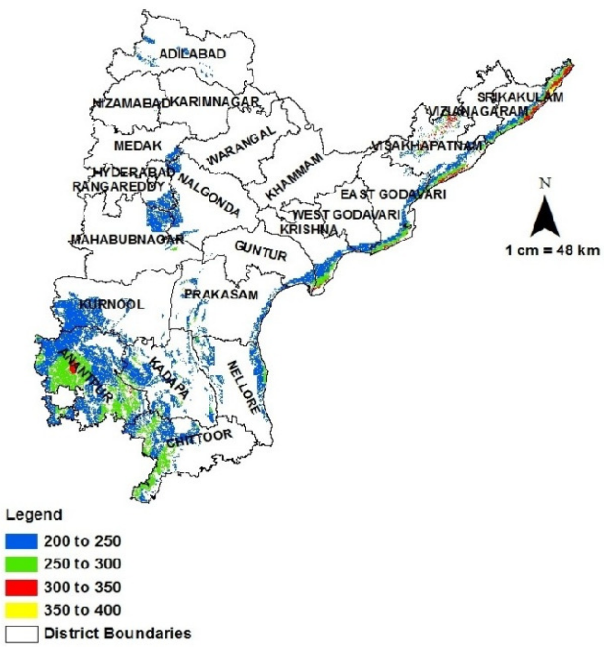

Figure 2.35: Agricultural - 80 m hub height

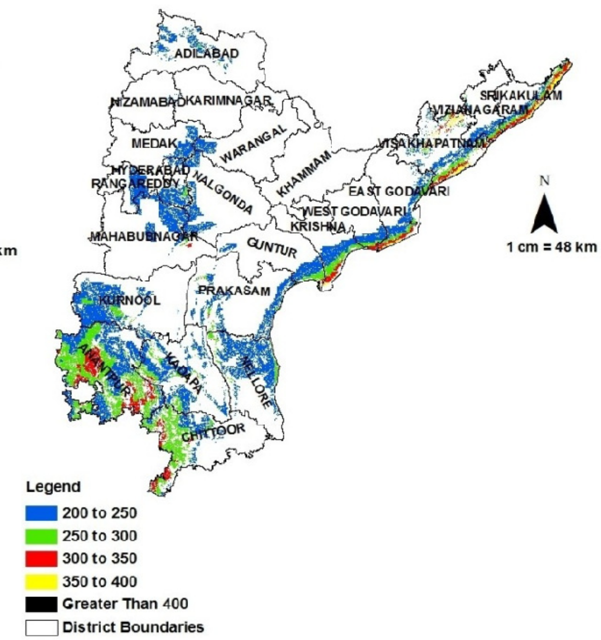

Figure 2.36: Agricultural – 100 m hub height

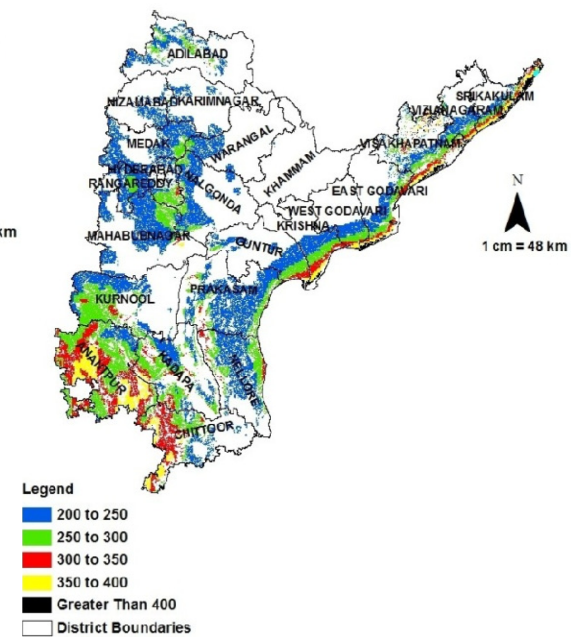

Figure 2.37: Agricultural – 120 m hub height

Table 2.9: Area of suitable agricultural land at different hub heights and WPD classes

Hub Height (Metres)	Area of suitable agriculture land (sq.km)					Potential from agricultural land (MW)
	200-250	250-300	300-350	350-400	>400	
80 m	27,520	9,277	1,313	148	0	2,41,000
100 m	37,622	14,378	4,895	837	96	3,64,300
120 m	51,989	26,882	12,055	5,542	1,384	6,16,500

- At 80 m hub height, 4% of the area suitable for wind power lies in the WPD category 300-400 W/m^2
- At 100 m, about 10% of the suitable land area lies in the WPD category 300-400 W/m^2
- At 120 m, nearly 20% of the suitable land area lies above 300 W/m^2 WPD
- Districts with good potential from agricultural lands at 120 m hub height are Ananthpur, Chittoor, parts of Kadapa and eastern coastline of AP.

Fig. 2.38 depicts wind power potential based on assumptions of 2% and 5% of agricultural land suitable at each height being available for wind power development.

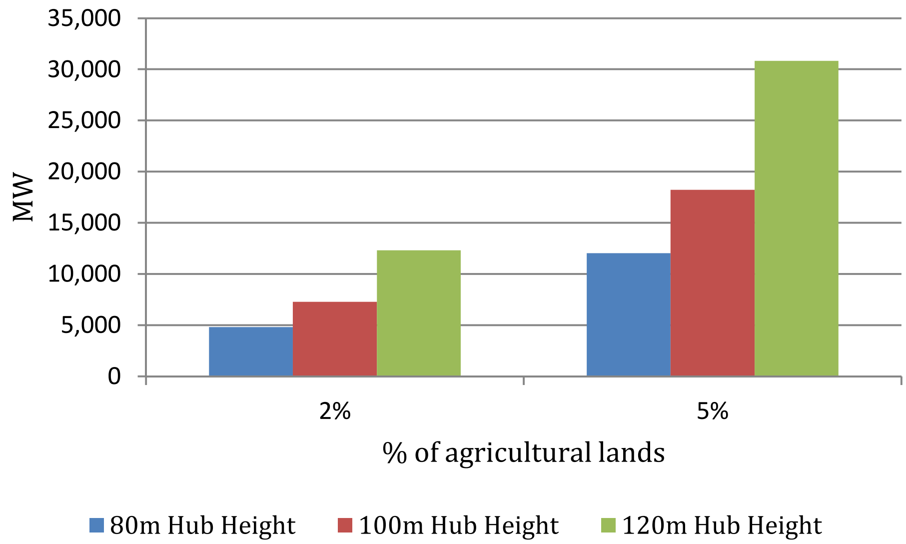

Figure 2.38: Potential based on % of agricultural land used

At a conservative estimate, if 2% of the best potential agricultural lands at each height are set apart for wind power development, then the potential is 4,820 MW, 7,290 MW and 12,330 MW for the hub heights of 80, 100, and 120 m respectively.

Total wind power potential for Andhra Pradesh is summarized in Table 2.10 for the following assumptions:

1) *Conservative*: A scenario where the State is able to set apart 25% of wasteland (including scrub forests) and 2% of agriculture land suitable at each height for wind power development
2) *Moderate*: A scenario where the State is able to set apart 50% of wasteland and scrub forest land as well as 5% of agriculture land suitable for wind power development
3) *Theoretical maximum*: A scenario where all land suitable for wind power at each hub height development are utilized

Table 2.10: Total Potential in Andhra Pradesh

Hub Height (Metres)	Conservative (MW)	Moderate (MW)	Outer limit Potential (MW)
80	27,000	56,500	3,30,00
100	36,000	75,800	4,79,00
120	53,000	112,700	7,80,00

References

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3 Cost of wind power generation

After estimation of installable potential for the three hub heights for KA and AP, it is of interest to estimate the cost of generation of wind energy based on the realization of this potential. While most current wind turbine installations in the Indian market are at 80 m, trends in the European market indicate an exponential growth in land-based turbine rotor diameter sizes over the past two decades, with a focus on increasing efficiency for volume of air delivered. As shown in Fig. 3.1, in terms of turbine capacity, there has been an increase in average turbine size from 250 kW to 1 MW between 1998 and 2007, in the Indian market [1]. Considerable improvements in technology (increased outputs of 19% to 29%) are expected, with recent announcements of wind turbines of higher hub heights and larger rotor diameters, designed for low wind speed regimes typical of Indian conditions [2], [3].

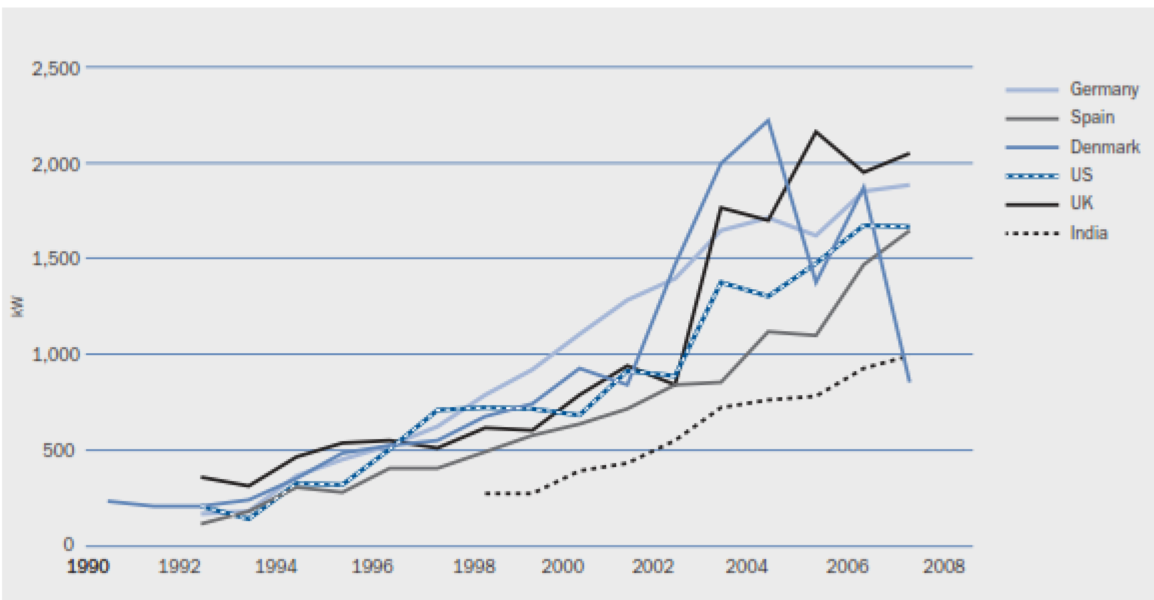


Figure 3.1 Development of the average wind turbine size sold in different countries (in kW)

(Source: EWEA Wind Economics report, 2009)

In this study, we examine the incremental cost of capital for tapping wind potential at higher hub heights. It is also important to evaluate if for a representative wind site, the extra cost incurred by setting up a turbine at a higher hub height, is compensated by increased energy generation, in terms of per-unit cost of electricity. Previous studies report a capacity of approx. 200 GW available at a levelized tariff of Rs. 4.5/kWh or less, and about 100 GW at Rs. 4.0/ kWh or less at all three hub heights, based on CERC norms [4]. Here, we attempt to calculate the levelized cost of generating wind energy, based on a Suzlon 2.1 MW turbine with rated speed suitable for Indian conditions, for the potential estimated in the previous section.

Analysis

Capital Cost Estimation

The cost of generating electricity depends on the following components:

- Turbine capital costs (mainly accounted for by the wind turbine and tower)
- Balance of system costs (interconnection and foundation construction, installation)
- Turbine lifetime
- Land costs
- Discount rates
- Tax/Depreciation benefits
- Maintenance costs
- Wind speed regimes and resulting net electricity generation

Our study aims to estimate the incremental capital cost for the higher hub heights of 100 m and 120 m, and its resulting impact on the Levelized Cost of Electricity (LCOE). For the purpose of our analysis, we have referred to publicly available CDM project financials reported for projects commissioned in India [5]. The project costs available for typical wind farm configurations at 80 m hub height are set as the baseline cost. The capital cost break-down for a typical farm installation at Kapattaguda, Karnataka is exemplified in Table 3.1:

Table 3.1: Capital Cost components for 10 MW plant at Kapattaguda, Karnataka

CDM Break-up Costs for Windmill Project of 10.00 MW at Kapattaguda, Karnataka (for Suzlon 1.25 MW WTG, at 80 m hub height)		
Component	Cost/ Rs. Lacs (2010)	% share in TCI
Wind Turbine Generator	400	63%
Transformer	12	2%
Tubular Tower	88	14%
Electrical Items	15	2%
Erection, Installation & Commissioning (incl. Processing Fees)	17	3%
Installation of Electrical Line	16	2%
Civil Foundation	35	6%
Power Evacuation Facility	35	6%
Land	15	2%
Total Capital Investment (TCI) as per Order	633	100%

In case of lack of availability of cost data at higher hub heights, the individual cost components can be scaled to 100 and 120 m, using a literature scaling model developed by Fingersch et. al [6]. The model projects cost estimates for increased size (corresponding to increase in hub-height) in terms of turbine rating, rotor diameter, hub height, and other key turbine descriptors. A set of scaling relationships have been developed (for each component of the turbine), as a function of the one or more of the turbine descriptors. These relationships are updated from a regression analysis on US industry data for typical configurations. Upon applying the same to CDM baseline costs at 80 m, it was found that the cost increase from 100 m to 120 m was not comparable to that from 80 m to 100 m. Given the limited field experience in installation of on-shore turbines at 120 m, we decided to proceed with industry estimates instead, to the extent available.

Hence, for the purpose of this study, estimates for increase in capital cost corresponding to increase in tower height were obtained in consultation with Black & Veatch (B&V), based on experience in turbine installations in the US market. Table 3.2 and Figure 3.2 summarize this cost break-down:

Table 3.2: Capital cost breakdown provided by B&V, for a typical 1.5 MW GE Turbine at 80m hub height, with corresponding scaling for additional 20m height

Component	% Share	Cost increase from 80 to 100 meters
Wind Turbine Generator and transportation	50%	The cost of turbine stays the same, but cost of tower increases
Wind turbine tower and transportation	16%	If not included in WTG cost, a 30-40% increase for the tower itself
Wind turbine erection	5%	5-15% increase in erection cost depending on crane requirements of model and hub height change
Civil/Site works	6%	No cost change to civil/site works
Wind turbine foundations	9%	20-30% increase in foundation cost
Electrical collection system	5%	No cost change to electrical collection system
Indirect project costs	4%	No change to indirect costs
Project substation and interconnection facilities	5%	No change to project substation cost

A median capital cost of approx. Rs. 5.9 Cr. /MW was observed from a set of recent CDM projects for turbines ranging from 1.25 – 1.56 MW at 75 – 80 m hub heights, which was set as the baseline cost at 80 m. Applying the above breakdown and scaling estimates obtained, to the CDM baseline costs, we arrive at a capital cost structure for 100 m and 120 m as shown in Table 3.3:

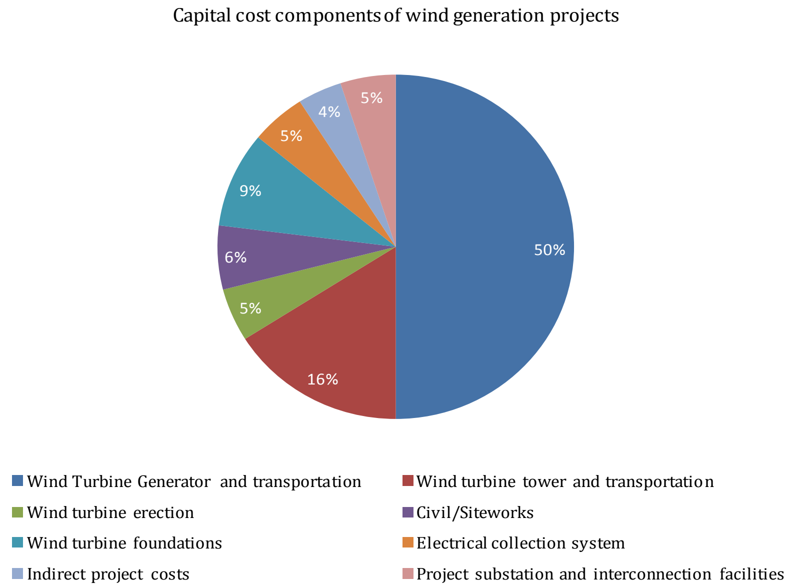


Figure 3.2: High level break-down of turbine components and balance of system costs (Inputs from B&V, mainly based on data for installations at 80m and 100m, in the US market)

Table 3.3: Scaled Capital costs (based on B&V inputs, applied to CDM baseline costs)

Component	Cost range at 100m (Rs. Lacs per MW)	Cost range at 120m (Rs. Lacs per MW)
Wind turbine generator (and transportation)	295	295
Wind turbine tower (and transportation)	127 – 132	172 – 185
Wind turbine erection	32 – 34	36 – 39
Civil/Site works	35	35
Wind turbine foundations	66 – 69	83 – 90
Electric collection system	30	30
Indirect project costs	24	24
Substation/interconnection	30	30
Total	640 - 648	703 - 727

Note: The costs are scaled for a pure increase in turbine tower height, for a typical 1.5 MW GE machine, in the range of mid- to high- points of the estimated increase. Cost increase for 120 m is based on limited field data.

