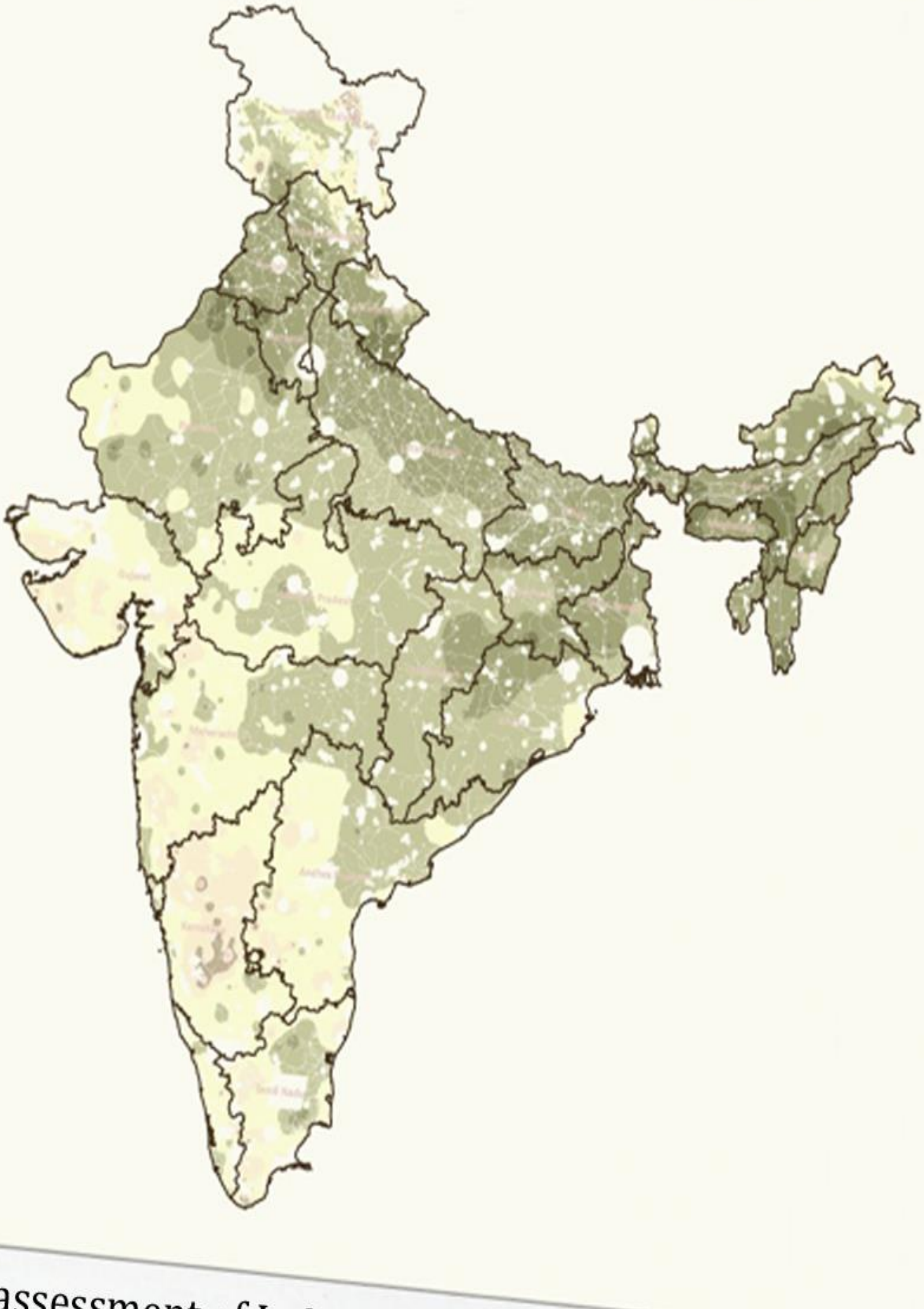

Re-assessment of India's On-shore Wind Power Potential

CSTEP
CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

WinDForce

SHAKTI
SUSTAINABLE ENERGY FOUNDATION

Re-assessment of India's On-shore Wind Power Potential

Submitted to

Ministry of New and Renewable Energy

(June 2015)

Jointly submitted by

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Shakti Sustainable Energy Foundation (SSEF) was established in 2009 to support India's developmental and energy security objectives. SSEF works towards facilitating India's transition to a sustainable energy future by promoting policies that encourage renewable energy, energy efficiency and sustainable urban transport.

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Disclaimer

This report has been jointly prepared by CSTEP, WFMS, and SSEF as part of the Committee for Reassessment of On-shore Wind Power Potential of India, constituted by the Ministry of New and Renewable Energy (MNRE). The report uses data that are in the public domain, and those facilitated by MNRE and SSEF's partner organisations. While every effort has been made for the correctness of data/information used in this report, neither the authors nor CSTEP, WFMS and SSEF accept any legal liability for the accuracy or inferences for the material contained in this report and for any consequences arising from the use of this material.

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Preface

India has an installed capacity of nearly 26 Giga Watt (GW) of on-shore wind as of 2015. It ranks fourth in the world in terms of on-shore wind capacity. This is mainly because on-shore wind technology has proved to be commercially a viable source of energy and is a steadily growing component of India's energy portfolio. The Government of India (GoI) has set a capacity addition target of 175 GW of renewables by 2022 of which 60 GW is envisioned to be met by wind. This implies that a rapid growth of installed wind capacity in the near future.

In this context, it is imperative to optimally harness the wind potential available in the country. Advancements in turbine technology have made it possible to tap the potential at higher hub heights of 80 m, 100 m and 120 m. This implies a significant increase in resource potential as compared to earlier turbines of 50 m hub height. As of last year, the official estimate for an 80 m hub height was 102 GW. However, there are different assessments from various independent organisations which have estimated this potential to be much higher. Multiple studies with varying assumptions and methodologies have produced a range of results.

Hence, it becomes important to reassess the technical wind potential in the country and understand the full extent of potential available by developing a uniform methodology with a common set of assumptions. From a policy perspective, this would help to implement appropriate policies to harness the technical potential.

The Ministry of New and Renewable Energy (MNRE), GoI constituted a Committee for the reassessment of On-shore Wind Power Potential of the country. Members of the Committee included representatives from MNRE, Association of Renewable Energy Agencies of States (AREAS), Indian Wind Turbine Manufacturers' Association (IWTMA), Center for Study of Science, Technology and Policy (CSTEP), WinDForce Management Systems Pvt. Ltd. (WFMS), Shakti Sustainable Energy Foundation (SSEF), Gujarat Energy Development Agency (GEDA) and the National Institute of Wind Energy (NIWE).

The Committee was assigned with the main task to reassess India's on-shore wind power potential at 100 m and 120 m using Geographical Information Systems (GIS) techniques along with data sets on Land Use Land Cover (LULC) and wind speeds. This was done by developing a common methodology after reviewing existing literature on India's on-shore wind power potential including various methodologies, inputs, assumptions and results. This report, which documents the assumptions and methodology used in the analysis, was jointly prepared by CSTEP, WFMS and SSEF and submitted for MNRE's consideration for revising the potential. For this exercise, two independent wind speed data sets were used by CSTEP and WFMS for the purpose of comparison and validation. The results of the analysis underwent a review by an Appraisal Committee identified by MNRE constituting relevant experts and their feedback was duly incorporated into the final version.

I am grateful to MNRE for giving us the valuable opportunity to conduct this analysis. This study was completed with the help of various individuals and organisations who have kindly facilitated access to the wind speed data sets that were crucial for the analysis. Thanks are due to the members of the Appraisal Committee for their valuable feedback on the methodology used in the study. I congratulate MNRE on their recent announcement of the revised potential at a 100 m hub height, and hope that this report contributes to discussions on the technical potential of on-shore wind resource in the country.

Dr. Anshu Bharadwaj
Executive Director
CSTEP

Executive Summary

Till recently, the on-shore wind power potential in India was officially estimated to be 102 GW at a hub height of 80 m.[1] About 26 GW of this potential has been installed in the country. However, there are multiple independent reassessment studies in the public domain that estimate the potential to be much higher. This is due to variations in assumptions and methodologies used. The main characteristic of these studies is that they take into account Land Use Land Cover (LULC) classifications and use a GIS-based methodology to estimate the wind power potential across the country. In order to achieve the national target of adding 60 GW of wind power capacity by 2022, it would be important to reassess the technical on-shore wind potential in the country and identify areas where the potential can be harnessed optimally. This would also be required to design and implement effective policies for capacity deployment. In this context, a Committee was constituted by the MNRE with an objective to reassess the technical on-shore wind potential of India for all major land types at a hub height of 100 and 120 m. As part of this Committee CSTEP, WFMS and SSEF conducted the reassessment exercise using two separate data sets and a common methodology. The methodology used for the analysis, and some of the key findings are discussed briefly below.

Methodology

Independent assessments have been carried out by CSTEP and WFMS, using two different wind speed data sets as an input. While CSTEP used data from 3-Tier, WFMS used a combination of data from NIWE masts, in-house mast data and National Center for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) data and process used meso-scale modelling. A common methodology (and assumptions) was used by the committee members based on the scope of the work and a comparative review of the existing studies on wind potential reassessment.

Annual average spatial wind speed data at hub heights of 100 m and 120 m was overlaid with LULC information in order to estimate the potential in three major land types of waste, agricultural and forest land (ranks 1, 2, and 3 respectively). A digital elevation model was used to generate slope and elevation information. Basic elimination criteria and buffers such as exclusion of built-up areas, water bodies, protected areas, and minimum wind speed and slope were applied to calculate the area feasible for wind deployment.