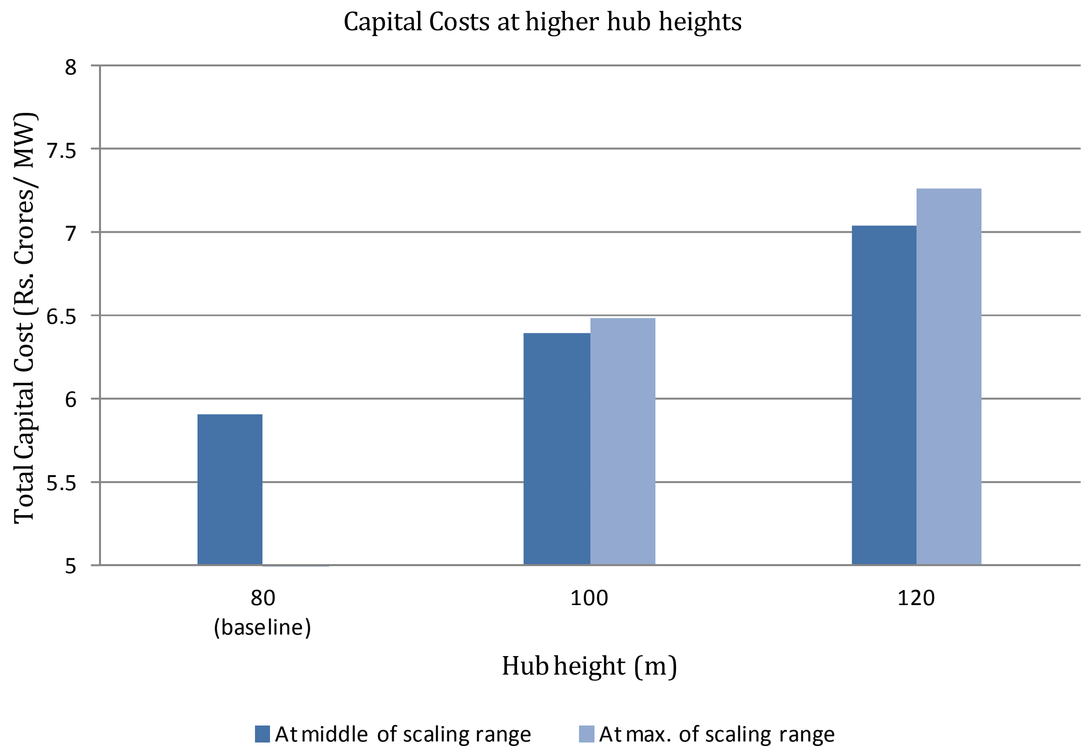


Figure 3.3: Scaled Capital costs (based on B&V inputs, applied to CDM baseline costs)

Levelized Cost of Electricity (LCOE)

The LCOE for the electricity generated by wind is based on the following formula:

$$LCOE_h = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(I+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(I+r)^t}} \quad (1)$$

Where,

$LCOE_h$ = Average lifetime levelized cost of electricity generation at hub height h m

I_t = Turbine capital investments in the year t

M_t = Operations and Maintenance expenditures in the year t

E_t = Net Electricity generation in the year t

r = Discount rate

n = Life of the system

LCOEs are calculated for a median WPD, and corresponding wind speed profile, representative of each WPD classification range detailed in the previous section (200 – 250 W/km^2, and so on). Power response curve of the Suzlon: S9X – 2.1MW turbine, with 97 m diameter, is considered. The machine is currently installable at hub heights of 80 m and 100 m. In order to measure the benefit of the extrapolated wind potential at 120 m, the same turbine is assumed, in principle, to be available at the latter height.

The electricity generated in a particular year is largely dependent on the choice of turbine. Output generated by the turbine is a function of a combination of factors such as the efficiency of the turbine (reflected in the response curve), the weibull characteristics of the wind speed incident on the turbine blades, and effects of air density, turbulence, and array configuration losses. We have chosen a representative market turbine with a demonstrated capacity factor suitable for low Indian speeds, for measuring the generated output. The methodology for the same is detailed below.

Assumptions/input values for LCOE

I_t : Turbine capital investment at the 3 hub heights as derived in Table 3.4 (the higher end of the range is considered)

80 m: Rs. 5.9 Cr. / MW
100m: Rs. 6.48 Cr. / MW
120m: Rs. 7.27 Cr. / MW

M_t : Rs. 9 Lakhs/MW; escalated at a rate of 5.72% p.a. over the life of the system, as per latest CERC norms [7]

E_t : This is a function of the wind speed probability density profile at a particular median site and the power response curve of the turbine selected at the respective height:

$$E_t = (\sum_{v=v_i}^{v_o} p_v * P_v * (1 - TF) * (1 - DF)) * 8760 * AF * (1 - Arr) * (1 - Arf) * (1 - Aux) \quad (2)$$

Where,

v_i = cut-in speed for the turbine

v_o = cut-out speed for the turbine

p_v = percentage of time the wind is available at speed v m/s, for a median WPD in ranges of classification at the respective hub height

P_v = power (kW) output from turbine corresponding to wind speed v m/s

TF = Turbulence factor (10%) affecting the turbine power response

DF = Air Density factor, expressed as function of site elevation, affecting the turbine power response

$$DF = site\_elevation * 0.0000918$$

AF = Availability factor of the turbine i.e. the ratio of the amount of time that it is able to produce electricity over a certain period and the amount of the time in the period (Assumed to be 97% as per recent observed performance of modern wind turbines [8])

Arr = Array losses for the 7Dx5D turbine configuration (Assumed to be 7% as per C-WET micro-siting guidelines [9])

Arf = Airfoil losses (Assumed to be 1% [10])

Aux = Auxiliary consumption of the wind farm configuration, assumed to be 1% [10]

8760 hours per annum

r: 13.8%

Discount rate as a weighted average cost of capital; for a 70:30 (Debt: Equity) ratio, with following interest rates:

Debt: 12%

Equity: 18%

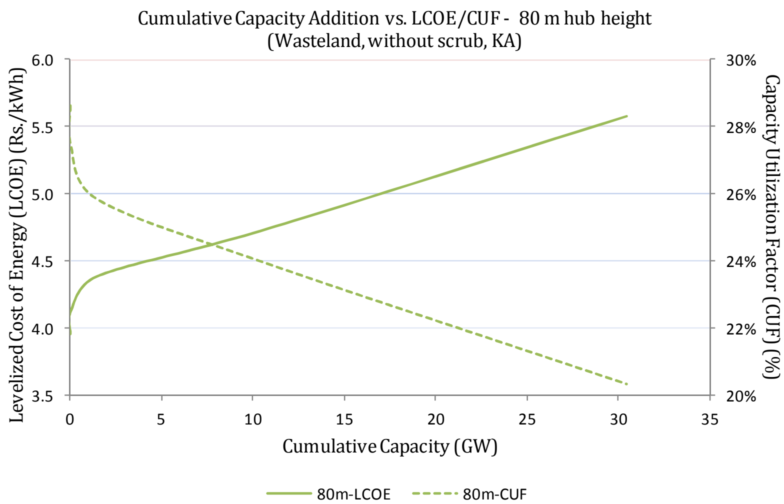
n : Life of the system is assumed to be 25 years as per CERC tariff norms on term of power purchase agreement [7]

Results

Net electricity generated by the turbine (described in the previous section), is used to derive the Net Capacity Utilization Factor (CUF) and resulting Levelized Cost of Electricity (LCOE) for a particular wind site. The chosen sites are representative of the WPD ranges at the three hub heights, through median WPDs. Although the annual speed profiles considered are a result of meso-scale modelling, net CUFs are derived for a more realistic estimate of the power generated at a particular site (accounting for reductions owing to other site-specific conditions).

If we consider cumulative capacity addition of potential estimated in the previous section, in a manner that utilizes the best potential first, following ranges for LCOEs, and corresponding CUFs, are observed. Results are indicated for 80 m and 100 m only, due to uncertainty in the capital cost estimates at 120 m hub height. However, relative comparison for the weighted average costs for all three hub heights are summarized later in this section.

Cumulative Capacity addition for Karnataka



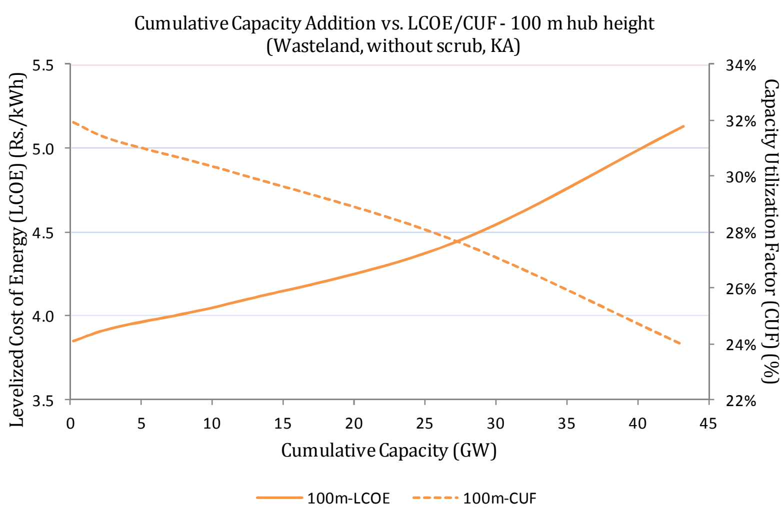
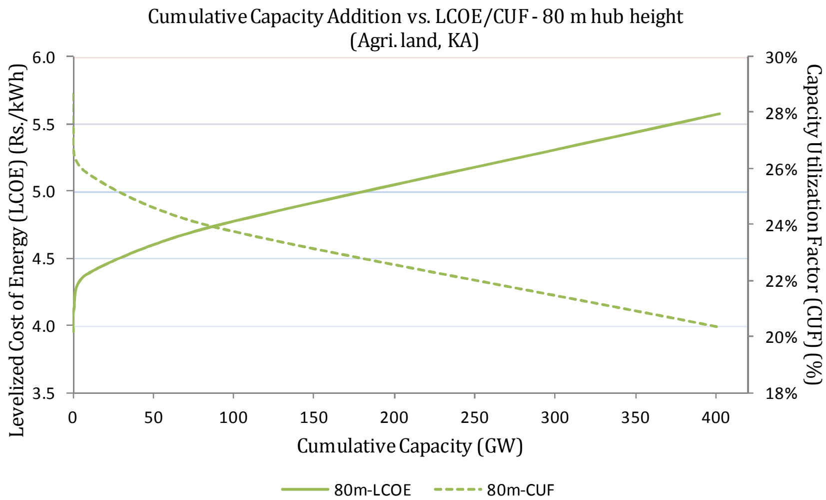


Figure 3.4: Cumulative capacity addition by wasteland type, in Karnataka



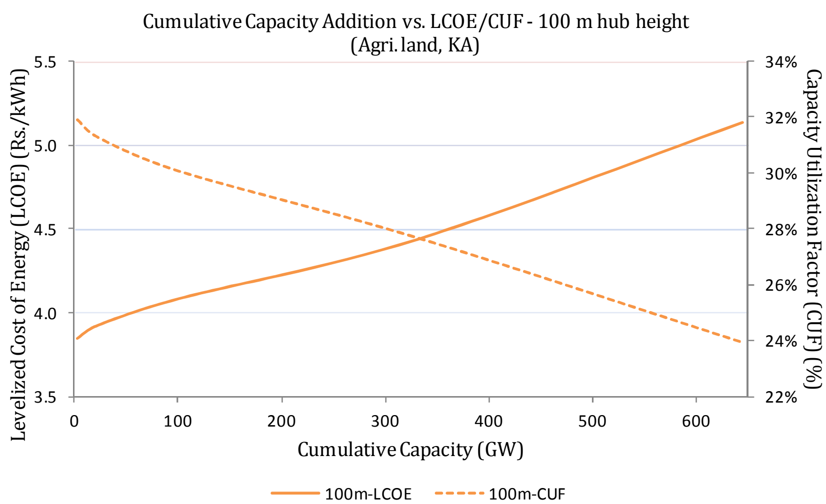
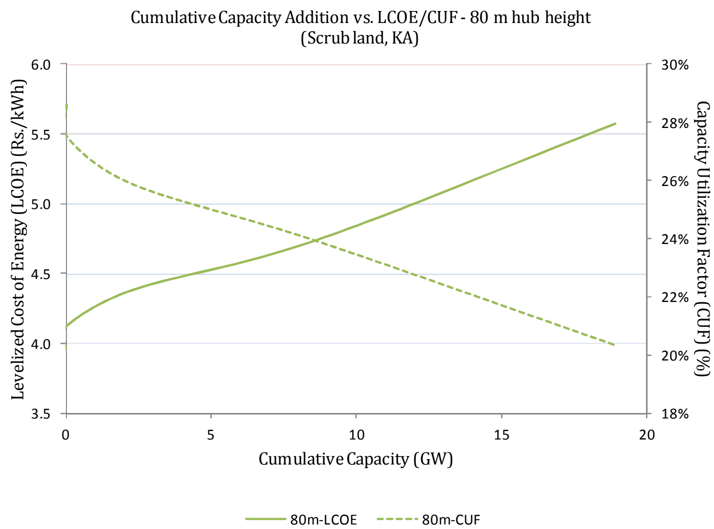


Figure 3.5: Cumulative capacity addition by agricultural land type, in Karnataka



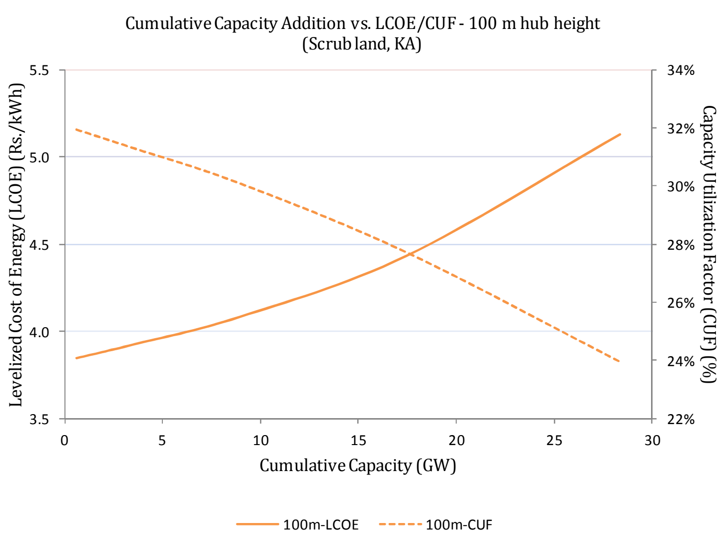
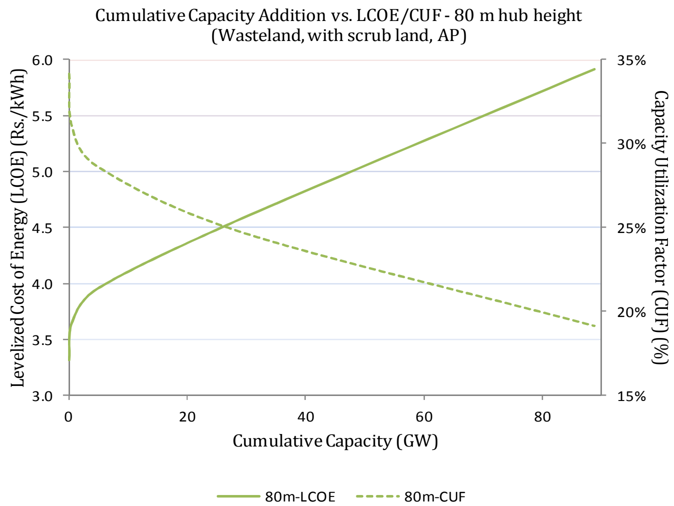


Figure 3.6: Cumulative capacity addition by scrub forest land type, in Karnataka (Note: Scrub forest land is classified separately for the state of Karnataka due to format of data classification at source)

Cumulative Capacity addition for Andhra Pradesh



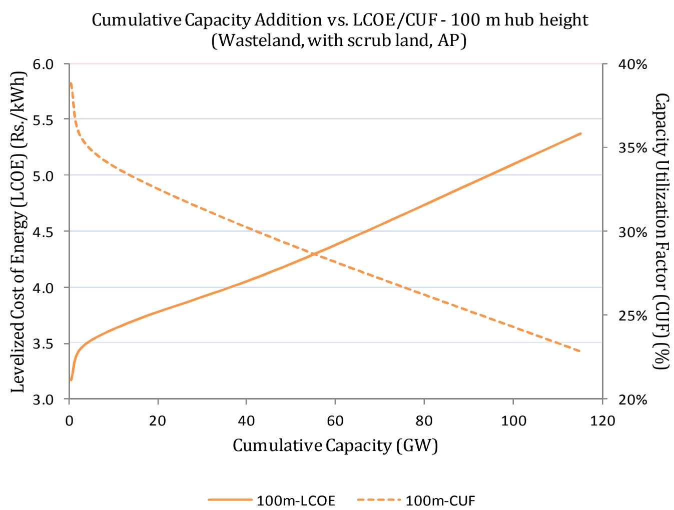
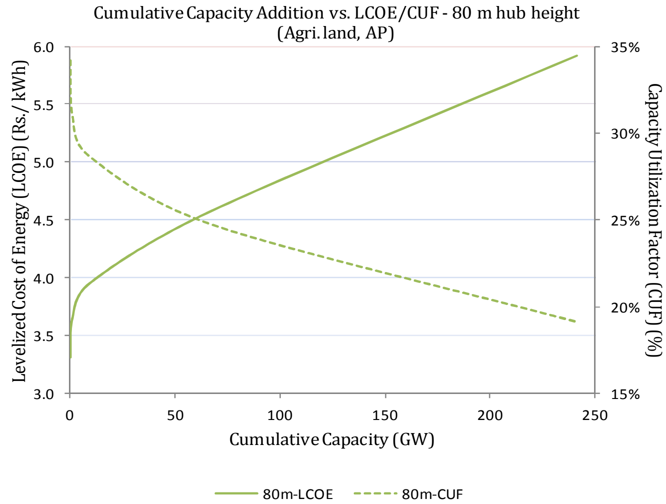


Figure 3.7: Cumulative capacity addition by wasteland type, in Andhra Pradesh



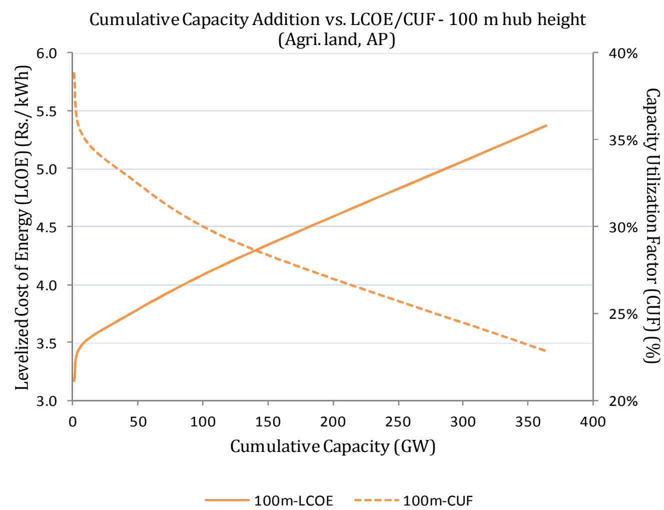


Figure 3.8: Cumulative capacity addition by agricultural land type, in Andhra Pradesh

The CUFs derived within the respective WPD ranges at the three hub heights, are summarized in Table 3.4, for both the states:

Table 3.4: Summary of CUF values for the three hub heights, in KA and AP

WPD range (W/ m²)	Karnataka			Andhra Pradesh		
	80 m	**100 m**	**120 m**	**80 m**	**100 m**	**120 m**
200 – 250	20%	24%	27%	19%	23%	26%
251 – 300	24%	28%	31%	25%	29%	33%
301 – 350	26%	30%	34%	29%	33%	37%
351 – 400	27%	31%	34%	31%	35%	39%
> 400	29%	32%	35%	34%	39%	43%

Weighted average results, by land-type:

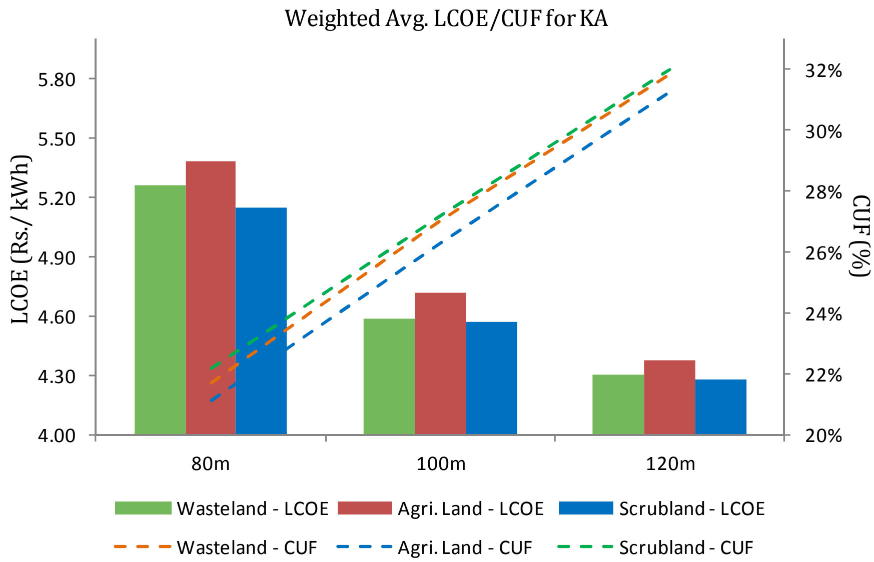


Figure 3.9: Weighted Avg. LCOE/CUF by land type, in Karnataka

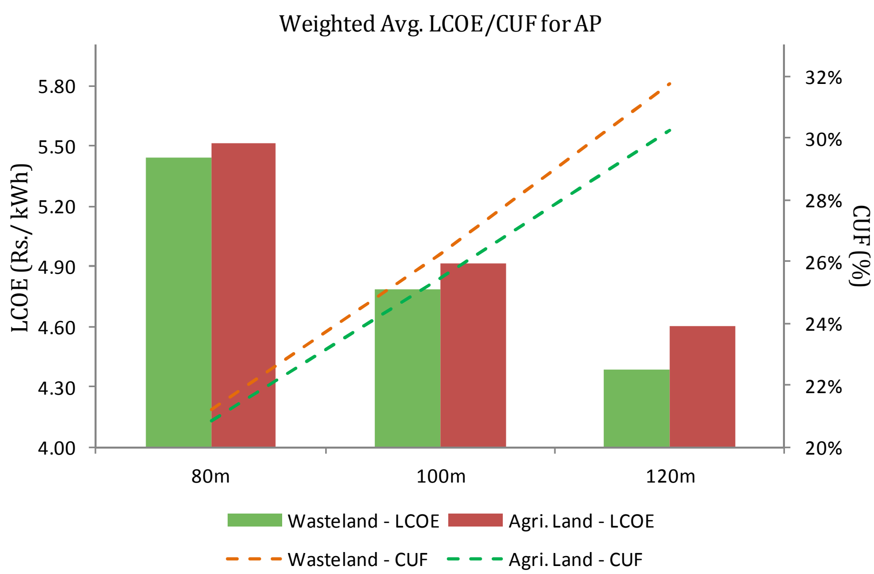


Figure 3.10: Weighted Avg. LCOE/CUF by land type, in Andhra Pradesh

Implications

To estimate the wind power potential intersected with land-use, a condition of a WPD greater than 200 W/km^2 has been applied to all hub heights. It can be observed in general that, in lands with higher potential, the cost of adding capacity is lower. CUF values range from 20% to 32%, and 19% to 39%, for KA and AP, at 80m and 100 m hub height respectively. As a result, LCOE ranges from Rs. 5.5/ kWh to Rs. 3.8/ kWh, and Rs. 5.9/ kWh to Rs. 3.2/ kWh, for KA and AP, at 80 m and 100 m respectively.

The extremities of LCOE values are higher/lower for AP, in comparison to KA. This can be attributed to the weibull characteristics at the median WPD locations in AP, which leads to a higher net production of energy at the higher end and lower production for lowest WPD range. This is incidental as the net production is a product of the shape of the weibull speed profile and the power response curve of the selected turbine (Eq. 2). The careful selection of the right turbine for a particular speed profile is hence recommended while micro-siting, to consider site-specific characteristics of the wind resource. The turbine should ideally be chosen such that its response curve complements the wind speed distribution of the site to yield maximum energy.

While the LCOE values improve across all WPD ranges, from 80 m to 100 m, in some cases the improvement in CUF values from 100 to 120 m is insufficient to compensate for the incremental capital cost incurred. The average results capture the overall improvements observed, weighted by the relative significance of the observed WPD ranges, and thus the corresponding potential. As can be seen, while there are overall improvements in the LCOE values in going to a higher height, the values are relatively higher for the potential in agricultural land. While inferring this result, it is important to note that the potentials at higher hub heights are owing to the additional land that is included in the analysis, by holding 200 W/m^2 as the qualifying WPD for the site to be suitable.

There are some assumptions worth mentioning with regard to potential conclusions from above observations. First, the result is dependent on the choice of turbine assumed for the three hub heights, and the capacity factors resulting from it. Technology improvements in newer turbines, designed for improved efficiency at lower wind speeds, will have a significant impact on the above estimates. Second, the capacity density factor from which the potential is calculated is based on an optimal wind farm array configuration for a fixed area. These configurations can be optimized further, based on spatial analysis of contiguous parcels of land practically available for wind farm installation.

Improvements in LCOE with benefits from increased wind power densities at higher hub heights may be achieved with an optimized choice of wind turbine, designed for speeds most suited to the wind speed measurements observed at the site. However, micrositing would provide a more realistic estimate of the impact of higher hub heights on the LCOE, which is outside of the current scope of this study.

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4. Field visits

So far we have estimated the wind power potential based on the intersection of WPD and LULC maps on various categories of lands in Karnataka and Andhra Pradesh. Only those parcels of lands were considered where wind power densities exceed 200 W/ m^2.

However, the availability of land, as shown in LULC maps, has to be established by detailed micro-siting. Land is often earmarked for several uses such as housing, industrial development, urban plans etc. Further, the suitability for wind turbine choice depends on features like wind speed, type of soil, gradient, proximity to road and transmission network etc.

Such a detailed analysis is beyond the scope of this study. However, we undertook limited field visits of selected sites in Karnataka and Andhra Pradesh to validate some basic land characteristics of sites with promising wind potential. The objective of field visits was to verify:

1. Land availability as per LULC
2. Type of land
3. Accessibility by road and
4. Grid connectivity

The sites selected were the largest parcels of land with WPD greater than 300 W/m^2 at 80 m hub height. Five locations were selected in Karnataka for verification of the above mentioned attributes as shown in Figure 4.1 and Table 4.1. For Andhra Pradesh, six locations were selected and are listed in Figure 4.2 and Table 4.3. Details of the attributes observed from the locations are summarized in Tables 4.2 and 4.4.

Karnataka

Table 4.1: Selected sites for field visits in Karnataka

S. No.	Site	Area of the site (Sq.km)	Annual Average WPD @ 80m (W/sq.m)	District	Lat / Long	Land classification
1	Bommagatta	83	266	Bellary	14.748/76.599	Wasteland
2	Buddenahalli	11	310	Bellary	14.906/76.603	Wasteland
3	Chelamanahalli	41	275	Bellary	14.879/76.655	Wasteland
4	Rajapura-1	41	282	Chitradurga	15.016/76.728	Scrub forest
5	Rajapura-2	24	294	Chitradurga	15.001/76.686	Agriculture

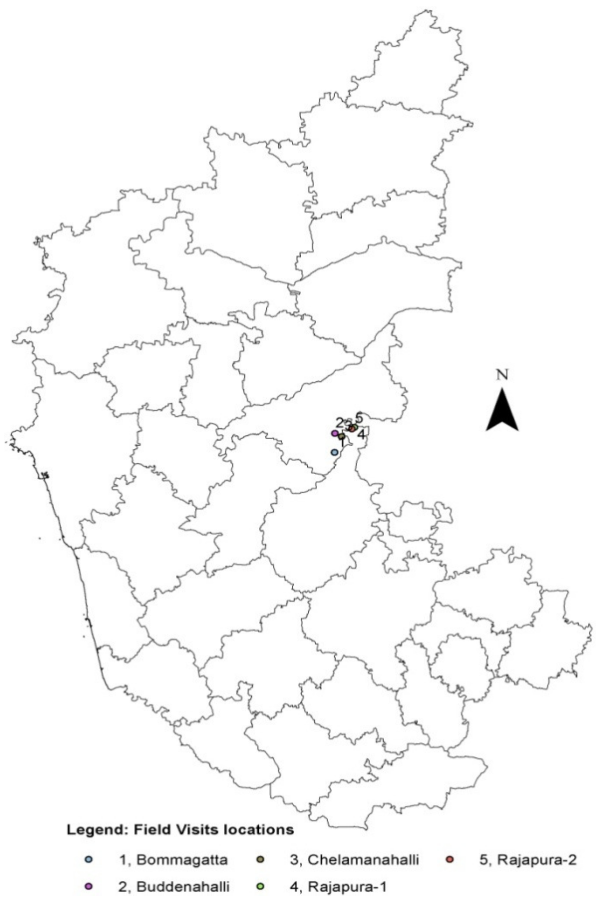


Figure 4.1: Karnataka map showing the five sites chosen for field visits

Table 4.2: Site inspection details for Karnataka

Site Name/ Parameter	Land Availability	Road Access	Road type/ Distance	Grid Access	Grid line type/ Distance	Distance from State capital (Bangalore) (km)
Bommagatta	Unoccupied wasteland	Yes	Mud road	Yes	1 HT line/ 1 km	245
	Type of land: Combination of level scrub forest and agricultural land Additional Observations: Appears to be a good location for wind power development subject to wind speed measurements. There is a wind monitoring station near the site.					
Buddenahalli	Unoccupied wasteland	Yes	Mud Road	Yes	1 HT line/ 4 km	286
	Type of land: Combination of small forest patches and agricultural land with small hills and rocks. Additional Observations: There is an existing wind mast near the site.					
Chelamanahalli	Unoccupied wasteland	Yes	Motorable	Yes	1 HT line	273
	Type of land: Site is on top of the rock mountain near the Chelamanahalli village					
Rajapura 1	Unoccupied Scrub forest land	Yes	Motorable	Yes	1 HT line	300
	Type of land: Forest land with small hills					
Rajapura 2	Unoccupied agricultural land	Yes	Motorable	Yes	1 HT line/ 6-8 km	320
	Type of land: Mainly agricultural land with small forest patches and small hills					

Andhra Pradesh

Table 4.3: Selected sites for field visits in Andhra Pradesh

Site	Area of the site (Sq.km)	Annual Average WPD @ 80m (W/sq.m)	District	Lat / Long	Land classification
Kadapa	28	279	Rayalseema	14.357/78.808	Wasteland
Kadri chinnapalli	40	303	Anantapur	14.338/78.186	Wasteland
Kadri tulapula	56	285	Anantapur	14.199/78.227	Wasteland
Kadri Udumalakurti	53	263	Anantapur	14.217/78.878	Wasteland
Puttaparthi 1	27	275	Anantapur	14.141/77.872	Wasteland
Puttaparthi nallamada	23	282	Anantapur	14.164/77.944	Wasteland

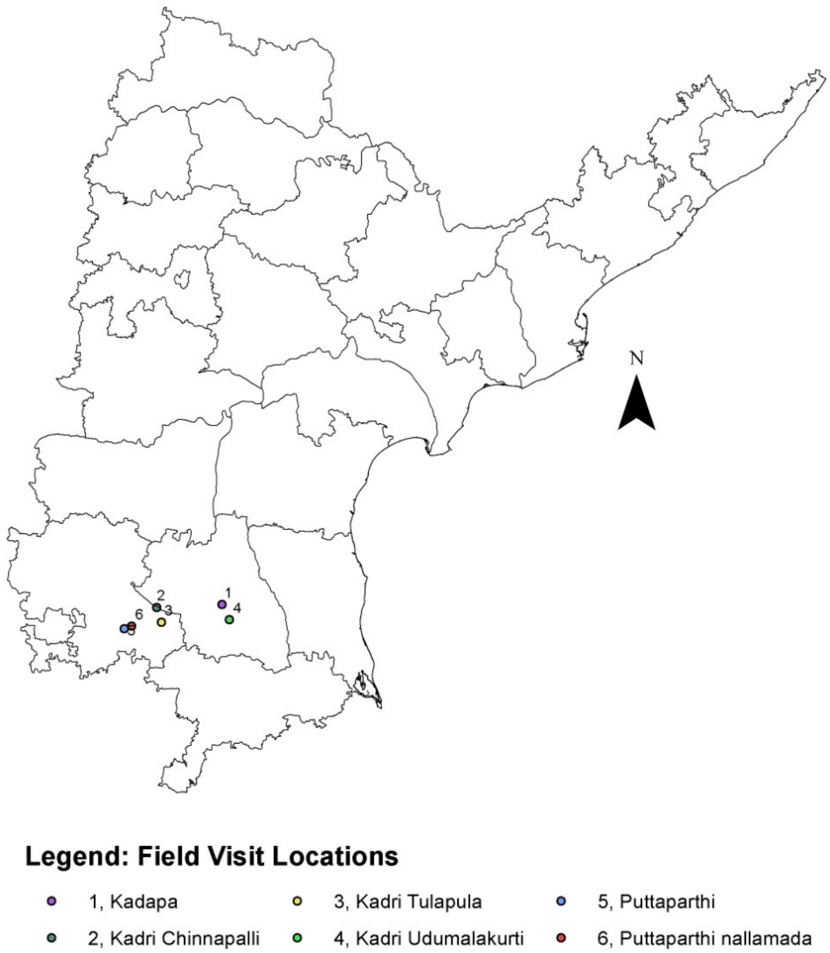


Figure 4.2: Andhra Pradesh map showing the six sites chosen for field visits

Table 4.4: Site inspection details for Andhra Pradesh

Site Name/ Parameter	Land Availability	Road Access	Road type/ Distance	Grid Access	Grid line type/ Distance	Distance from State capital (Hyderabad) (km)
Kadapa	Unoccupied	Yes	Mud road	Yes	1 HT line/ 5km	400
	Type of land: Scrub forest land					
Kadri Chinnapalli	Unoccupied	Yes	Approx. 2 km. from motorable road	Yes	1 HT line/ 3 km	450
	Type of land: Scrub forest land					
Kadri Tulapula	Unoccupied	Yes	Approx. 2 km from motorable road	Yes	1 HT line/ 3 km	465
	Type of land: Scrub forest land					
Kadri Udumalakurti	Unoccupied	None	Not accessible	Yes	1 HT line/ 3km	480
	Type of land: Scrub forest land					
Puttaparthi 1	Unoccupied	Yes	1 km from motorable road	Yes	1 HT line/3.5 km	440
	Type of land: The site is on the hill top and surrounded by the agriculture land					
Puttaparthi nallamada	Unoccupied	None	Motorable	Yes	1 HT line/ 4 km	450
	Type of land: Scrub forest land on a hilly terrain					

The sample sites which were found to be suitable for wind power development using the LULC maps from KSRSAC are verified by field visits and most of them are found to be available for wind farm development. The roads leading to the identified site were verified to exist as per the road network map from LULC data.