A representative turbine of 2 MW with a 100 m rotor diameter was used to calculate the wind power potential at the two hub heights, based on a comparative analysis of different wind turbine generators. The deployable potential was calculated for two capacity density configurations of 5D x 7D and 3D x 5D (where D is the rotor diameter of the turbine). The potential was calculated for all states which satisfied the basic criteria mentioned above.

Key Findings

Wind Power Potential: The range of total wind power potential estimated from the two independent assessments conducted by CSTEP and WFMS is summarised below. The potential is reported for the capacity density configurations of 5D x 7D:

[1] Has been revised to 302 GW for a 100 m hub height, after completion of this study

Total Wind Power Potential

Hub Height (metres)	Estimated Wind Potential-CSTEP (5D x 7D layout) (GW)	Estimated Wind Potential-WFMS (5D x 7D layout) (GW)
100	2,759	2,161
120	2,959	2,540

Potential for 3 Land Categories at 80, 100, and 120 m Hub Height

	GW Potential - CSTEP		GW Potential - WFMS	
Land Rank	**100 m**	**120 m**	**100 m**	**120 m**
Rank 1 (Waste Land)	1,001	1,149	591	653
Rank 2 (Agricultural Land)	1,279	1,409	1,222	1,435
Rank 3 (Forest Land)	479	401	349	453
TOTAL	2,759	2,959	2,162	2,541

As shown in the Table above, most of the potential lies in agricultural land and waste land, namely ranks 2 and 1 respectively. Close to 50% of the estimated potential lies in agricultural land. Most of the remaining potential lies in waste lands. A maximum of 17% of the potential is in plantations, evergreen areas, and deciduous forests. There is a substantial amount of potential (up to 2,500 GW) to be harnessed in ranks 1 and 2 categories of land. On waste land alone, there is a minimum of about 590 GW, with up to a maximum of 1,000 GW of potential estimated at a hub height of 100 m, as shown below:

GW Potential for Waste Land and Agricultural Land Categories at 100 m and 120 m

	GW Potential - CSTEP		GW Potential - WFMS	
Land Rank	**100 m**	**120 m**	**100 m**	**120 m**
Rank 1	1,001	1,149	591	653
Rank 2	1,279	1,409	1,222	1,435
TOTAL	2,280	2,558	1,813	2,088

As mentioned previously the capacity mentioned above is based on a 5D x 7D array configuration which has shown to cause the least array of losses due to interference between the turbines. It results in a capacity density of 5.7 MW per sq. km. An estimate based on a more optimal configuration of 3D x 5D layout is also calculated in this study, which represents the most optimistic estimate of the technical potential in the areas considered. This densely packed layout results in a capacity density of 13.3 MW per sq. km, and increases the technical potential to 6,439 GW and 6,905 GW at 100 and 120 m respectively from CSTEP's results. For the second set of results from WFMS, potential increased to 5,043 GW and 5,927 GW at 100 and 120 m respectively. In actual projects, the layout of the turbines may differ, depending on what is suitable for the region-specific terrain. For instance, in regions with gradual hillocks, the turbines may be spaced on top of the hillocks and spaced as a linear string. Since the assessment of region-specific terrains is out of the scope of this study, the two layouts mentioned above are assumed to represent the range of possible layouts for turbines.

Hybrid Potential: The two sources of solar and wind have been observed to have complementary resource profiles. This report also examines the technical potential in co-located wind and solar sites across the country, and estimates that nearly 10 GW of solar-wind hybrid potential is available.

Estimated CUF Ranges: The minimum CUF obtained, by intersecting the wind speed profile (with weibull shape parameter k = 2, for a minimum wind speed of 6 m/s) is 24%. Most of the estimated wind potential lies between 24-34%. A very small percentage of the estimated potential has a CUF of 42-44%.

Optimisation of Land: Most of the potential is concentrated in the seven states of Tamil Nadu, Andhra Pradesh, Telangana, Karnataka, Rajasthan, Gujarat, and Maharashtra. Even if 100% of the potential in these states is tapped, the total land area under wind farms will be ~15% of India's total land area in case of a capacity density layout of 5D x 7D (shown below):

Land Utilisation for Estimated Potential

		5D x 7D	3D x 5D
Capacity installed per sq. km.	**MW/sq. km**	**5.71**	**13.33**
Wind power potential at 100 m	MW	2,759,703	
Total footprint area	sq. km	27,597	
India's total land area	sq. km	3,287,263	
Total land required for tapping the full potential	sq. km	482,948	206,978
Total land required as % of India's total land	%	14.69	6.30
Footprint area as % of India's total land	%	0.84	
Potential in 7 wind-rich states	MW	2,332,912	
Potential in 7 wind-rich states as % of total potential	%	85	
Total land required in 7 wind-rich states	sq. km	408,260	174,968
Total area of these 7 wind-rich states	sq. km	1,442,870	
Total land required as % of the total area of 7 states	%	28.29	12.13
Footprint area of the capacity installed in wind-rich states	sq. km	23,329	
Footprint area as % of total area of 7 states	%	1.62	

This requirement reduces to less than half for a 3D x 5D layout. This range is indicative of the limits of the actual requirement which may lie between the two extremes depending on site-specific conditions. The methodology discussed above and implications of the findings on policy are detailed in the respective sections of the report.

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1. Introduction

1.1. Background

Wind energy is a very important contributor in the global power sector, today, contributing nearly 4% of overall electricity generation. Exponential growth in wind power development across the world, particularly in the last few years, has led to this position. Continued technological development and innovation in design and manufacturing has resulted in large-scale deployment of onshore projects and, to a significant extent, offshore projects. With 370 GW (WWEA, 2015) of installed generation capacity and deployment in more than 100 countries, modern wind turbines have made the transition from a fringe technology to a mainstream electricity generation option. The drivers for this significant thrust in technology, innovation and worldwide deployment are many. The main drivers include energy security, climate change and energy access, while employment and economic development are added benefits.

India, with nearly 26 GW of wind power capacity, ranks 4th in the world in terms on installed capacity. Capacity addition in 2015-16 was around 3,420 MW. The growth seen in wind power development has been exponential, as shown in Figure 1 and Figure 2 (Hossain, 2014) (Joshi, 2014).