Further descriptive details and pictures of the site can be found in Annexure 1.

5. Grid Integration of Wind Power

Introduction

As seen in the previous chapters, there is large wind power potential in the two states under consideration. The estimation of potential was found to be not merely a technical question based on WPD mapping, but also dependent on system-level aspects such as land-use, cost, road connectivity, and grid accessibility and connectivity. In this chapter, we focus on the issues related to the ability of the grid to absorb increasing quantum of variable wind power generation, in the process of planning for the realization of the estimated potential.

Wind as a resource, like solar, is characterized by both variability and unpredictability. When considering issues for wind power integration, there are mainly two types of challenges from the grid operator's perspective. The first is power evacuation, i.e. transporting power from the wind farm to the grid and subsequently to the load centre. This requires investment in transmission infrastructure. The second is operational, i.e. managing the variability and unpredictability of the wind. Since wind power generated is a function of the cube of the wind speeds at the site, even small deviations in speeds can cause substantial changes in power output.

Power Evacuation

If considered at the plant-level, power evacuation might appear as a simple technical challenge. For instance, installation of a 500 MW wind farm would need a transmission line of similar rating. However, when considered in the context of the complete transmission network, there are more factors to be taken into account.

Power transmission operates in a mesh, with different points acting as load demand and supply points, depending on the condition of the grid. For instance, if Karnataka plans for a large capacity wind farm near a big load centre, it is likely that the entire power generated could be absorbed locally, and enhancement of existing transmission infrastructure may not be required. However, when the available wind power cannot be absorbed locally, then it will flow over the extra high voltage transmission system to the other load centres at longer distances. Thus, the impact of adding a large wind farm at a point needs to be modelled at the systems level, taking into consideration all connected nodes of the network, through grid-level power flow analysis.

Managing variability and uncertainty

Wind power is variable and unpredictable by nature. Weather predictions can provide a reasonable estimate, especially on a seasonal or multi-day level, but to know the output at 15 minute intervals with certainty is non-trivial.

Traditional power grids are designed to handle variations in load by adjusting the generation to match with the loads in real time. For this purpose, power generation sources such as coal and nuclear plants which are not capable of fast ramping up/down are generally run as base load generation. However, hydro, open-cycle gas, and diesel based plants are generally operated to meet the variations in the load demand as they can be quickly ramped up and down as per the requirement.

Electricity demand continuously varies as different appliances come online. Thus, the load demand varies continuously over the hour, day, month and year. The addition of wind into the power generation mix introduces variability at the supply side, in addition to the variability of load demand in the system. Grid operation will have to respond to both diurnal and seasonal variations of wind in addition to the variation in load demand.

Lower penetrations of wind power, say 15-20% by capacity, may be handled by the system relatively easily but large additions will have a major impact on the grid stability and will have to be planned keeping in view the safety of the grid. However, there is no proven "maximum" level of wind penetration. The optimal limit for a particular grid will depend on the existing mix of generating sources, pricing mechanisms, capacity for storage, demand response and other factors. An interconnected electricity grid should include reserve generation and transmission capacity to allow for equipment failures, known as spinning reserves. This reserve capacity can also serve to regulate the varying power generation by wind plants. However, in India, we often do not have such spinning reserves for maintaining the reliability of the system, and depend on load shedding to maintain real time supply demand balance.

Wind power generating stations are treated as 'must-run' as per Indian Electricity Grid Code, unless grid security at stake [1]. Hence, the grid should have the capability of absorbing wind generation by backing down other generating sources when wind generation is high and compensate for its loss when required. In several countries, markets for such balancing services exist. However, in India, such markets are at a nascent stage of development. Also, states lack adequate generating resources to meet their energy and peak load demands. Quick ramping generating sources must thus be planned for, along with planning for addition of wind on a large scale to meet the requirement of total energy, peak demand, and variability of wind. Another issue to be kept in mind is excess wind generation when the system demand is low. In such cases, the options for grid operators are currently limited to backing down hydro and other quick ramp down generation to the extent possible before curtailing wind generation itself. For efficient utilization of wind capacity, this excess can be diverted to appropriate storage systems.

In other countries with high penetration of wind in the system, the grid has both spinning reserves (~ 20%) as well as quick starting generators such as open cycle gas turbines. In India, we have no spinning reserves and quick ramping sources are limited. Hydropower is attractive from an operational perspective, in that it can turn on or off almost instantly, and it also has very low marginal costs of generation. It is also, in most states, inherently cheaper for utilities as most hydro plants are older units that are already amortized (see Figure 5.1 for Karnataka values).

Figure 5.2 shows the present generation mix of the installed capacity in Karnataka and Figure 5.3 shows the growth of generation capacities of wind and hydro in Karnataka over last 10 years. As can be seen, the growth of hydro is not commensurate with the growth of wind generation. The present hydro power generation capacity in Karnataka is nearly 3,600 MW [2] which is sufficient to absorb the variation in the existing wind power generation. It is important to note that requirement for back up sources may coincide with the peak load demand. Today, Karnataka uses hydro as peaking power, but if it is used for this purpose, it cannot simultaneously be used as backup when the wind power reduces during peak periods.

At present, there are only a few large scale hydro plants under construction, in states with large anticipated wind power capacity. In Karnataka, only Gundia hydro-power project of 200 MW is currently planned. Large hydro projects have long gestation periods and also face environmental challenges due to their adverse ecological and social impacts. Hence, in the future, it is necessary that other fast ramping generation sources and storage be included to realize the wind power potential in the state.

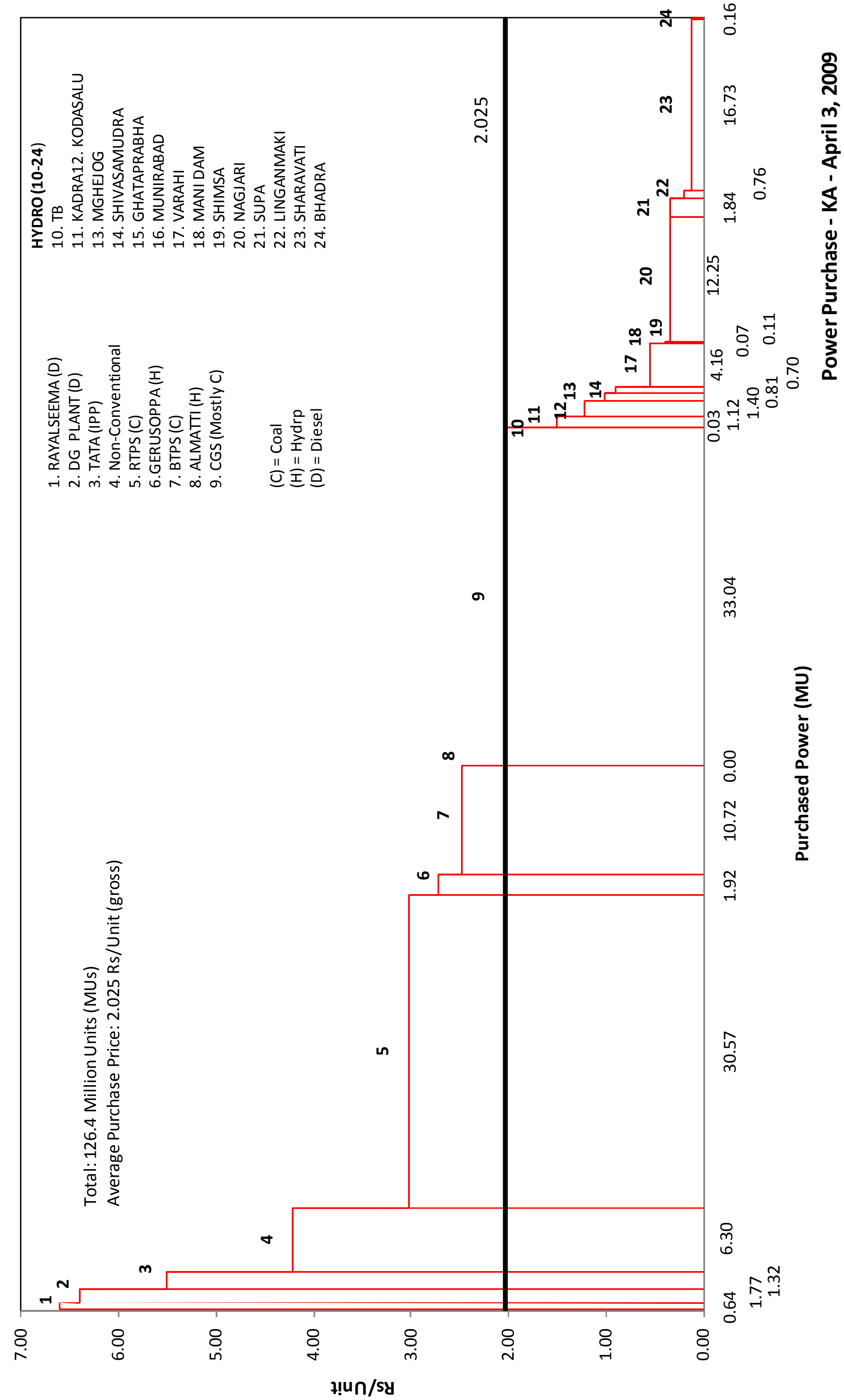


Figure 5.1: Karnataka Power purchase (on April 03, 2009)

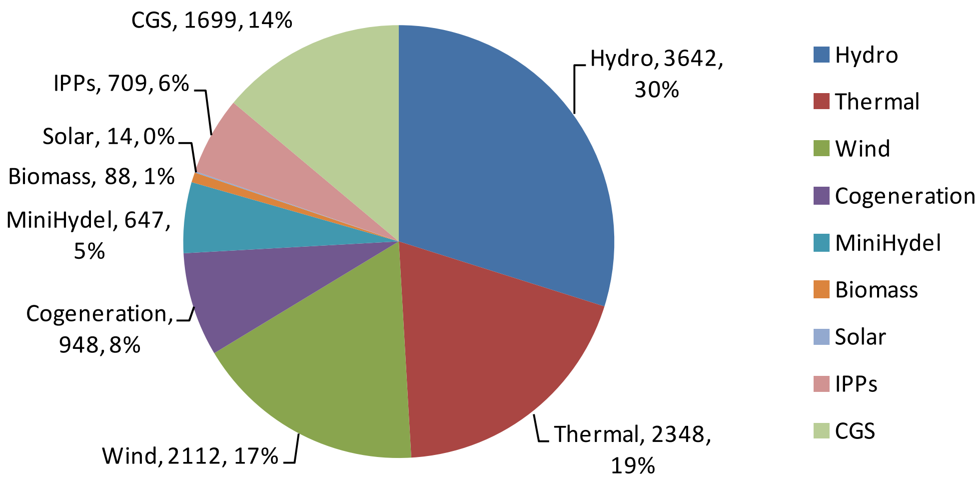


Figure 5.2: Installed Power Generation Capacity (MW) in Karnataka

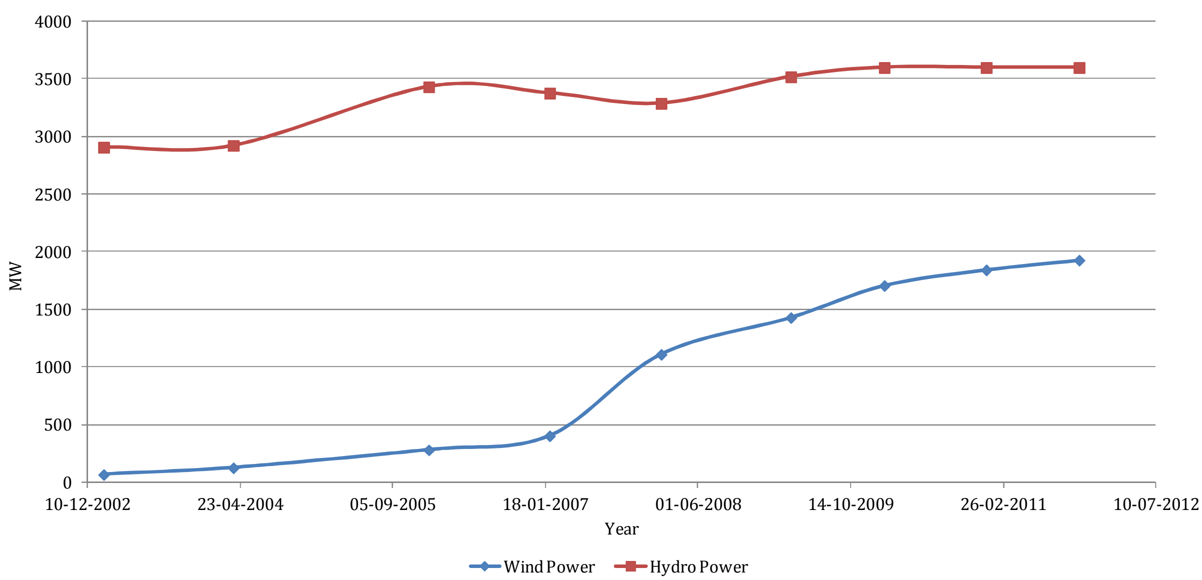


Figure 5.3: Hydro and wind power generation capacity growth in Karnataka

Analysis of wind power generation in Karnataka

In Karnataka, as shown in Figure 5.4, wind power generation (on secondary y-axis) is high during the monsoon periods when the load demand is low (on primary y-axis). This gives opportunity to back down hydro generation and store water in reservoirs to use it for power generation during low wind seasons. However, there is a limit up to which the backing down of conventional generation is possible. Hence, beyond certain levels of wind power penetration in the system, there is a need to plan for either grid level storage or inter-regional power transfer. Else, there may be instances when wind power may have to be curtailed in order to maintain grid stability.