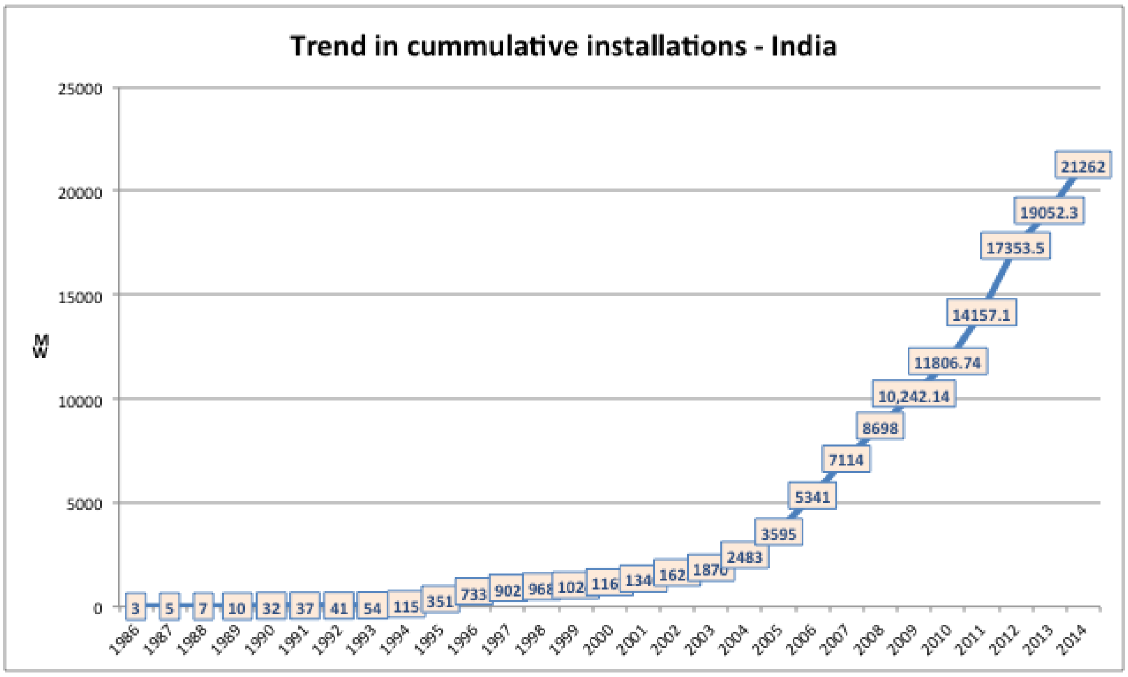


Figure 1: Growth of Installed Wind Power Capacity in India

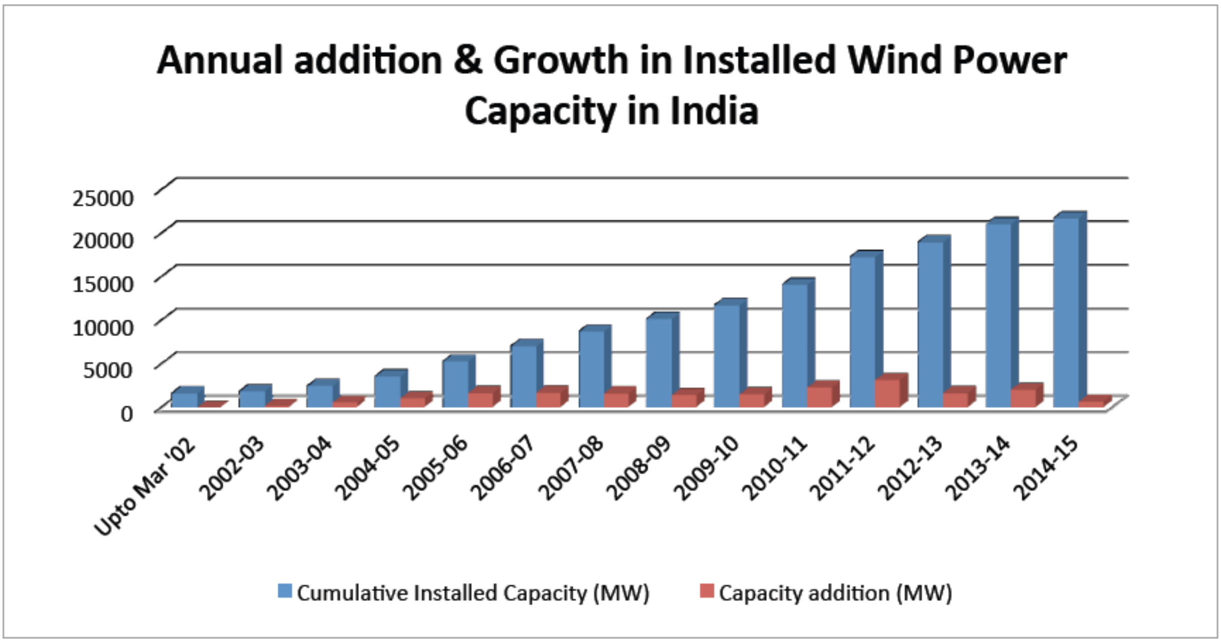


Figure 2: Cumulative and Annual Capacity Additions

Today, there are nearly 20 wind turbine manufacturers in India, with about 52 turbine models certified by the National Institute of Wind Energy (NIWE) for grid connection. The total manufacturing capacity established in the country is about 10,000 MW/year (Mehra & Hossain, 2015).

In March 2015, Renewable Energy (RE) sources formed 12% of India's total installed capacity of 268 GW. Out of this, the share of wind capacity was the highest at 9% (23.4 GW). Between 2006 and 2015, the wind industry added between 1500-3000 MW per annum (Figure 1, Figure 2). This is primarily because wind technology has been technically and commercially viable in India for more than a decade now. Today, wind energy is a key constituent of India's energy basket.

Recognising the immense potential of the resource, the Government of India (GoI) had announced a target of installing 60 GW of wind by 2022 in 2015 (MNRE, 2015). This implies a quantum jump from the current level of annual deployment. Therefore, the Prime Minister's Council on Climate Change has proposed to induct a National Wind Energy Mission under India's National Action Plan on Climate Change (Jai, 2015).

1.2. Motivation for the Study

The Government of India and policy makers are faced with the fact that India has vast wind energy potential. However, there have been different studies and assessments, producing different results. From a policy perspective, it is important to have an understanding of the extent and scale of potential so that appropriate policies can be devised to harness the potential. In India, the official wind energy potential estimate, published by NIWE is 102.7 GW at 80 m (NIWE)[2]. Currently, this estimate is taken into consideration for policy making, and more importantly, for assessing the level of deployment in different states.

Hossain et al. (2011 and 2013) (Hossain, Sinha, & Kishore, 2011) (Hossain J. , 2013) conducted a pioneering assessment of wind potential in India in 2011. They estimated that the country's wind power potential is significantly higher than the official estimates. This assessment has subsequently been revalidated by a number of independent studies. The Lawrence Berkley National Laboratory (LBNL) re-assessed the wind power potential for the entire country in 2012 (Phadke, Bharvirkar, &

[2] Has been recently revised to 302 GW for a 100 m hub height, after completion of this study

Khangura, 2012). In parallel, several assessments were conducted for different wind-rich states with support from Shakti Sustainable Energy Foundation. These include studies by the World Institute of Sustainable Energy (WISE) (WISE, 2012), The Energy and Resources Institute (TERI) (TERI, 2012) and Center for Study of Science, Technology and Policy (CSTEP) (CSTEP, 2013). All these assessments have indicated a potential of almost 2,000 GW for onshore wind farms with wind turbines at 80 m height and nearly 1,000 GW of offshore wind potential. These results are much higher than the official estimates published by NIWE.

Thus, it has become imperative to re-assess India's wind potential. Some of the latest re-assessments conducted in countries such as the U.S. and China have found much higher wind energy potential with advanced technology – higher utilisation factors, hub heights, and rotor diameters of wind turbines.

China's official wind power potential has increased by 800% and that of the U.S. by 50% (see Figure 3). Wind potential estimates for the US, expressed in terms of energy, have increased by almost 400% (Junfeng, Pengfei, & Hu, 2010) (Elliott, 2011) (US-DOE, 2008). All over the world, it is well established that a systematic analysis based on Geographic Information System (GIS) provides an accurate way to identify land with the potential for development of wind power.

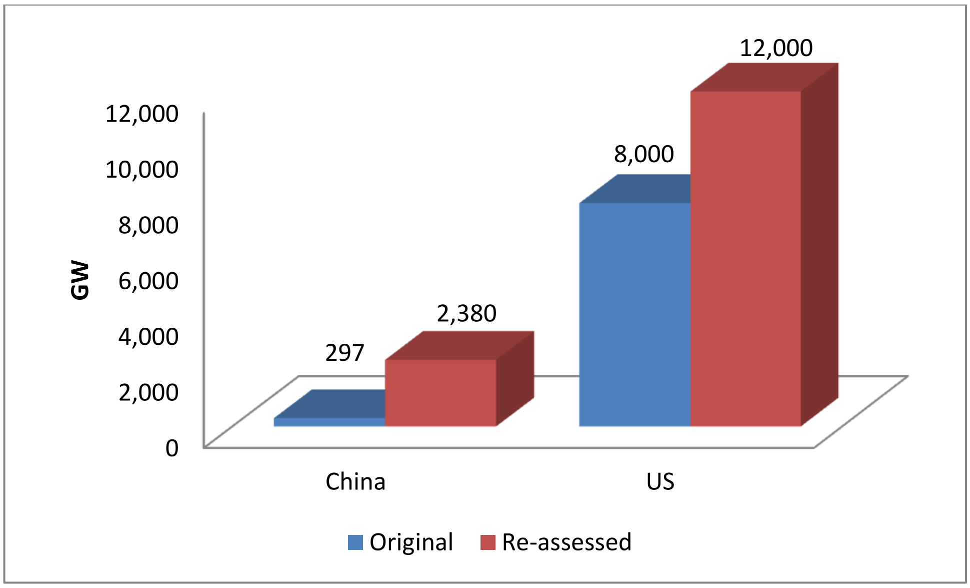


Figure 3: Wind Potential Re-assessments in China and US

In contrast, the potential estimate by NIWE presented in the 2010 Indian Wind Atlas, assumes that only a certain percentage of land would be available for wind energy development. The pipeline of projects in Karnataka and Tamil Nadu already exceed their official potential estimates, with many more windy sites yet to be tapped.

The downside is that the under-assessed potential estimates restrict deployment in states, and more so, prevent stakeholders to draw an ambitious vision for the sector. This has implications for the government and policy makers.

All these developments suggest that a systematic and publically available database of India's wind resource could potentially trigger accelerated deployment and have major implications on the Indian power sector policy.

1.3. Objectives

Recognising the significance that wind potential estimates bear on the outlook for the sector, the Ministry of New and Renewable Energy (MNRE) constituted a Committee of experts in September

2014 (MNRE's office Memorandum No. 58/91/2014-WE) (Appendix 1). The objective of this Committee was to re-assess and report India's onshore wind power potential.

1.4. Scope of Work

The following tasks were assigned to the Committee:

- Review and compile existing literature on India's onshore wind power potential, including various methodologies, inputs, assumptions and results
- Develop a common methodology for re-assessing India's onshore wind power potential at 100 m and 120 m using GIS techniques along with data sets on Land-Use Land-Cover (LULC) and wind speeds
- Use a minimum of two different wind speed data sets/data sources for the purpose of comparison and validation
- Analyse the results obtained, to arrive at a wind potential for India at 100 m and 120 m respectively
- Present the results to relevant stakeholders, as identified by MNRE
- Submit the final report to MNRE, clearly documenting the methodology and assumptions

This report is a documentation of the above activities which was submitted to MNRE for consideration towards revision of the on-shore wind power potential. The report is structured as follows: Section 1 describes the scope of the work and presents a comparative review of the national level studies that have re-assessed India's on-shore wind power potential; Section 2 details the methodology used by CSTEP and WFMS for the analysis, along with the data sources and assumptions used; Sections 3 presents the results of the analysis of the two sets of input wind speed data that was used by CSTEP and WFMS respectively. The wind power potential results are presented in tabular and graphical format, for the three major land types of waste land, agricultural land, and forest land for hub heights of 100 m and 120 m; Section 4 summarises the wind power potential on waste lands; Section 5 presents a preliminary assessment of the solar-wind hybrid potential in India, as per a geo-spatial analysis conducted by CSTEP (this was an exercise taken up as an addition to the initial scope of the study as the data was available for analysis); Section 6 concludes with the summary of the results across various CUF ranges, and discusses the policy implications of the outcomes of the study.

1.5. Review of Literature

Results from different potential estimation studies are shown in Figure 4. There is a vast variation in the results obtained from these studies.

1.5.1. National Level Studies

NIWE is MNRE's nodal agency for wind development in India, formerly known as the Centre for Wind Energy Technology (CWET). NIWE had published the results of a wind assessment (NIWE, Wind Resource Assessment), where the total wind power potential in nine states was estimated at 48,562 MW, at a hub height of 50 m, assuming 1% of land availability in the identified windy regions and a land requirement of 12 hectares per MW. In April 2010, NIWE re-assessed the wind potential and presented with a new figure of 49,130 MW of installable potential in windy states in its wind atlas, which was prepared in collaboration with Risoe, Denmark (NIWE, Estimation of Installable Wind Power Potential at 80 m level in India). This analysis assumed land availability to be 2% in all states, except the Himalayan states, North-eastern states and Andaman and Nicobar Islands. In the Himalayan states, North-eastern states and Andaman and Nicobar Islands, land availability was assumed to be 0.5%. In the analysis, NIWE assumed that 9 MW of wind power capacity can be installed per square kilometre (average of 5D x 7D, 8D x 4D and 7D x 4D spacing, where D is the rotor diameter of the turbine). The off-shore potential has not yet been assessed. Similarly, NIWE carried out an exercise, without any validation, with the Karlsruhe Atmospheric Mesoscale Model (KAMM) generated meso-scale map and estimated an installable potential of 102,788 MW at 80 m hub height.

In 2011, J. Hossain et al. (Hossain, Sinha, & Kishore, 2011), concluded that the outer limit of the extent to which wind farms can be set up in India with currently prevalent technologies, in regions of interest other than the urban and the Himalayan areas, to be around 4250 GW at 80 m.

In 2012, LBNL's (Phadke, Bharvirkar, & Khangura, 2012) re-assessment of India's wind power potential using a globally accepted methodology and showed that "the re-assessed onshore developable wind potential at 80 m hub height in India below the cost of Rs.6/kWh is 2006 GW after assuming that farms, forests, other protected land and geographically hard terrains are not available for wind farm development".

This potential is likely to be higher as better technology gets deployed. Excluded areas include slopes greater than 20 degrees, elevation greater than 1500 m, forests, snow-covered areas, water bodies, and other protected areas along with crop lands. However, such a meso-scale assessment needs to be validated through field-level studies for the purpose of project development.

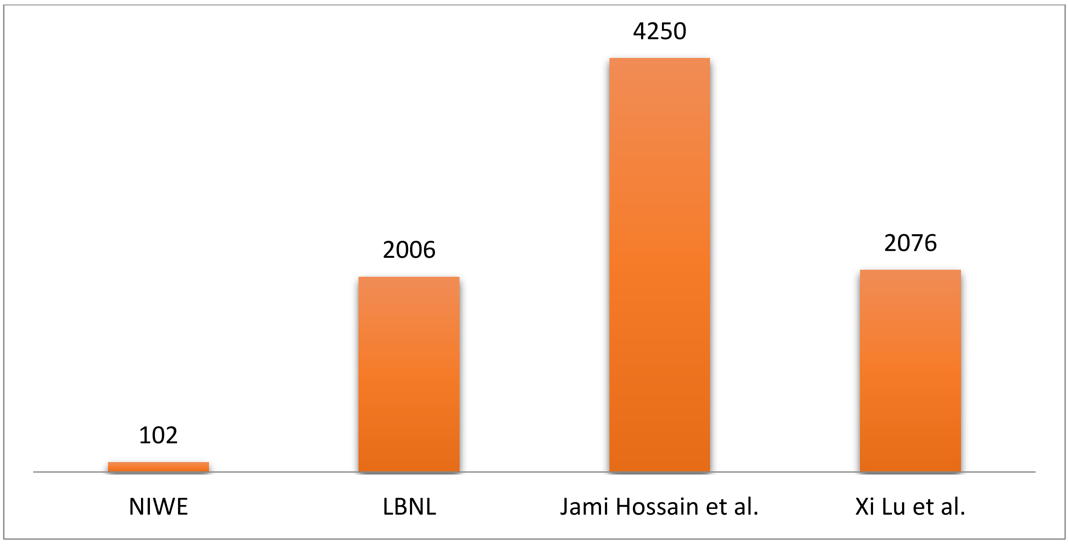


Figure 4: Estimates of India's Wind Power Potential at 80 m Hub Height (GW)

Even though such differing estimates, as described above, give starkly varying figures of potential, the outcomes of various potential studies underline the fact that wind energy potential or the supply side would not be a constraint in achieving 60 GW of wind by 2022. The common finding is that the present official wind potential estimates are hugely under-estimated. Hence, there is a need to realistically re-assess the state-wise potential of wind resources in the country.

1.5.2. State Level Studies

Several independent studies have been conducted over the last four years to re-assess the wind power potential in the resource-rich states of India (see Figure 5). All these reports present large wind potential, which are orders of magnitude higher than the existing official estimates.

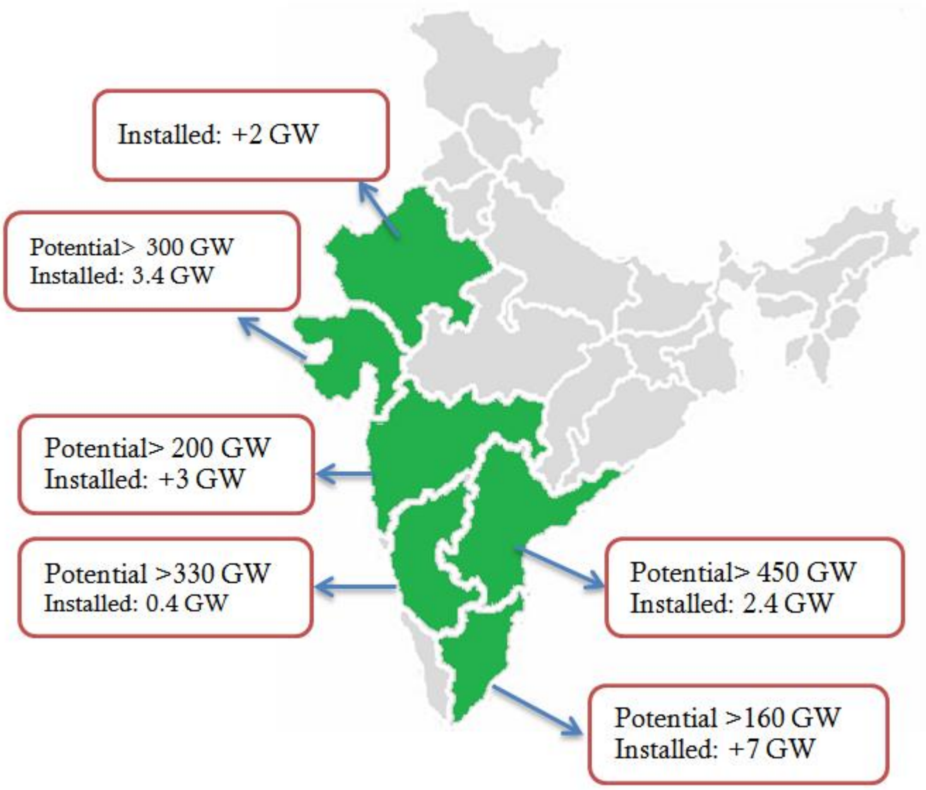


Figure 5: State-level Re-assessments of Wind Power Potential and Installed Capacities

1.5.3. Comparison of Wind Potential Studies

Table 1 below compares the salient features of the existing studies that have estimated the potential both at an All India, and state levels.

Table 1: Comparison of Wind Potential Studies

Parameter		**WISE**	**TERI**	**CSTEP**	**LBNL/B&V**
State →		Tamil Nadu	Gujarat	Karnataka & Andhra Pradesh	All States
WPD	Data Source	AWS Truepower	CWET wind atlas	3-TIER, KREDL, CWET Wind Atlas	3Tier
	Resolution	200m	5 km by 5 km	· 3.6 km x 3.6 km for 3-TIER · Data from KREDL & CWET are for selected locations	3.6 km by 3.6 km
	Costs	Non- disclosure agreement signed with AWS Truepower	No data purchase, but the digitisation of WPD map from wind atlas	Rs. 14,89,050/- (3-TIER data) + Rs. 5,000/- (CWET Wind Atlas)	$10,000
	Validation	Modelled data-Not validated		3-TIER data was validated using actual measured data from KREDL & CWET	
LULC	Data Source	NRSC ISRO LULC 2010-11	Landsat TM/ETM – 1: 250 000	Karnataka state remote sensing application centre (KSRSAC)	GlobCover

	Resolution	62.88 m	30 m	LULC data and slope vector data on 1:50000 scale	0.3 km by 0.3 km
	Costs	Nil	Rs. 1.5 lakh	Rs. 6,00,000/-	Free
	Validation	Validated by NRSC, Govt. of India	By comparing with wasteland Atlas and Land sat series data set were geometrically and radiometrically corrected as per the specification of Global Land Cover Facility (GLCF) network.	Data is based on Multi-temporal Satellite images and KSRSAC has also validated it by field survey	
Key assumptions		Exclusions	Areas with wind power density equal to or greater than 200 W/m^2 at 80 m level above ground. This has been taken from the Indian wind atlas.		
		WPD < 150 W/m^2			
		Slope > 15%			
		Elevation > 1500 m			
		Net CUF > 15%			
		Geographical exclusions: Water bodies, rivers, railroads, settlements, roads, forest etc.)			
		Net CUF = Gross CUF*0.97*0.95^5 (Gross generation discounted on account of Machine, grid availability, air density correction, Internal line losses till metering point, Array losses, hysteresis and miscellaneous losses, etc.)			
		Two land-use scenarios:	1. Land with scrubs, other wastelands (barren land, degraded grazing land, Rann area or saline land) considered suitable for wind projects.		200 W/m^2 and higher wind density, slope above 20 degrees and elevation above 1500 m. Excludes Protected areas, water bodies, rural and urban population areas and forests.
Land exclusion criteria			2. Land parcels of minimum 20 Ha has been considered as wind farm developable area.	The following land will not be considered:	
		Category 1: Wasteland + non forest scrubland		Land with WPD < 200 W/m^2, slope > 20 degrees, elevation>1500m,	
		Category2: Non irrigated Farmland (Kharif +Rabi + Current Fallow)		Forests, water bodies, built-up areas and protected areas.	