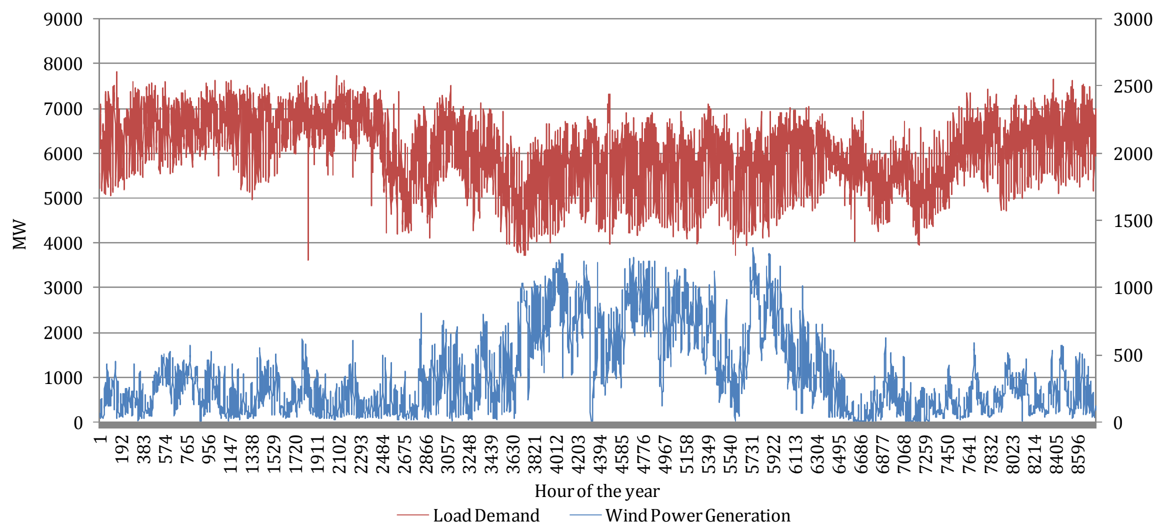


Figure 5.4: Hourly average load demand and wind power generation in Karnataka (2011)

With better wind forecasting techniques, there is scope for partial or complete back down of thermal generation over a period of time, thus saving coal reserves. But this option has a trade-off in terms of the efficiency and the plant load factor. If thermal generation is backed down partially, it would result in multiple problems like increased heat rate, poor performance in terms of coal consumption and higher emissions of CO_2 and NO_x. Additionally, frequent ramping up and down of thermal units may result in higher maintenance cost and reduced life span of the generating units.

Figure 5.4 shows the variations in cumulative wind power output of the state at one minute intervals over the period Oct.'10 to Sept.'11. It can be seen from the figure that there are both diurnal as well as seasonal variations in wind power generation. In high wind seasons, wind can cater to almost 15% of the average load requirement of the day. However, there are diurnal variations to be addressed, as can be observed from Figure 5.5.

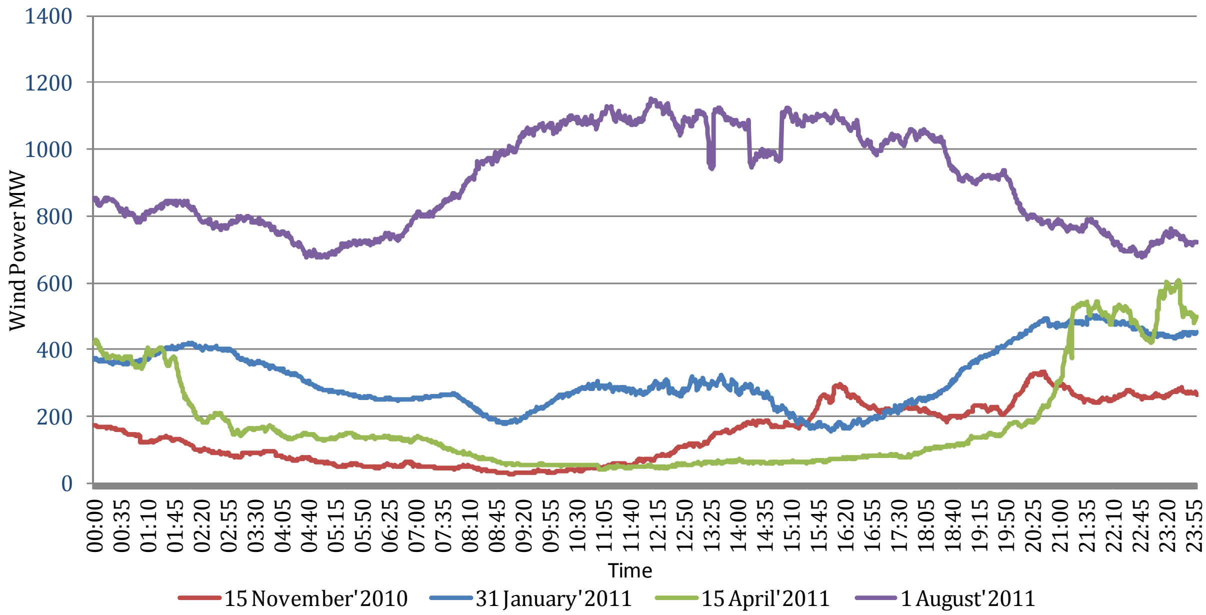


Figure 5.5: Variation in wind power output on four different days

Figure 5.6 to Figure 5.9 show the variation in wind power output with respect to the variation in load demand on four typical days. (Note: The wind power is at secondary y-axis and load at primary y-axis in all four figures)

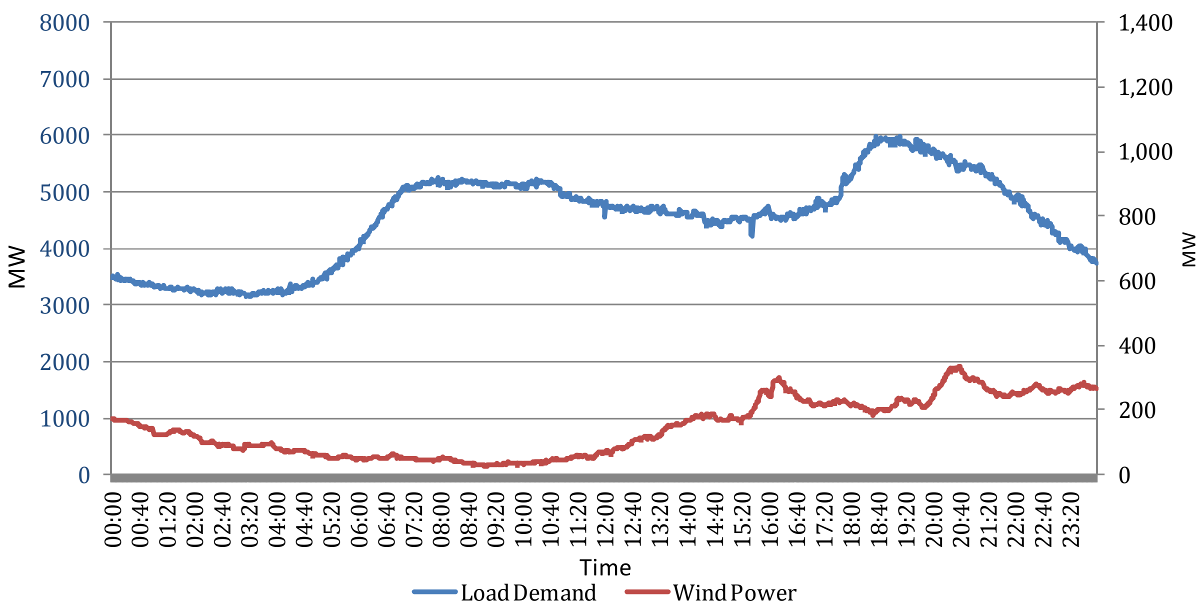


Figure 5.6: Variation in wind power output and load demand on 15 Nov'10

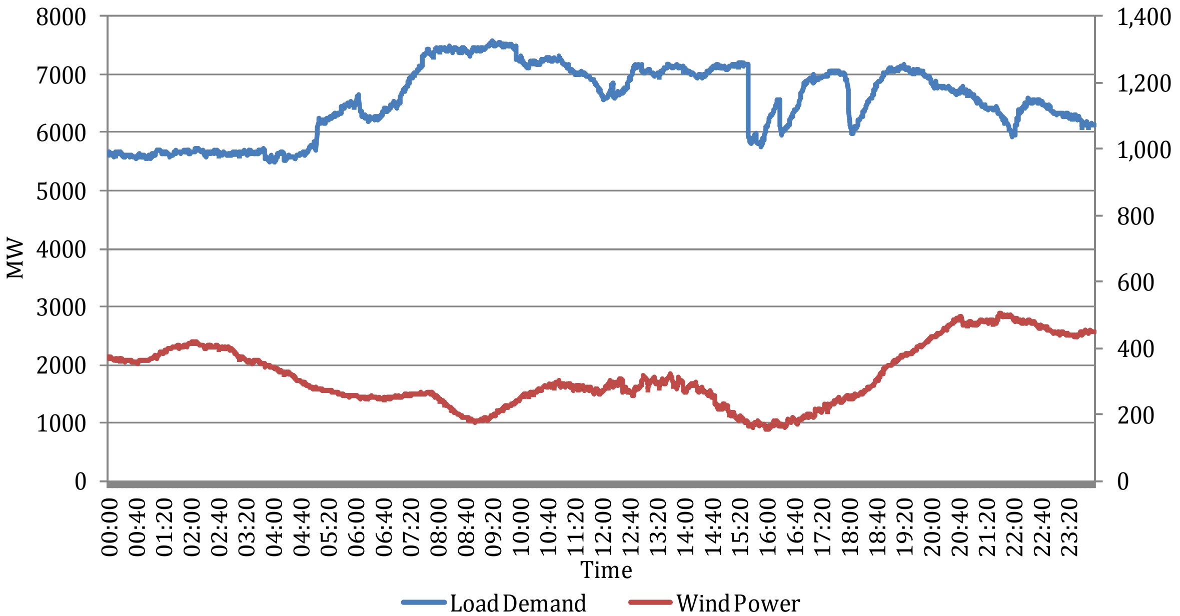


Figure 5.7: Variation in wind power output and load demand on 31 Jan'11

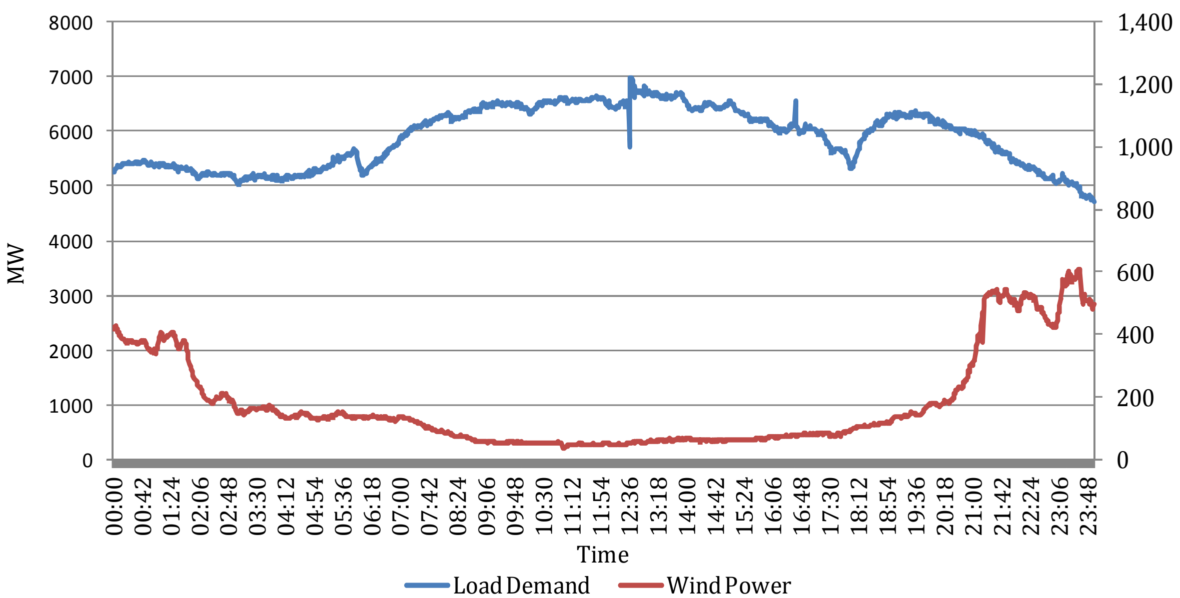


Figure 5.8: Variation in wind power output and load demand on 15 April'11

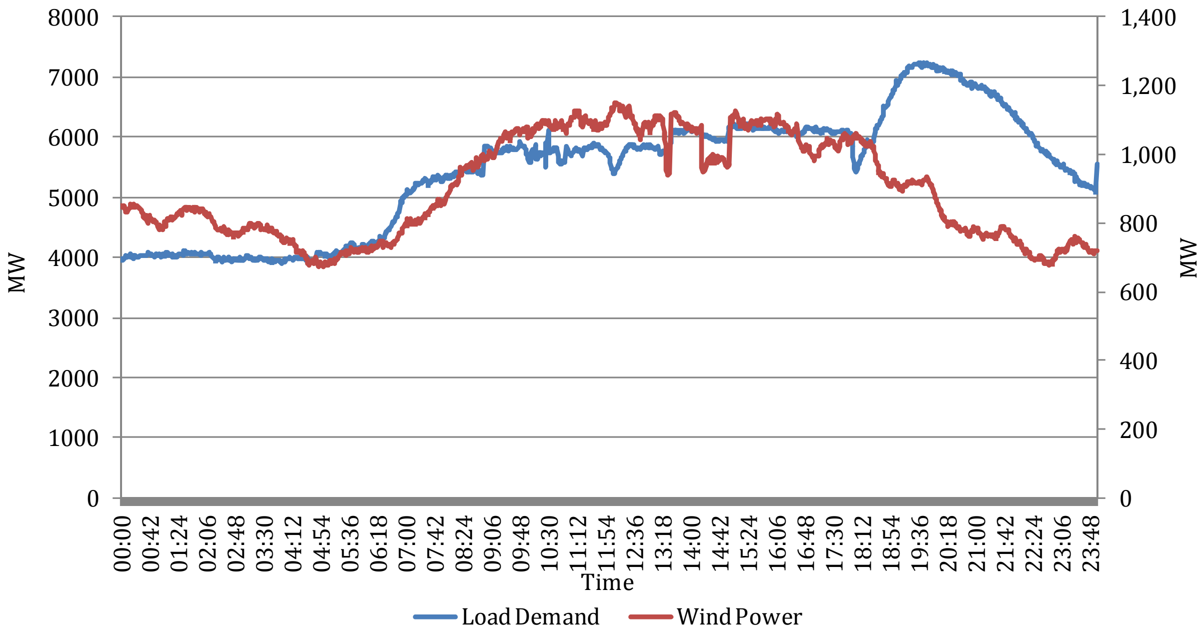


Figure 5.9: Variation in wind power output and load demand on 1 Aug'11

Ramp analysis of wind power

In order to estimate the characteristics and capacity of storage/back-up generation required, we need to analyse the extent of wind power variations in the system. Figure 5.10 and Figure 5.11 show wind power generation in Karnataka in April'2011 and August'2011, representative of low-wind and high-wind seasons, respectively.

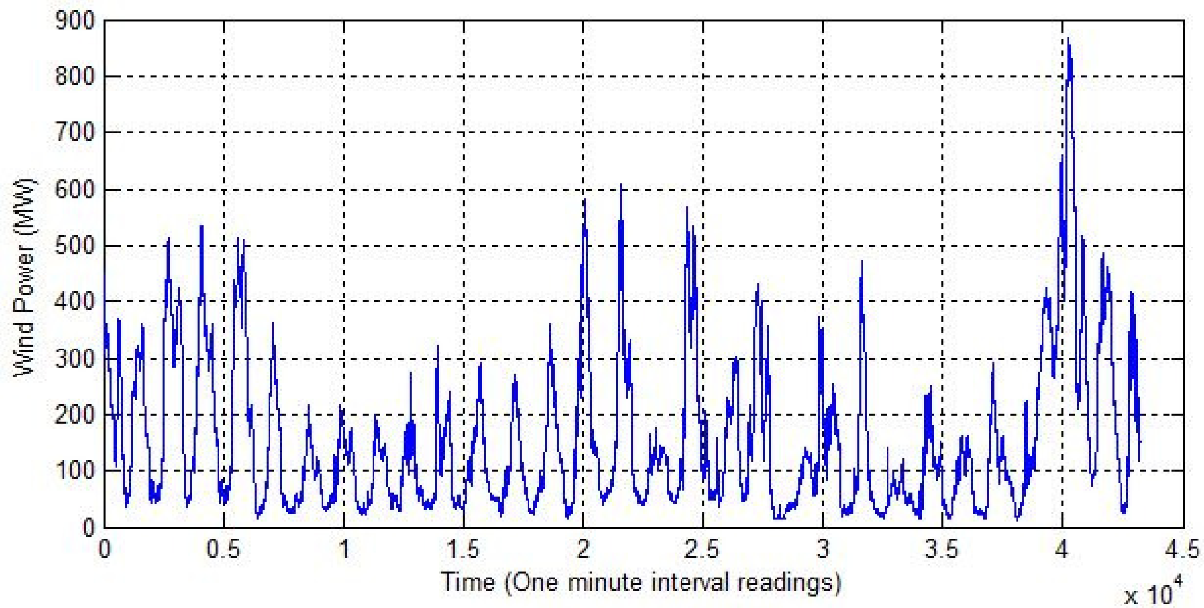


Figure 5.10: Wind Power Generation in Karnataka in April'2011

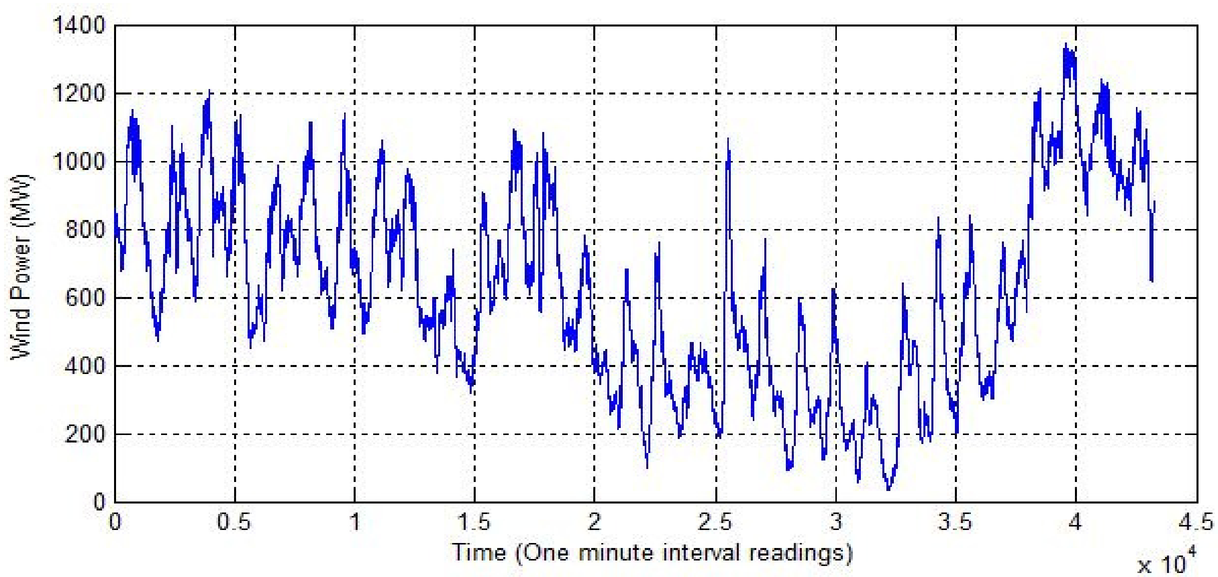


Figure 5.11: Wind Power Generation in Karnataka in August'2011

Ramp events are defined as the large variations in the wind power in short time periods [3]. The ramp is considered as positive or negative depending on whether the generation increases or decreases over time. Negative ramps are usually more challenging to deal with as the grid operators have to find other fast ramp-up generation sources to replace the decrease in wind power and maintain the supply demand balance in real time. The severity of a ramp event will depend on the existing generation mix of the system and there is no standard threshold limit to call a deviation as the ramp event.

We have considered 15-, 30-, and 60 minute time blocks for calculating the ramps. The difference between the maximum and minimum value within a block is taken as the ramp for that time block. Figure 5.12 and Figure 5.13 show the number of times negative ramps are observed during two months, for the time blocks under consideration. This was analysed on an installed capacity of 1800 MW.

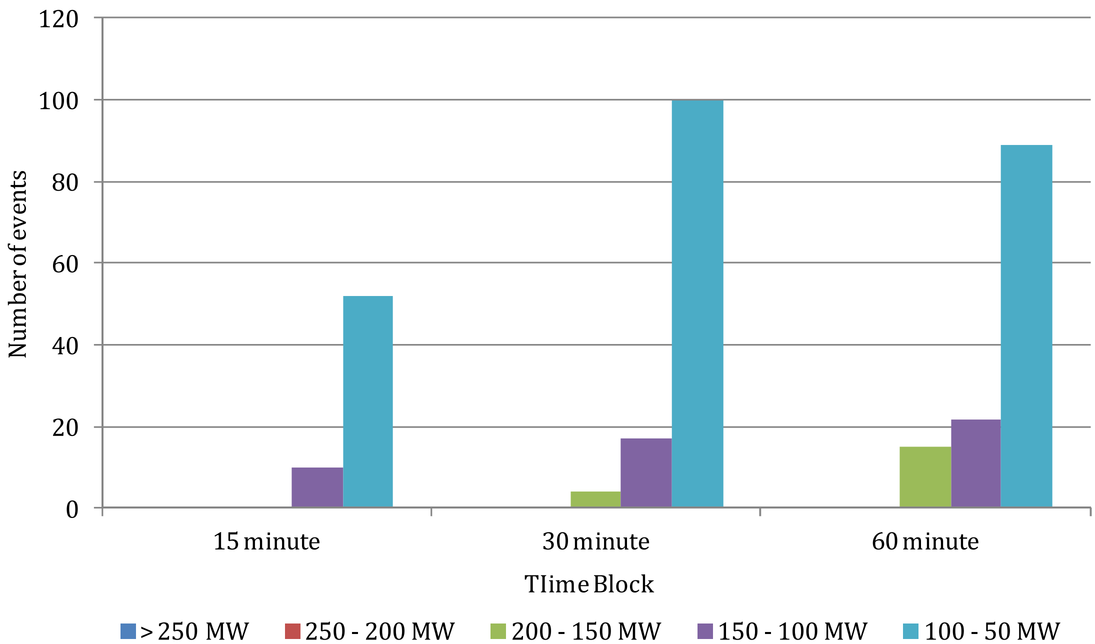


Figure 5.12: Negative Ramps observed during different time intervals in April'11

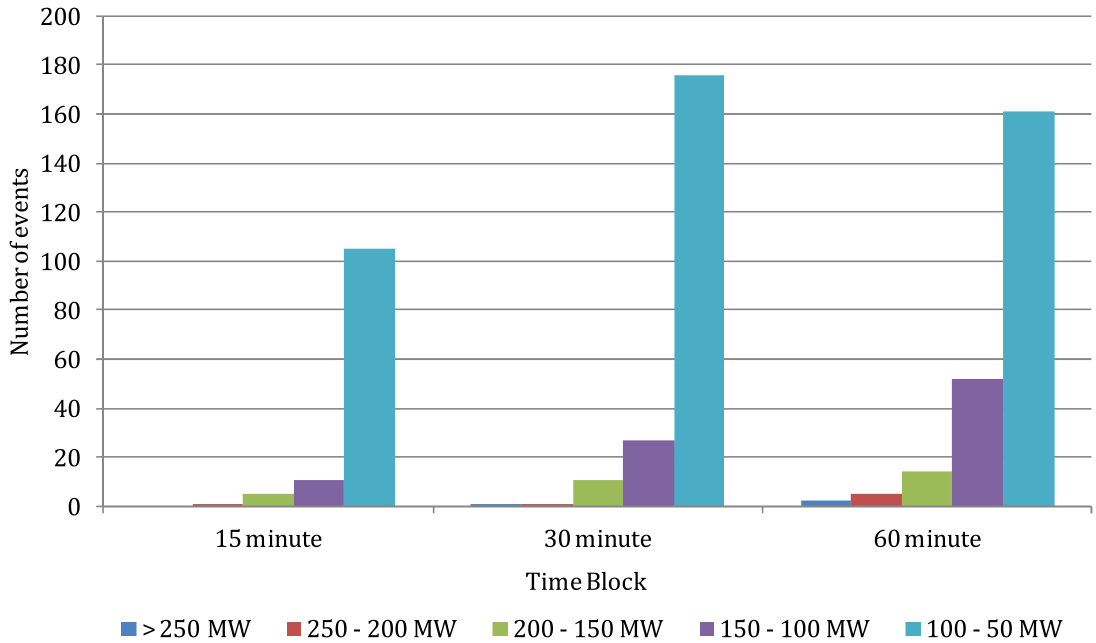


Figure 5.13: Negative Ramps observed during different time intervals in August'11

As summarized in Table 5.1, higher ramp-downs are more frequent in the month of August which is the high wind season. Fluctuations of high magnitude are observed mostly in the time blocks of 30 and 60 minutes. In August, it was observed that there were 11 incidents of loss of generation of the order of 100 – 150 MW (5 - 8% of installed capacity) within 15 minute time periods. Similarly, there were 66 incidents of loss of generation of the order of 100 - 200 MW (5 - 11% of installed capacity) in a 60 minute period. There was also a higher magnitude of loss of generation above 200 MW observed 7 times in the month for 60 minute blocks.

At present, Karnataka is able to manage this variability with its large hydro reserves. However, if the state has to install large wind power in the future, it has to plan for alternatives in the form of storage or quick-ramping alternate generation sources to manage these variations. Even if the states were to realize conservative estimates of potential from Section 1, say 25000 MW, this requires planning for capacities of the order of 2500 MW that can ramp up within several short (15 minute) and medium (30 - 60 minute) durations. Better forecasting techniques can improve predictability of such ramp events.

Table 5.1: Ramp-down frequencies for typical seasons of wind generation

		15min		30min		60min
April'11						
>250		0		0		0
200-250		0		0		0
150-200		0		4		15
100-150		10		17		22
50-100		52		100		89
August'11						
>250		0		1		2
200-250		1		1		5
150-200		5		11		14
100-150		11		27		52
50-100		105		176		161

Mechanisms to manage wind power intermittency

Ancillary Services

In addition to generators that supply required energy (kWh) as per a schedule, a well-functioning grid requires additional services to operate smoothly. Termed ancillary services, these are typically enabled by a market environment. Below are some services that fall in the scope of the same:

- Normal Operations
  - Regulation
  - Load following
- Contingency Operations
  - Spinning Reserves
  - Non-spinning Reserves
- Other Services
  - Voltage Support
  - Black start

The first two are utilized continuously, on timescales of seconds or minutes. The Indian grid allows its frequency to deviate much more than Europe or the US, but the use of Availability Based Tariff (ABT) has helped narrow the frequency bands in recent years.

The overall cost of ancillary services is a small fraction of the total kWh cost, but the exact number depends on the load profile and supply position. The cost of ancillary services, for instance the cost of spinning reserve capacity that is rarely dispatched but required for stable and secure operation of the system, is typically shared across all modes of generation. Similarly, there is a need for incorporating the cost of wind variability in the system.

Storage

Globally, pumped hydro is one of the most reliable and proven grid-scale storage technologies in current grid operations. The round-trip efficiency of pumped storage is estimated at 70%. However, establishment of pumped hydro systems depend on the availability of suitable sites. There are only a handful of pumped hydro projects in India (Bhira, Maharashtra, 150 MW; Kadamparai, Coimbatore, Tamil Nadu, 400 MW (4 x 100 MW); Nagarjuna Sagar PH, Andhra Pradesh, 810 MW (1 x 110 MW + 7 x 100 MW); Purulia Pumped Storage Project, Ayodhya Hills, West Bengal, 900 MW; Srisailam Left Bank PH, Andhra Pradesh, 900 MW (6 x 150 MW); Tehri Dam, Uttranchal, 1000 MW). Karnataka has also planned 1500 MW of pumped storage capacity, but the project has not yet started due to delays in getting clearances from various agencies.

In addition to pumped hydro systems, upcoming technologies for storing power, especially for short periods of time, are batteries, flywheels, compressed air energy storage, etc. However, for grid level storage, these technologies are still at a nascent stage and only a few pilot projects are in operation across the world. The economics of these systems are yet to be proven for large scale deployment. Detailed evaluation of various storage technology options is presented in the next chapter.

Smart Grid

Smart grid technology uses information and communication technology to monitor and control generation and load. Since the technology includes ability to monitor every point in the power supply system, it can be employed for monitoring generation from wind farms, collecting real-time wind data for forecasting, and implementing demand response.

References

1. http://www.powermin.nic.in/transmission/pdf/Indian_Electricity_Grid_Code.pdf
2. Karnataka Power Transmission Corporation Limited (KPTCL)
3. C. Kamath, "Understanding Wind Ramp Events Through Analysis of Historical Data", September 1, 2009, *IEEE PES Transmission and Distribution Conference and Expo*. Available at https://computation.llnl.gov/casc/StarSapphire/pubs/LLNL-CONF-416432.pdf

6. Storage Options

Background

Energy storage technology review

We now consider the viability of energy storage systems. There are several options for energy storage: Pumped Hydroelectric Storage (PHS) systems, Compressed Air Energy Storage (CAES) systems, flywheels, batteries and super-capacitors. In this chapter, we provide a brief overview of these options and compare them on the basis of their suitability for grid-level energy storage. Figure 6.1 provides an overview of current status of different energy storage technologies [1]. PHS and lead acid batteries are presently the most mature storage technologies for grid applications. Na-S systems also have great potential for supporting wind integration. Other advanced batteries such as Zn/Air, Li/metal, flow batteries and Na-ion are under various stages of development.

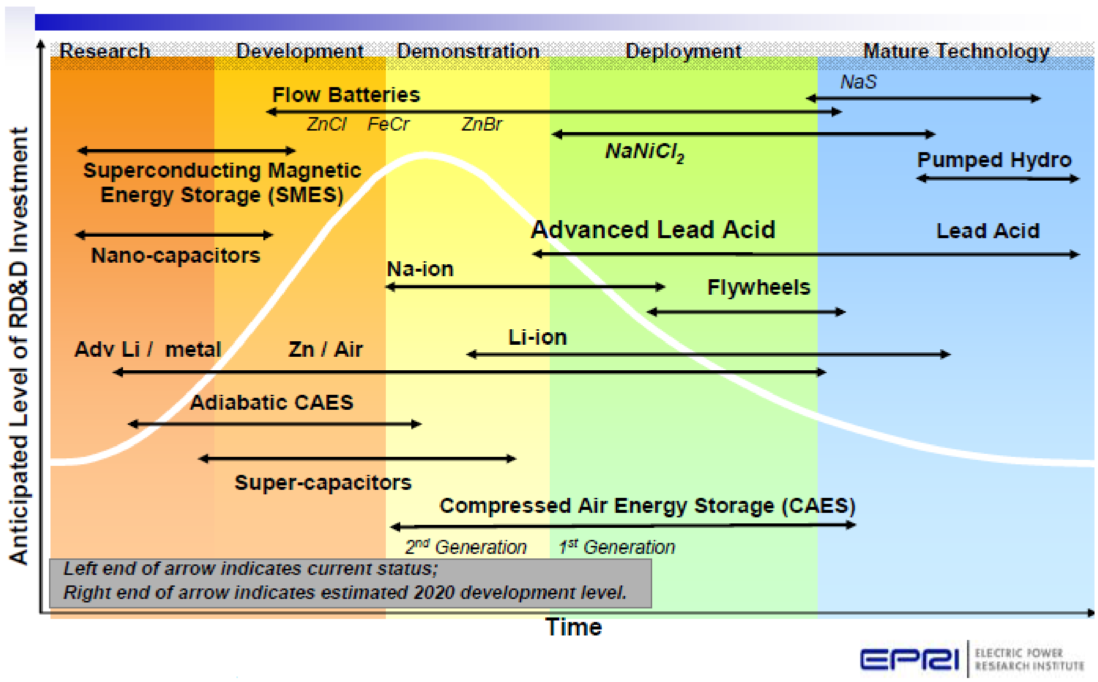


Figure 6.1 Current status of different energy storage technologies

a) Pumped hydroelectric storage (PHS) system

PHS is the most popular, simple and mature technology for electric energy storage. It consists of two large reservoirs located at different elevations and pump/turbine units. During off-peak hours, excess energy is used to pump water from the lower to the higher reservoir. When the grid requires electricity, water is released from the higher reservoir, down the pipe through the turbines to the lower reservoir. Typically, the motor and the generator are the same component with difference in its function during charging and discharging [2, 3]. Figure 6.2 shows a schematic of the PHS system.

PHS systems are ideal for absorbing higher generation available during off-peak hours to store it for utilisation during peak hours for meeting the extra demand, because of their high storage capacity, long cycle life, fast response time, high round-trip efficiency, and low operation and maintenance costs. PHS is thus a good substitute for expensive peaking plants. In fact, most PHS systems were developed as peaking units.