	At 80 m hub height, 6815 km^2 of Category 1, and 23940 km^2 of Category 2 , totalling 30755 km^2		Area under Karnataka's waste and scrub forest land at the 3 hub heights (in sq. km.): 7,834 (80 m); 11,353 (100 m); 12,867 (120 m)	
	Tamil Nadu Total Land Area = 130,058 sq. km,		Area under Karnataka's agricultural land at the 3 hub heights (in sq. km.): 63,793 (80 m); 102,317 (100 m); 121, 904 (120 m) Karnataka's total land area: 991,791 sq. km. Agricultural and wasteland wind potential in Karnataka as a % of total land area (at 100 m hub height): 11.5%	7%
Land area suitable for wind projects as a percentage of total land area	Wind Potential Land area (with above assumptions) =		Area under Andhra Pradesh's wasteland at the 3 hub heights (in sq. km.): 14,110 (80 m); 18,285 (100 m); 26,000 (120 m)	
	30,755 /130,058 = 23.6%		Area under Andhra Pradesh's agricultural land at the 3 hub heights (in sq. km.): 38,250 (80 m); 57,825 (100 m); 97,850 (120 m) Andhra Pradesh's total land area (including Telangana): 275,045 sq. km. Agricultural and wasteland wind potential in Andhra Pradesh as a % of total	

			land area (at 100 m hub height): 27.7%	
MW/sq. km figure	7	9	It is a function of the turbine rotor diameter and wind speeds. Hence, it will vary from 7-10 MW/ sq.km.	9
	· Onshore potential assessment done at 80, 100 and 120 m.	1. Potential estimates based on the prioritisation of renewable energy technologies and also the integrated potential estimates considering the possibility of installing wind turbines and solar PV power plants in the same project site.	3-TIER data is validated with actual measured values.	
Any other key feature of the methodology	· CUF based categorization done using Weibull c and k parameters for cumulative distribution and turbine power curve.	2. Potential estimate for both crop land as well as not crop lands.	LULC data from KSRSAC is the most accurate and updated source for Karnataka land usage details	
	· Suzlon S-82 power curve used for CUF determination at 80 m.	3. The study also included the potential assessment for solar, biomass and tidal power apart from wind power potential and integrating the other resource availability.		
Final estimates of the wind potential	At 80 m	Final geographical potential estimated as 215 GW (non-crop land) and 850 GW (crop land)	Karnataka:	2,006 GW at 80m
	· Wasteland + non forest scrubland potential of		80m: 451,300 MW	
	47,705 MW		100 m: 716,200 MW	
	· Non irrigated farmland potential of 167,580 MW		120 m: 849,000 MW	
	· Total potential – 215,285 MW		Andhra Pradesh:	
			80m: 330,000 MW	
			100 m: 479,000 MW	
			120 m: 780,000 MW	

Caveats	1. Modelled data on wind resource at three heights 2. Derived weibull c and k values at 100 m and 120 m 3. Minimum contiguous land area criterion not employed	The data used were all secondary data and there were no ground verification of the land areas identified for actual availability.	Assessment of wind power potential in Andhra Pradesh depends on the data made available from NRSA/ARSRAC	
Challenges faced	Data retrieval from Tamil Nadu (TNEB, TWAD, PWD, etc)	1. Difficulty in collection of relevant data, and it took longer time. 2. Integration of the entire data base in GIS platform and further developing the same data in open source tool was a critical exercise.	Getting the data from different agencies at reasonable rates and in time.	Land cover data has general categories that are not sufficient to describe some areas in the country.

2. Methodological Framework

Independent assessments have been carried out by CSTEP and WinDForce Management Services Pvt. Ltd. (WFMS), based on a common methodology and assumptions as mutually agreed by the committee. The only difference between the two assessments is the wind speed data used as input. While CSTEP uses data from 3-Tier, WFMS uses a combination of data from NIWE masts, in-house mast data and National Center for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) data and process it using meso-scale modelling.

2.1. Common Methodology

- LULC data obtained from the National Remote Sensing Centre (NRSC)
- Digital elevation model used to generate slope and elevation
- Elimination criteria and buffers applied to calculate the area available for wind deployment
- Area categorised into different land types
- Wind power potential calculated based on a capacity density factor for 5D x 7D and 3D x 5D, and for two hub heights – 100 m and 120 m; here D is the rotor diameter of the turbine considered for the assessment
- CUFs calculated for corresponding speed categories using weibull characterisation for average wind speeds, assuming weibull shape parameter k = 2, for a 2 MW power curve.

2.1.1. Land Use Land Cover (LULC)

NRSC provide a harmonised land cover database spanning across India. This data set has been used to rank LULC classification. National level LULC maps of 1:250,000 scale using multi-temporal Advanced Wide Field Sensor (AWiFS) data sets is published on an annual basis. AWiFS data covering the entire country between July, 2012 and May, 2013 were used for land cover analysis. In this project, LULC data for India was downloaded from Bhuvan (NRSC). Bhuvan, ISRO's Geoportal is an initiative to facilitate users to download thematic services such as LULC, soil information etc. Information on the spatial spread and monitoring of the dynamics of LULC is the basic requisite for planning and implementing various developmental activities. NRSC has also carried out various studies on LULC mapping. This mapping is done at two scales – 1:250,000 and 1:50,000. Currently, the 1:250,000 mapping is available for download in raster data format.Table 2 summarises the LULC classification scheme and provides a brief description of classes as per NRSC. The main LULC classes are and their spatial distribution across India is represented in Figure 6 and Figure 7 respectively.

Table 2: Description of Land Use and Land Cover Classes

S. No.	Description - 1	Description - 2	Classes from NRC LULC 50K Mapping Project
1	Vector	Urban	Residential, Mixed built-up, Public / Semi Public, Communication, Public utilities / facility, Commercial, Transportation, Reclaimed land, Vegetated Area, Recreational, Industrial, Industrial / Mine dump, Ash / Cooling pond
		Rural	Rural
		Mining	Mine / Quarry, Abandoned Mine Pit, Land fill area

2	Agriculture	Crop Land	Kharif, Rabi, Zaid, Two cropped, More than two cropped
		Plantation	Plantation - Agricultural, Horticultural, Agro Horticultural
		Fallow	Current and Long Fallow
		Current Shifting Cultivation	Current Shifting Cultivation
3	Forest	Evergreen/Semi evergreen	Dense / Closed and Open category of Evergreen / Semi Evergreen
		Deciduous	Dense / Closed and Open category of Deciduous and Tree-clad Area
		Forest Plantation	Forest Plantation
		Scrub Forest	Scrub Forest, Forest Blank, Current and Abandoned Shifting Cultivation
		Swamp/Mangroves	Dense / Closed & Open Mangrove
4	Grass/ Grazing	Grass/ Grazing	Grassland: Alpine / Sub-Alpine, Temperate / Sub Tropical, Tropical / Desertic
5	Barren/ Unculturable/ Wastelands	Salt affected Land	Slight, Moderate & Strong Salt Affected Land
		Gullied/ Ravinous Land	Gullied, Shallow ravine & steep ravine area
		Scrub Land	Dense / Closed and Open category of scrub land
		Sandy Area	Desertic, Coastal, Riverine sandy area
		Barren rocky	Barren rocky
		Rann	Rann
6	Wetlands/ Water bodies	Inland Wetland	Inland Natural and Inland Manmade wetland
		Coastal Wetland	Coastal Natural and Coastal Manmade wetland
		River/stream/ canals	Perennial & Dry River/stream and line & unlined canal/drain
		Water bodies	Perennial, Dry, Kharif, Rabi and Zaid extent of lake/pond and reservoir and tanks
7	Snow and Glacier		Seasonal and Permanent snow

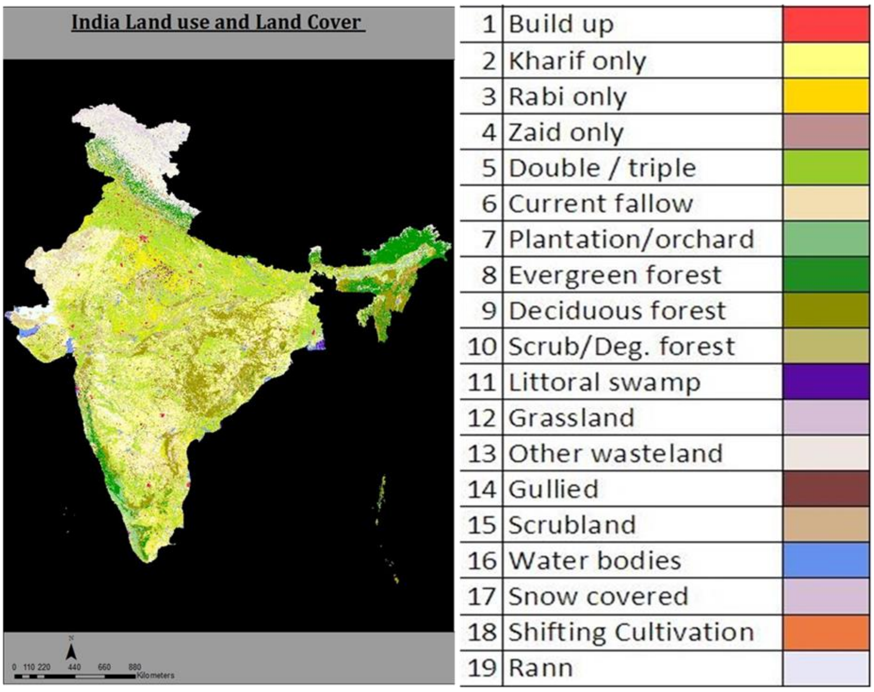


Figure 6: Map of Spatial Distribution of Various Land Cover Categories

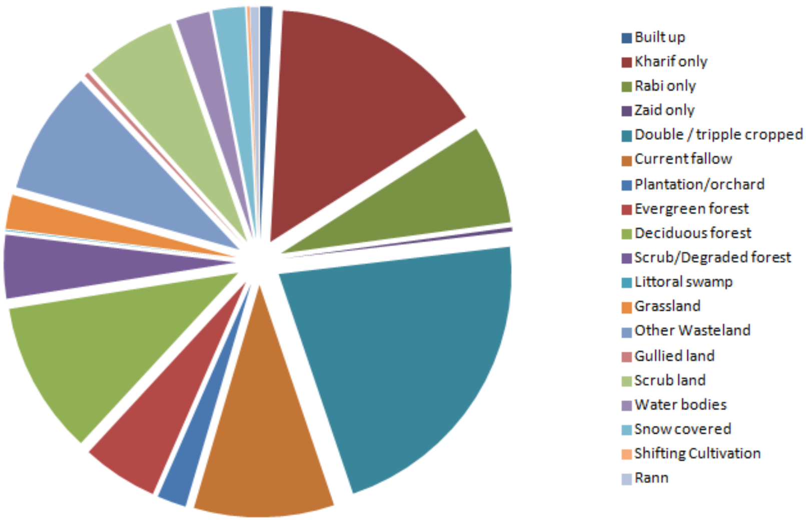


Figure 7: Spatial Distribution of Various Land Cover Categories (2012-'13)

2.1.2. Layers used for Modeling

2.1.2.1. Digital Elevation Model (DEM)

High quality DEM data from the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) instrument of the Terra satellite is freely available for 99% of the globe. ASTER provides high-resolution images of Earth in 14 different bands of the electromagnetic spectrum, ranging from visible to thermal infrared light. The resolution of images ranges between 15 and 90 m. The ASTER data are used to create detailed maps of surface temperature of land, emissivity, reflectance, and elevation.

DEM data from United States Geological Survey (USGS) Earth Explorer, at 30m resolution has been used (CGIAR-CSI, 2008).

2.1.2.2. All India Roads Network

The Road network shape file consists of all India primary and secondary roads, which was downloaded from DIVA-GIS[3]. After applying a buffer of 500m on both sides of the road network, the resultant shape file was used for eliminating areas from LULC which are not suitable for the development of a wind power plant. DIVA-GIS is a free GIS software for map making and geographic data analysis.

2.1.2.3. All India Railway Network

The Railway network shape file consists of all operational, under construction and unexamined/un-surveyed railway lines in India which were downloaded from DIVA-GIS (DIVA-GIS). After applying a buffer of 500m on both sides of the Railway network, the shape file was used to eliminate those areas from LULC which are not suitable for the development of wind power plants.

2.1.2.4. Protected Areas

The protected area shape file consists of all protected areas such as National Parks, sanctuaries, forest reserves, Biosphere Reserves, Birds Reserves, world heritage sites, marine national parks, etc. The shape file was used to eliminate these areas from LULC after applying a buffer of 500 m. The data was downloaded from the online interface for the World Database on Protected Areas (WDPA), a joint project of International Union for Conservation of Nature (IUCN) and United Nations Environment Programme (UNEP), and a comprehensive global database on terrestrial and marine protected areas (IUCN-UNEP).

2.1.2.5. Water Bodies

Water bodies are the one of the classes in the Bhuvan LULC 19 categories. Therefore, the water bodies shape file was extracted from the Bhuvan database (NRSC). The water bodies shape file consists of all types of water bodies in India such as lakes, canals, tanks, rivers, streams, ponds, etc.

2.1.2.6. Urban Agglomerations

The urban agglomeration shape file was developed by WFMS, consisting of the all major urban agglomerations with a population of more than 0.01million in India. They have further been divided into 6 different classes according to the size of the population, based on which the buffer size has also been varied.

The 6 classes of agglomerations and their respective buffer areas are listed in Table 3 below:

[3] http://www.diva-gis.org/gda

Table 3: Urban Agglomerations and Buffers

Population of the Urban Settlement (in Millions)	Buffer Applied (in kms)
0.01 – 0.05	2
0.05 – 0.1	5
0.1 – 1	10
1-5	25
5-10	25
Greater than 10	50

2.1.2.7. Elimination of Areas having Slope Gradient of More than 45 Degrees

Using the select by attribute tool from the attribute table of the land-use shape files, areas having more than a 45 degree slope were selected and deleted as they are unsuitable for the development of wind farms.

2.1.2.8. Built-up Areas

Area extracted from the Bhuvan database (NRSC)

2.1.2.9. Airports

The airport shape file consists of all the domestic and international airports in India, which was downloaded from ShareGeo Open, a spatial data repository that promotes data sharing between creators and users of spatial data (EDINA). This shape file was then used for eliminating area from LULC after applying a buffer of 10,000 m.

The buffers used for eliminating area from the LULC are listed in Table 4 below:

Table 4: Buffers for Eliminating Areas from LULC

Land Type/Category	Buffer Applied (in metres)
Built-up areas	1,000
Water bodies	500
Road network	500
Protected areas	500
Airports	1,000
Railways	1,000
Cyclonic buffers incorporated at entry points of main cyclones in India	25

Figure 8 below shows the buffer layers considered for elimination from the estimation of the technical potential.

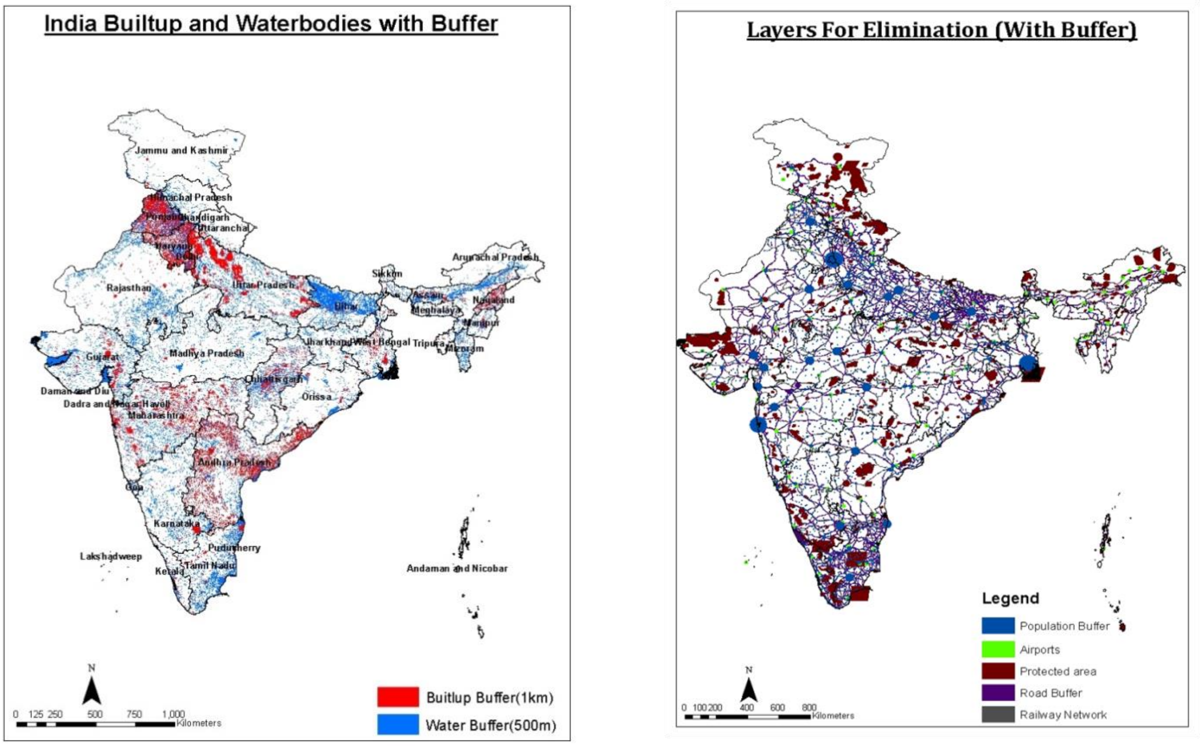


Figure 8: Buffer Analysis

2.1.3. Assumptions

The LULC of Bhuvan has 19 land categories, which is further sub-divided into 3 land categories each (wasteland, agriculture and forest) according to the most suitable to least suitable. As mentioned earlier, some land classes were eliminated because they are not suitable for wind power plants like built-up areas, water bodies, littoral swamps and gullied and snow cover areas. LULC categories were ranked according to the suitability of the land type (see Table 5) for the deployment of wind projects. Rank 1 signifies the most suitable type of land while Rank 3 is the least suitable as there it is less feasible to realise wind potential in forest areas due to ecological concerns. Apart from the three major land types mentioned above, those land types which are not suitable at all have been eliminated. These include built-up, littoral swamp, gullied and snow-covered areas, and water bodies.