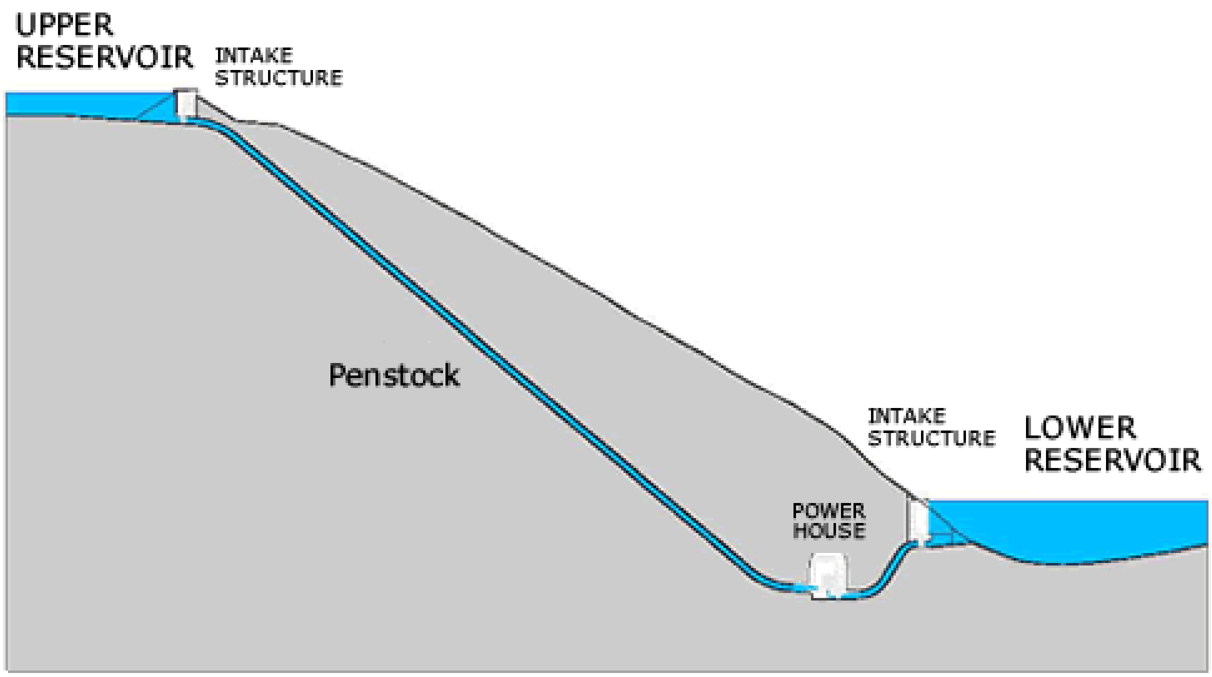


Figure 6.2 Schematic of pumped hydro storage system [4]

PHS systems are now being developed with the objective of grid integration of wind power. China, for example, is planning to build a 3.6 GW PHS system in Hebei province to support high wind power capacity additions [5]. In India, Central Electricity Authority (CEA) has identified 56 sites for PHS systems with total estimated potential of 94,000 MW [6]. A list of existing and planned PHS systems in India is given in Table 6.1 [7,8].

Table 6.1 Existing and planned PHS system in India

Serial No.	Scheme (commissioned year)	Installed Capacity (MW)	Total (MW)
1	Kadana stage I - Gujarat	2 x 60	120
2	Paithon – Maharashtra (1984)	I x 12	12
3	Nagarjunsagar - A.P. (1985)	7x 100	700
4	Kadamparai - T. N. (1986)	4x 100	400
5	Panchet hill - D.V.C. (1980s)	1 x 40	40
6	Ujani – Maharashtra (1994)	1 x 12	12
7	Bhira – Maharashtra (1996)	1 x 150	150
8	Sardar Sarovar- Gujarat (2006)	6 x 200	1200
9	Ghatgar- Maharashtra (2008)	2 x 125	250
10	Srisailam - A.P_(1984)	6x 150	900
11	Purulia - West Bengal (2007)	4 x 225	900
12	Koyana Stage IV – Maharashtra(1990s)	4 x 250	1000
13	Bhivpuri – Maharashtra	1 x 90	90
14	Tehri stage II – Uttranchal (2006)	4 x 250	1000
	Total Operational		6774 MW
	Schemes Under Planning/Proposal		
1	Shravathi- Karnataka (under planning)	4x225	900
2	Kali – Karnataka (Proposed)		600
	Total		1500 MW

b) Compressed air energy storage (CAES) system

Compressed air energy storage (CAES) system is based on storing energy in the form of compressed air in underground caverns or specially designed fabricated tanks. It generates electricity by releasing compressed air into an expansion turbine driving an electric generator. High energy and power capacity, fast response time, longer expected lifetime and lower safety concerns make CAES a good storage solution for wind farms. They can be used for storing extra energy produced by the wind farms during off peak hours to meet higher demand during peak hours. The cost is also generally lower than PHS systems due to lower capital and operating costs in addition to the longer lifetime that helps attaining a lower amortized cost [2, 3]. A schematic of the CAES storage system is shown in figure 6.3.

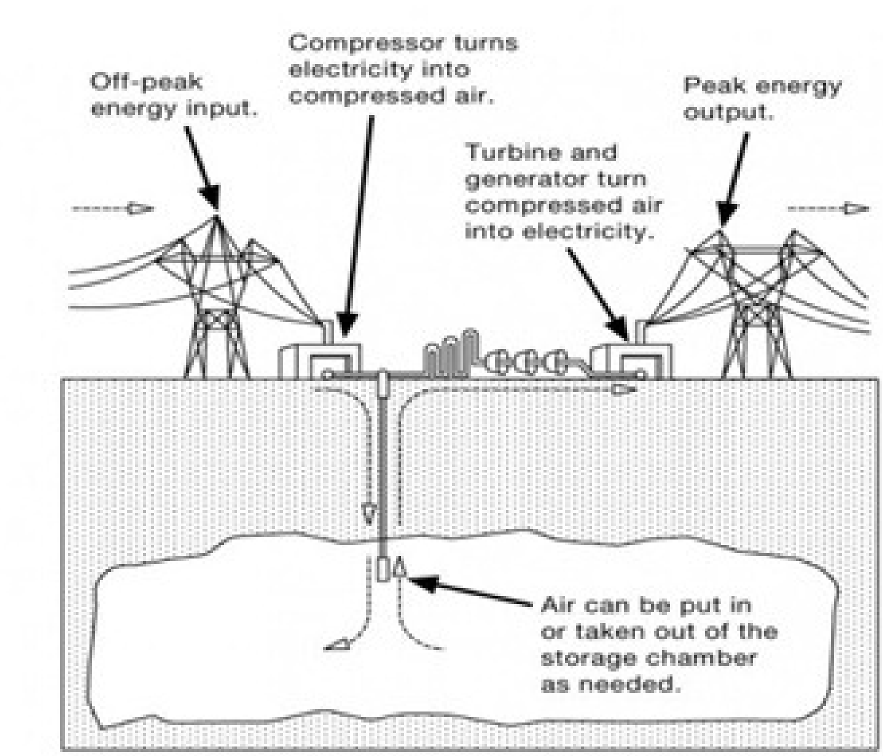


Figure 6.3 Schematic of CAES system [10]

At present, two CAES facilities are operational: 290 MW in Huntorf, Germany (1978) and 110 MW in McIntosh, Alabama (1991) [9]. As of now, India does not have any CAES installation.

c) Flywheels

A simple form of kinetic energy storage, flywheels store energy in rotating mass as angular momentum. They have fast response times of 4 milliseconds or less and have high efficiency for short durations of storage. Disadvantages include high initial cost and high rate of self-discharge due to frictional losses. There should be a continuous maintenance power flow into the flywheel system to compensate for frictional losses. Flywheels charge by drawing electricity from the grid to increase rotational speed, and discharge by generating electricity with the slowing down of the wheel's rotation [2, 3, and 9].

d) Sodium-Sulphur (Na-S) Battery

Figure 6.4 shows the basic orientation of each electrochemical cell in the Na-S battery. The cell consists of molten sulphur as the negative electrode and molten sodium as the positive electrode, separated by a solid beta alumina ceramic electrolyte.

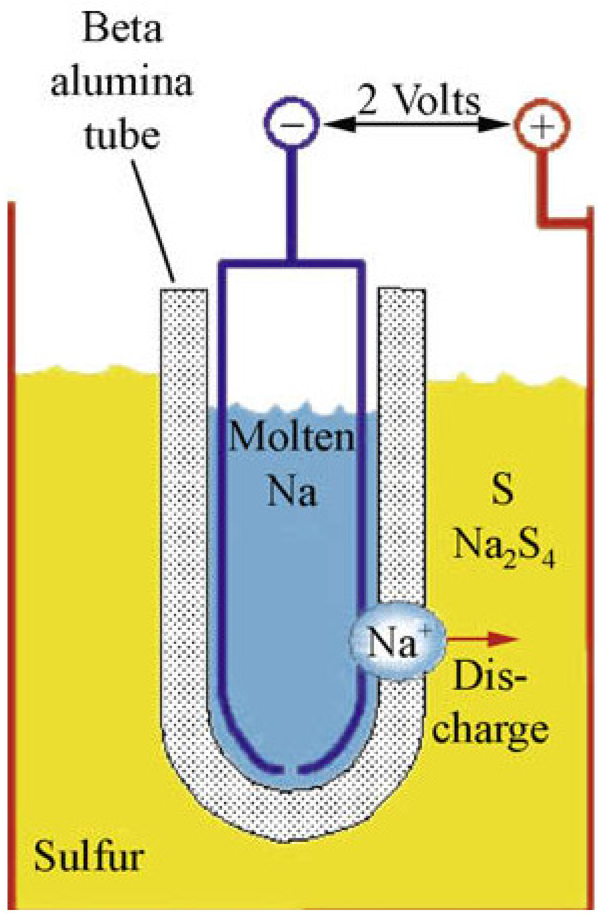


Figure 6.4 Schematic of Na-S cell [11]

During discharge, the negative sodium electrode gets oxidized at the sodium/beta alumina interface producing sodium pentasulphide (Na_2S_5). During charging, sodium polysulphide releases the Na^+ ions that return to the sodium electrode. Generally, a maintenance power is required for the Na-S battery system to maintain the operating temperature of 300-350°C [9, 12].

Na-S batteries are the second largest energy storage systems after PHS systems. The global installed capacity of Na-S batteries is 316 MW across 221 projects [13]. The Electric Power Research Institute (EPRI) expects this to increase to 606 MW by 2012 [14].

e) Sodium Nickel Chloride (Zebra) Battery

The Sodium/ Nickel chloride battery, also known as ZEBRA battery, has evolved from the Na-S battery with the added advantage of having potentially better safety characteristics and a higher cell voltage. The Na/$NiCl_2$ battery is a high temperature system (270-350^{0}C). The Zebra battery has the ability to survive overcharge and deep discharge effects. It can also attain higher cell voltage, reducing the number of interconnected modules for high power storage and thus possess better safety features. However, the ZEBRA batteries have lower energy density (Wh/kg) and power density (W/kg) compared to the Na-S battery [2, 12, and 15].

f) Super capacitors

Super capacitors are devices that store energy in the electrical double layer (EDL) that forms at the interface between an electrolytic solution and an electronic conductor. The most attractive feature of super capacitors compared to batteries is their ability to charge and discharge rapidly since no chemical reaction takes place. Moreover, they can practically be charged at any rate as long as the system stays at the designed temperature range, which is typically -55^{0}C to 85^{0}C. Super capacitors possess almost unlimited recyclability as the mechanism of electricity storage is based on excess and deficiency of electrons rather than chemical changes [2, 16].

Table 6.2 compares relevant technical parameters of the afore-mentioned technologies [2, 12, and 14]. It should be noted that except super capacitors, all systems included in table 6.2 are modular and can be configured in both smaller and larger sizes.

Table 6.2 Comparison of technical parameters of selected energy storage technologies for wind integration

Energy Storage Systems	**Mechanical**			**Chemical**		**Electrical**
Technical Description	PHS	CAES	Fly-wheels	NaS battery (300-350°C)	$Na/NiCl_2$ or Zebra battery (270-350°C)	Super Capacitor
Storage capacity/ Specific Energy	1680-14000 MWh	1080-2700 MWh, up to 3600 MWh for CT-CAES	5 MWh	150-240 Wh/kg	95-120 Wh/kg	2.5-15 Wh/kg
Power capacity/ Specific Power	280-1400 MW	135-180 MW	20 MW	150-230 W/kg	150-200 W/kg	500-5,000 W/kg
Capacity Duration	6-10 hours (>10 hours)	8-20 hours	~0.25 hours	<6 hours	~ 2-6 hours	1-30 seconds
Roundtrip Efficiency	80-82%	60-80%	90%	80%	70-80%	90-98%
Lifetime (Cycles, Years)	>13,000, ~ 40-60 yrs	>13,000 ~ 30 yrs	>20,000, ~ 15 yrs	2,500(100% DOD); 4,500(80% DOD), ~ 15 yrs	> 2500 ~3500 at 80% DOD lifetime~ 10-15 yrs.	~ 20 yrs
Response time	60-90s from shutdown; 5-15s from on-line to full load.	5-12 min with ramp rate of 30% of maximum load per min	4 ms	1 ms	1 ms	4 ms

Storage systems can be installed either at the wind farm level or at centralised locations depending on their economic viability.

Illustrative Analysis

We now present some results of analysis of Na-S battery and PHS systems. In designing an energy storage system, two factors are critical: size (MW) and hours of storage. As stated in the previous section, wind power generation could have diurnal variations to the extent of 100% of installed capacity. In Karnataka, with an installed wind capacity of nearly 1,800 MW [17], the generation varied by almost 300 MW within 15 minute intervals [18].

As an illustration, we have considered a wind farm with storage of 20% of installed capacity and up to three hours of storage. In another example, we have developed a simple model for the volume of upper water reservoir required with respect to the amount of wind energy that can be stored at different hydraulic heights.

Economics of Na-S

Following parameters were considered as the basis for cost analysis of the Na-S battery. The methodology is elaborated in Annexure 2.

- Wind plant capacity : 1 MW
- Capacity Factor: 22%
- Plant Life: 25 years
- Storage System : Na-S battery with net efficiency of 80%
- Storage capacity : 20% of installed capacity (200 kW)
- Backup duration : 3 hrs
- Cost of Battery : USD 550 per kWh [19] ($ 1= Rs. 50)
- Discount rate : 13.8%
- Escalation rate: 5.72%
- O&M cost : 2.5% of aggregate capital cost
- Charging cost: Rs 3.5 per kWh.
- Battery Life : 12.5 years

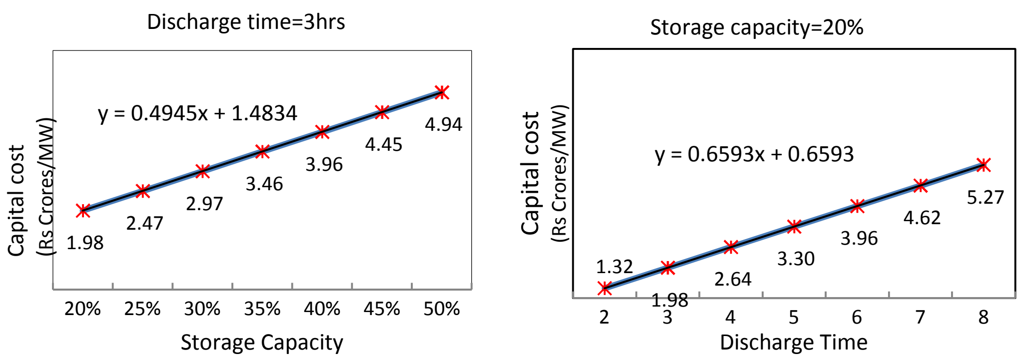
Assumptions:

- The battery system will undergo one cycle of charge and discharge at 90% Depth of Discharge for all 365 days in a year. This results in battery life of 12.5 yrs [20])
- In the absence of any appropriate data on 'balance of system' cost, it has not been included in the cost estimation.
- Escalation rate is applied for O&M and charging costs

Capital Cost

The estimated capital cost of storage is Rs. 1.98 Cr./ MW of installed capacity, for the baseline assumptions mentioned above. Figure 6.5 (a) plots the change in capital cost with varying storage capacity (as percentage of installed wind plant capacity) at fixed duration of discharge i.e. 3hrs. and figure 6.5 (b) plots the same for change in duration of discharge at fixed storage capacity, i.e. 20% of installed capacity.

From the regression equations in the graphs, we observe that for the same energy capacity (kWh) of Na-S storage system, the capital cost increases at a higher marginal rate per kWh (0.6593, figure 6.5 (b)) with increase in duration of discharge than with increase in power capacity (0.4945, figure 6.5 (a)).

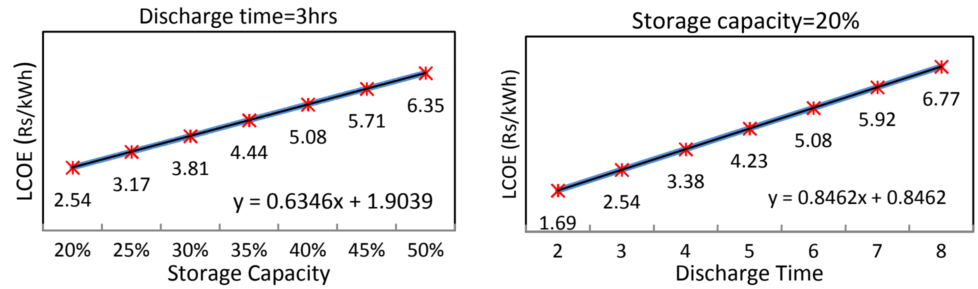


(a) **(b)**

Figure 6.5 Variation in capital cost of Na-S storage: (a) for different storage capacities with 3 hours discharge time, and (b) for different discharge time at 20% storage capacity.