Table 5: Rank-wise LULC Classes

Major Land Type	LULC Class	Rank
Waste land	*Currently Fallow*	**1**
	Grass Land	
	Other Wasteland	
	Scrubland	
	Rann Area	
Agricultural land	*Kharif*	**2**
	Rabi only	
	Zaid Only	
	Double/Triple	
	Scrub/Degraded Forest	
	Shifting Cultivation	
Forest land	*Plantation/Orchard*	**3**
	Evergreen Forest	
	Deciduous Forest	
Unsuitable land	*Built-up*	**Masked, not suitable**
	Littoral Swamp	
	Gullied	
	Water Bodies	
	Snow covered	

- The MW potential for a unit area of suitable land was calculated based on the following criteria:
    - A potential of 5.7 MW/sq. km has been calculated considering 5D x 7D turbine spacing configuration for the entire country
    - Similarly, a potential of 13.3 MW/sq. km has been calculated considering 3D x 5D turbine spacing configuration for the entire country
- A cut-off at 20% Capacity Utilisation Factor (CUF) has been considered to assess the final wind power potential
- The Weibull shape parameter (k) has been assumed to be of the order of 2
- The average representative power curve for a 2 MW Wind Turbine Generator (WTG) has been developed based on the following criteria:
    - The power curves of typical wind turbine models (see Figure 9) were analysed in terms of the percentage of rated power over a wind speed range of 0 – 25 m/s. Different WTGs which were considered are shown in Figure 7. K82 WTG was removed while calculating the final power curve since its power curve was not in accordance with the power curves of other WTGs which were considered.

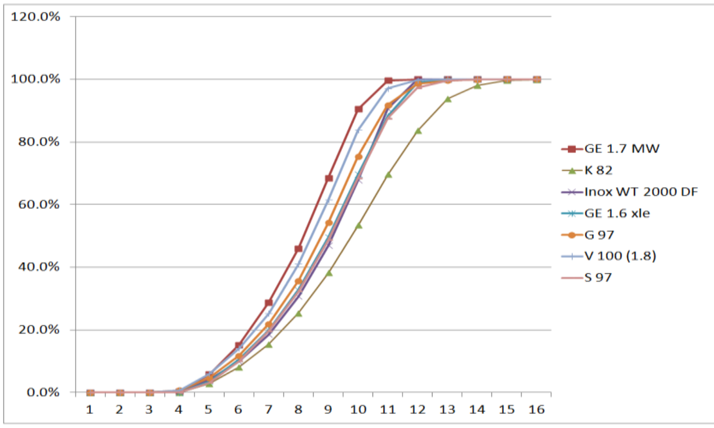


Figure 9: Comparative Analysis of Different Power Curves for Different WTGs

- The power curves of the different WTGs were found to exhibit similarity and therefore an average representative curve (see Figure 10) was arrived at and converted into a 2 MW rated power curve for 100 m hub height and 100 m rotor diameter

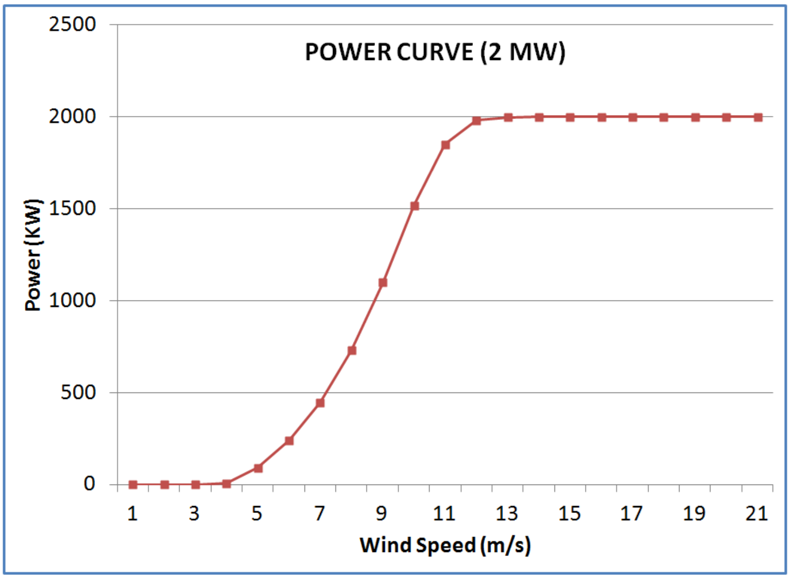


Figure 10: Power Curve for 2 MW WTG

2.2. CSTEP's Input Data

CSTEP's wind speed data set is sourced from the company 3-TIER. The scientifically derived data layers have been integrated directly into a GIS-mapping software for in-depth analysis, including site prospecting, sorting, and selection, by first converting it from a raster into a vector format (as shown in Figure 11).

Third-party layers, such as elevation, land-use, topography, transportation, and transmission infrastructure have also been used, to factor in many of the variables that affect the viability of a site. This helps to identify promising locations more quickly, and understand potential flaws in a proposed site, early in the prospecting process.

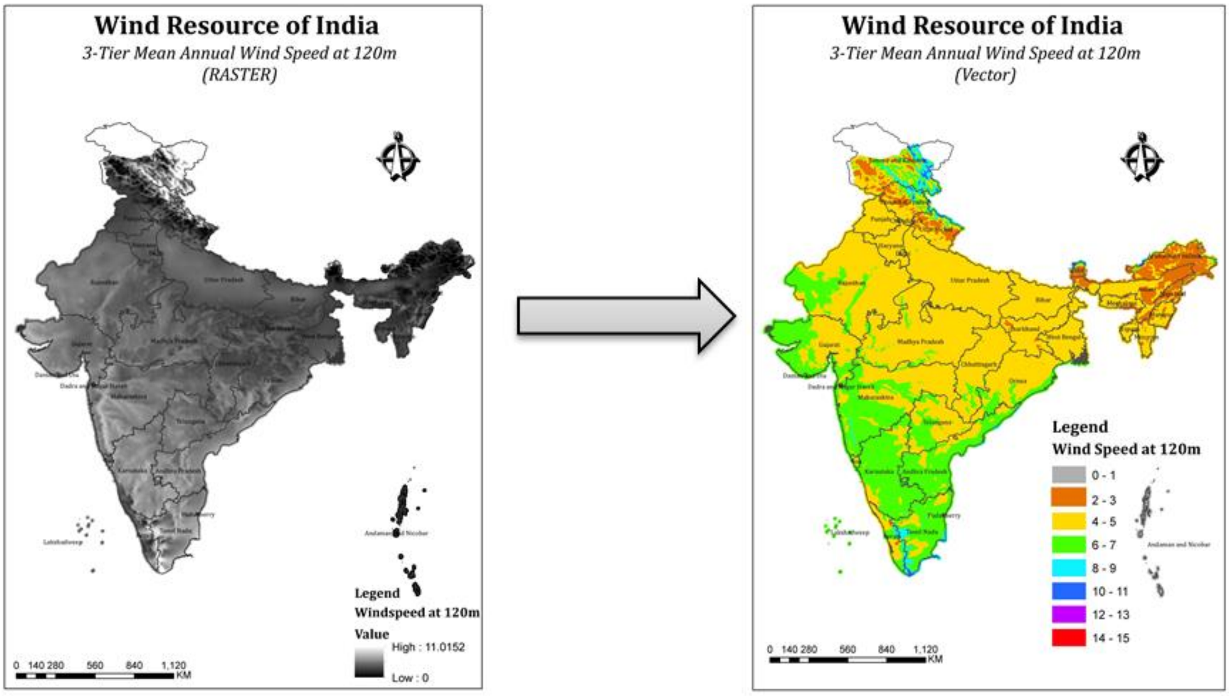


Figure 11: Raster to Vector Conversion

An all India DEM, from USGS Earth explorer, was used to calculate the elevation and slope of the area of the various land types that were considered for the analysis. Converting the DEM raster into vector provided the elevation in metres and the slope has been calculated using a slope tool surface analysis, available in the spatial analyst extension (see Figure 12).