Incremental LCOE

Incremental LCOE is increase in LCOE for integrated wind plant on account of increased storage system cost. The estimated increment in LCOE, for a 1 MW wind farm with 22% CUF, and Na-S storage system of 20% for three hour duration, will be Rs 2.54 per kWh. Figure 6.6 (a and b) shows sensitivity analysis for incremental LCOE. As expected, the marginal rate of increase in LCOE is higher for increasing backup duration (0.8462, figure 6.6 (b)) than for increasing power capacity (0.6346, figure 6.6 (a)).



(a) (b)

Figure 6.6 Variation in Incremental LCOE of Na-S storage: (a) for different storage capacities with 3 hours discharge time, and (b) for different discharge time at 20% storage capacity

Table 6.3 lists down the capital cost and LCOE for various configuration of Na-S battery storage system. Regression equations in the last columns explain the rate at which cost increases.

Table 6.3 Capital cost and Incremental LCOE for various configurations of Na-S battery (a) for a constant discharge time of 3 hours and (b) for a constant storage capacity of 20% of total wind capacity.

(a)

Discharge Time = 3 hours								
Storage as % of Installed capacity (1MW) (X)	20%	25%	30%	35%	40%	45%	50%	Regression equation
Capital cost	1.98	2.47	2.97	3.46	3.96	4.45	4.94	y=0.4945x+1.4834
LCOE	2.29	2.86	3.44	4.01	4.58	5.16	5.73	y=0.573x+1.7189

(b)

Storage = 20% of installed capacity								
Discharge Time (Hrs) (Y)	2	3	4	5	6	7	8	Regression equation
Capital cost	1.32	1.98	2.64	3.30	3.96	4.62	5.27	y=0.6593x+0.6593
LCOE	1.53	2.29	3.06	3.82	4.58	5.35	6.11	y=0.764+0.764

Based on our cost analysis, it can be concluded that for the storage system of same energy capacity (kWh), it is more economical to invest in low duration high power capacity storage system i.e. power intensive storage systems than high duration low power capacity storage i.e. energy intensive storage systems. For instance, a 100kW Na-S battery with backup duration of 3hrs is more expensive than a 300kW Na-S battery with 1hr duration, however energy capacity of both are same i.e. 300 kWh.

Pumped Hydro Storage

We developed a simple model of a PHS system to understand the relationship between the storage capacity (m^3) of the reservoir and hydraulic head height, given the desired maximum amount of energy to be stored. This can be helpful in making decisions related to reservoir volumes and power rating of installed storage system for different possible hydraulic heights while designing PHS systems. Following assumptions were made.

A reversible turbine is used to act as pump while storing wind energy and turbine while generating hydro power. Efficiency of pump is η_P, 80% and that of turbine is η_T, 80%, providing net cyclic efficiency η=64%.

Following formula is used for the analysis,

$$Vh = \frac{\eta x P_s x t}{\rho x g}$$

Where P_S (MW) is the input wind power to the system, t (s) is the duration of storing energy, ρ (kg/m^3) is the density of water and g (m/s^2) stands for gravitational acceleration.

Table 6.4 shows the volume of upper reservoir per MW of wind power to be stored by PHS for various hydraulic heights, assuming discharge for 7 hours. For instance, the upper reservoir should have a minimum volumetric capacity of 1.37 million m^3 at a head height of 60m to store and discharge 25 MW wind power for 7 hours.

Table 6.4 Volume estimation for PHS upper reservoir per MW storage required at various head heights

Height (m)	**Volume of upper reservoir per MW of storage for 7 hours (thousand m^3/MW)**
60	55
80	41
100	33
120	27
140	23
160	21
180	18
200	16

Figure 6.7 shows how the volume of upper reservoir of the PHS system per MW of stored wind power varies with respect to hydraulic height when discharge is for 7 hours.

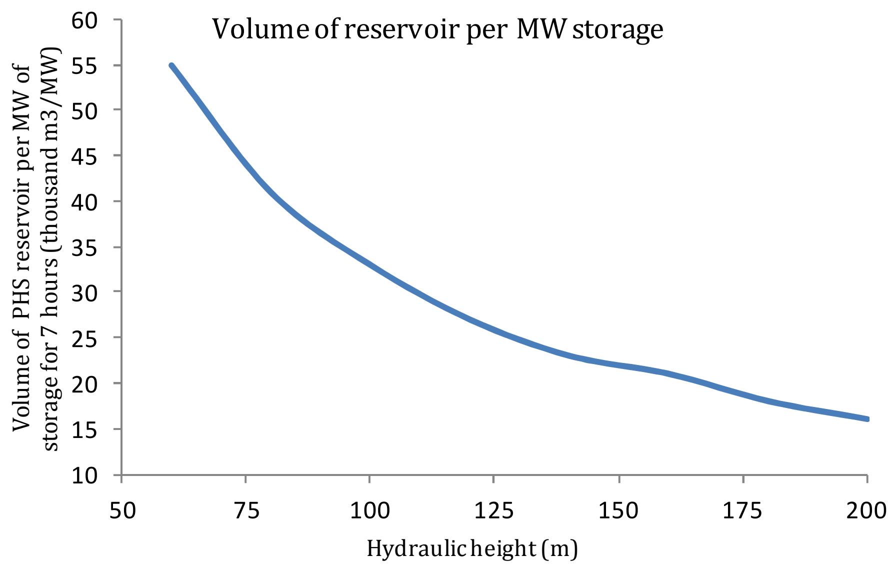


Figure 6.7 Volume of upper reservoir per MW of wind power versus hydraulic heights

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7. Conclusions

The results indicate that availability of potential is not a constraint for development of wind power in both Karnataka and Andhra Pradesh. Karnataka has about 49,000MW from wasteland and scrub forest lands at 80m hub heights. Out of this about 10,000 MW is available at sites where net CUFs of at least 25% can be expected. A. P. has about 89,000 MW from wasteland and scrub forest land at the same height. Out of this, 28,000 MW is available at sites with a net CUF of at least 25%. At 100 m hub-height, Karnataka has 71,000 MW from wastelands and scrub forest lands and A.P. has about 1,15,000 MW from the same land type. Potential from wastelands and those from scrublands, subject to clearances from the Forest department could be prioritized for wind power development. Out of the 10 suitable sites for which field visits were undertaken, all were found to match the land use type indicated as per satellite land use data and were unoccupied.

There is very high wind potential from agricultural land in both States. It is recognized that it is not feasible to use all suitable agricultural lands for establishing wind farms. However, there is scope for considering some of the highest potential agriculture lands for mixed land use between agriculture activities and wind power development subject to impact assessment studies. Even if 5% of suitable agricultural land at each height, situated in the high WPD categories, can be considered for mixed land use, the potential in Karnataka and A.P. is 20,000 MW and 12000 MW respectively at 80 m hub height. At 100 m hub-height, potential from agricultural land is 32,000 MW and 18,000 MW respectively in Karnataka and A.P.

There will be considerable operational challenges for grid operators to balance supply and demand when higher wind capacity is connected to the grid. This is because wind resources have both variability (daily, seasonal) and unpredictability. Better preparedness for managing this externality is essential for efficient utilisation of wind power. This needs to take place along with wind capacity additions through systems and markets that can provide ancillary services. Even if the states were to realize conservative estimates of wind power potential, say 25-30 GW, ramp events of magnitude 2500-3000 MW within short (15-min) and medium (30-60 minute) durations can be expected to be frequent based on past wind generation data. Managing them will require technical and institutional coordination and development of market mechanisms for load balancing services. Better forecasting techniques can improve predictability of such ramp events. Planning for Pumped hydro systems along with high capacity additions in the State can efficiently utilize capacity by storing excess wind-based generation during off-peak hours in order to use it during peak demand hours.

Policy implications

1) There is very high wind potential available from scrub forest and wastelands for both states, some of them from very high wind quality sites that can yield CUFs of 25%. There is opportunity for state nodal agencies to identify some of these high wind potential wastelands/scrub forest lands and expedite clearances for them

2) Karnataka and A.P. have very high potential from agricultural land, with some sites that can yield close to 30% CUF. Such lands could be considered for mixed-use of agriculture and wind power generation, subject to social and ecological impact assessment studies

3) Choice of turbine has a significant impact on the efficient utilization of wind potential at any site. States that saw large capacity additions in the early development phase of wind power in the country can address externalities created due to high-potential lands being locked up by low-capacity and low-efficiency wind turbines. Appropriate incentives for repowering can facilitate capacity enhancements in some of the already identified high potential sites

4) Efforts for improvement in data collection and forecasting techniques are essential to enable efficient scheduling of wind power

5) Strict implementation of Renewable Portfolio Obligation (RPO) in all States is a necessity to ensure off take of wind power and efficient utilization of potential. Since this has cost implications for utilities and other obligated entities, better price discovery mechanisms for wind energy and competitive procurement of wind power may be considered along with RPO enforcement

6) As wind power potential in the country is non-uniform, southern and western states with high potential should be able to export excess wind energy to others during high wind generation months, and take advantage of complementary resources during low-wind-generation months. This requires advance planning for inter-State and inter-regional transmission capacities, and co-ordination between transmission utility and state renewable development agencies

7) Short-term power markets play an important role for managing diurnal variations in wind. Therefore, current transmission capacity constraints faced by power exchanges need to be solved

8) Various storage options can be considered based on cost, capacity and ramping times. Development of PHS and CAES systems, cheaper storage options in terms of per unit cost, must go hand in hand with wind capacity additions

9) Investments in quick-ramping capacity, that can come online for shorter time frames can be incentivized through well-developed capacity markets

Annexure 1

Field Visit Details

Karnataka

Details of sites chosen are further outlined below accompanied by pictures of the site

Bommagatta

Bommagatta is a Village in Sandur Taluk in Bellary District in Karnataka. It is 15.6 kms from its taluk main town Sandur and is located 44.9 km distance from its District Main City Bellary. It is located 245 km distance from its State Main City Bangalore.

Figure 1: Mud road leading to the chosen site

Buddenahalli

The selected site is around 3 kms from the village on the main road from Buddenhalli to Mattajanhalli. It is 32 Km from its taluk main town Sandur, 65 km from its district main city Bellary and is around 286 km from Bangalore.

Figure 2: High Tension line passing near the site

Chelamanahalli

The selected site is around 1.5 km from the Chelamanahalli village on the main road from Appaynahalli to Mattajanhalli. This site is around 52 km from Bellary and is 273 km from Bangalore.

Figure 3: The picture shows that the area has hillocks

Rajapura 1

The selected location is around 2.5 km from village Rajapura, on Rampur to Rajapura road. The site is located nearly 130 km from Bellary and is around 300 km from state main city Bangalore.

Figure 4: Picture shows that the site is accessible by road

Rajapura 2

The selected land is around 2.5 km from village Rajapura and is on Rampur to Rajapura village main road. The site is around 148 km from its district main city Chitradurga and is nearly 320 km from state capital Bangalore.

Figure 5: The selected site has small rocky hills with cultivated land nearby

Andhra Pradesh

Kadapa

Kadapa is a city (Municipal Corporation) in Rayalseema, a region of the south-central part of Andhra Pradesh. The selected location is 7 km from the main city and is on the way to Bangalore from Kadapa and is around 400 km from state capital Hyderabad.

Figure 6: Mud Road towards the site near Kadapa

Kadri chinnapalli

The selected site is 4 km from the village Chinnapalli and is located on the way to Pulivendula from Kadri. It is around 100 km from the district main city Anantapur and is 450 km from state capital Hyderabad.

Figure 7: The location is scrub forest land

Kadri Tulapula

The selected site is around 2 km from the main village Tulapula. It is around 105 km from its district headquarters at Anantapur and is 465 km from state capital Hyderabad.

Figure 8: The location is on top of the hill and cannot be reached by road

Kadri Udumalakurti

The selected site is around 4 km from the village Udumalakurthi and lies on the way to Pulivendula from Kadri. The site is nearly 30 km from its main taluk Rayachoti, 190 km from district headquarters at Anantapur and is 480 km from state capital Hyderabad.

Figure 9: The snapshot of the selected location

Puttaparthi

The selected site is around 7 km from the village Telugurayancheruvu, and is nearly 80 km from its district headquarters at Anantapur. Puttaparthi and is on the way to Nallmada. The site is nearly 440 km from Hyderabad.

Figure 10: Road leading to the selected site

Puttaparthi Nalmada

The selected site is nearly 5 km from the main village Nalmada and is deep inside the forest on a hilly terrain. The site is around 90 km from the district headquarters in Anantapur. The site is 450 km from state capital Hyderabad.

Figure 11: The location as seen from a distance

Annexure 2

Storage Economics

The appendix provides the approach taken for the economic analysis of the sodium sulphur battery for wind integration.

Cost estimation methodology

System costs [1, 2] are based on many factors and vary widely from system to system. Systematically, they can be divided into six categories. Following symbols are used for calculation of present value of storage system cost and total lifetime energy output.

System Costs		System Parameters	
C_{PC}	Power capacity cost [Rs/kW]	P_{Max}	Power capacity of the system [kW]
C_{EC}	Energy capacity cost [Rs/kWh]	E_{Max}	Energy capacity of the system [kWh]
C_{PCS}	Power conversion system costs [Rs/kW]	C	Cycle life of Battery.
C_{BOP}	Balance of plant costs [Rs/kw]	N	Years of operation [years]
C_{OMF}	Fixed O&M Costs [Rs/kW-yr]	n	Number of cycles per day
C_{OMV}	Variable O&M costs (Rs/yr)	L	Length of discharge cycle.
A_{gen}	Annual energy production from energy storage system (kWh/yr)	D	Number of days storage is operated each year.
η	Efficiency of the system	e	Escalation rate
PV_{TG}	PV of total energy generation	i	Inflation Rate
PV_{TC}	PV of integrated storage system costs	d	Discount/interest rate.
LCOE	levelized cost of energy (Rs/kWh)	r	Replacement period

Energy storage system costs (C_{EC}) [Rs/KWh]

This is the overnight capital cost of the storage device itself. Since most systems can be scaled up by interconnecting multiple units in series/parallel combinations, it will be assumed that this methodology correctly approximates the system costs.

Cost of Storage system,

$$PV_{TSS} = C_{SS} = \frac{E_{Max} \times C_{EC}}{\eta}$$

Replacement costs (C_{RC}) [Rs/kWh]

Up-front capital costs do not tell the whole story for many storage technologies because they have limited lifetimes or cycle lives. This aspect of technology performance needs to be compared with other systems that do not require significant replacement costs during a 25-year lifetime.

Present value of Replacement Costs,

$$PV_{TRC} = C_{SS} \times \sum_{r} \left[\frac{1+i}{1+d}\right]^{r}$$

The number of terms in above equation is equal to number of replacements during the life time of plant. The replacement period 'r' can be calculated as

The number of terms in above equation is equal to number of replacements during the life time of plant. The replacement period 'r' can be calculated as

$$r = \frac{C}{n \times D}$$

Power Conversion System Costs (CPCS) [Rs/kW]

This category consists of all components between the storage device and the utility grid including power conditioning equipment, control systems, power lines, transformers, system isolation equipment, and safety sensors. Present value of power conversion system costs

$$PV_{TPCS} = P_{Max} \times C_{PCS}$$

Balance of Plant Costs (C_{BOP}) [Rs/kW]

This category encompasses construction costs and engineering, land, access routes, taxes, permits, and fees. Present value of BOP costs

$$PV_{TBOP} = P_{Max} \times C_{BOP}$$

Operation and Maintenance Fixed Costs (C_{OMF}) [Rs/kW-yr]

This is an annual costs for the routine maintenance required to keep the system operational. The units for this cost are dollars per kW of installed capacity, per years of operation (so Fixed OM costs of 5Rs/kW-yr for a 1kW system would cost Rs5 per year). Thus, Present Value of total lifetime O&M costs is

$$PV_{TOM} = P_{Max} \times C_{OM} \sum_{j=0}^{N-1} \left[\frac{1+e}{1+d}\right]^{j}$$

Operation and Maintenance Variable Costs (C_{OMV}) [Rs/kWh-delivered]

This is a cost based on the amount of energy delivered by the device that accounts for any costs incurred based on system usage. These costs are typically extremely low for energy storage systems and therefore are assumed to be significantly less than all other costs, and therefore ignored.

Present value of total storage system costs (Rs)

It is the sum of all the above mentioned six categories of costs.

$$PV_{TC} = PV_{TSS} + PV_{TRC} + PV_{TPCS} + PV_{TBOP} + PV_{TOM}$$

Energy output (KWh)

Assuming that no degradation in production takes place, the annual energy production from energy storage system can be calculated by using the formula

$$A_{Gen} = P_{Max} \times D \times n \times L$$

Present Value of total life time energy production

$$PV_{TG} = A_{Gen} \sum_{j=0}^{N-1} (1 + i)^{-j}$$

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