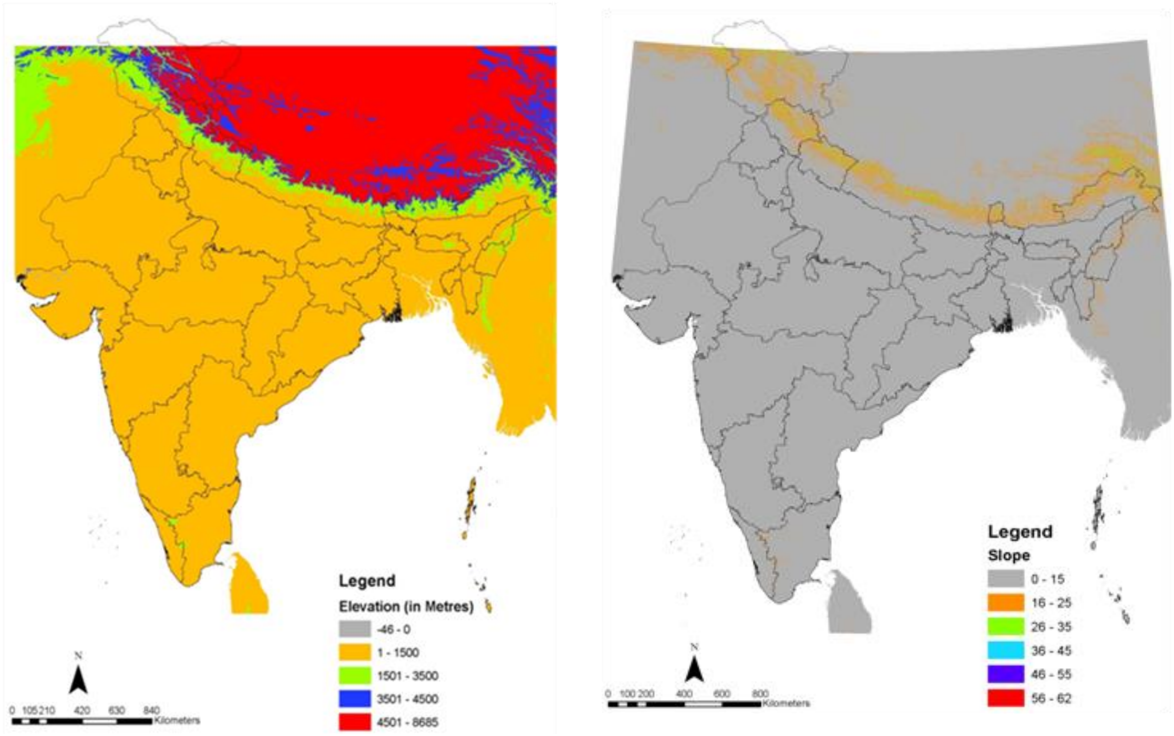


Figure 12: Elevation and Slope Map of India

2.3. WFMS's Input Data and Uncertainty Assessment

An initial meso-scale modelling for wind resource mapping was carried out for the study (see Figure 13) in a GIS environment using wind mast data, and NCEP/NCAR's re-analysis. WFMS used a proven meso-scale modelling technique which has been combined with global long-term wind speed data sets. The model creates a hypothetical boundary layer field of wind speed across the Region of Interest (RoI) using NCEP/NCAR's processed re-analysed data. Other inputs in the model include measured wind speed data, high resolution LULC and a DEM. These data inputs have been used in the model to derive wind speed map at a specified height at a resolution of 5 sq. km.

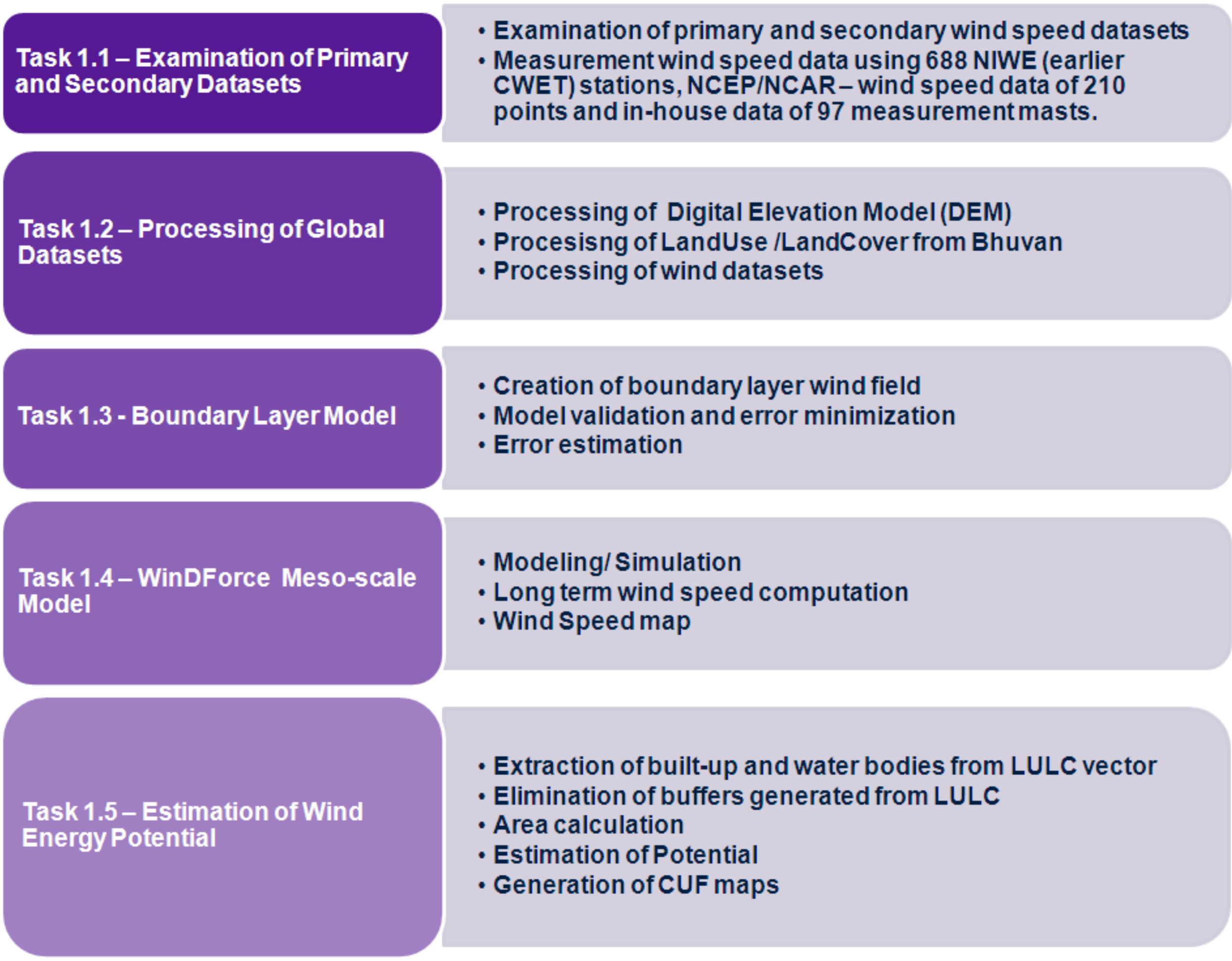


Figure 13: Methodological Framework

2.3.1. Examination of Primary and Secondary Data Sets

Measured wind speed data is an extremely important aspect of any wind resource assessment exercise. The measured data was used in the modelling exercise in two parts. In the first part, the complete data of 98 masts was used in the creation of a boundary layer. In the second part it was used for revalidating the model and computing the error in estimation (of the order of ~+-10%). For this task, the measured wind speed of the 688 NIWE masts was taken from NIWE. The measured data was critically examined for erroneous or unrealistic records, which have been excluded. The specific aspects that were examined included:

- Data check - Continuity/ absurd values/ periods of sensor malfunction
- Data recording period

2.3.1.1. Other Input Data

WFMS also collected information on RoI from the viewpoint of suitability of wind power projects such as environmental, forests, parks and reserves, industrial and urban expansion plans, aviation, seismicity, water bodies, railway tracks and roadways. Some of the areas which are not suitable for wind farms have been masked out in the analysis and other areas were ranked in the order of suitability. Normally, for wind farm development, barren and flat areas are considered most suitable, agricultural areas and sparse shrubs and grass lands are relatively less suitable while protected areas such as national parks, wildlife sanctuaries, bird sanctuaries, and urban areas are considered not suitable at all. Each grid element over RoI was then categorised from the view point of its suitability for wind farm development.

2.3.2. Processing of Global Data Sets

The data set procured for RoI has been evaluated in terms of data gaps, anomalies and discrepancies. The long-term NCEP/NCAR re-analysis, NIWE's wind speed data sets of the masts falling in RoI, Land Use/Land Cover, Digital elevation model, etc. were used as an input in the Boundary Layer Model of WFMS's meso-scale model. NIWE's measured wind data is available over periods of 2-3 years, over the last 30 years or so. The measured data used in the modelling exercise lies in a time window of 2-3 years, and it is assumed that the mean values of this data approaches the long-term average at that location.

2.3.2.1. Other Data Sources

The modelling exercise requires other data sets such as contour and terrain data (from DEM), along with the measured wind speeds in RoI etc. which are available as open data:

- NCEP/ NCAR re-analysis data provides wind speed gridded data at 2.5 deg latitude and 2.5 deg longitude, at different pressure levels. This data, in its processed form derived for RoI, has been used in the modelling exercise.

- NIWE has a total of 790 wind masts installed on the land and at varying heights of 20 m, 25 m, 50 m and 100 m. The data is periodically published by MNRE. Over the years, NIWE has continued to provide updated processed information on wind speeds in India. Although this data set is country-wide, it is not uniformly spread. In the final assessment, data from a total of 688 NIWE stations has been considered.

- WFMS has a strong database of wind speeds for around 100 locations in the country. These are measurements of wind speeds in different periods over the last ten years, at different heights varying from 50-100 m. These masts are widely spread across the country. This data has also been used to validate the wind speeds assessed using WFMS's meso-scale model.

2.3.3. Boundary Layer Model

In this task, as mentioned previously, a hypothetical field of wind speeds at a boundary layer termed as Boundary Layer Wind (BLW) has been created for the RoI using the following data sets:

(1) Processed NCEP/NCAR Reanalysis;

(2) NIWE measured data;

(3) WFMS internal database; and

(4) Land Use Land Cover (LULC) and Digital elevation model.

It is assumed that BLW is free of disturbances from local terrain, vegetation and settlements and buildings. In the past, this model has been validated over a large number of wind measurement points in India and also at a broad level for countries like Kenya, and Malaysia. The model results when compared with actual results, at national levels such as in Kenya and India showed a Mean Absolute Error in Estimation (MAE) lower than 10%.

Boundary Layer Model has been validated by WFMS at a country-level for India and Kenya, to yield an error of the order of 10%. For this study, WFMS has arrived at a Mean Absolute Percentage Error (MAPE) of 7.6 % (Figure 14).

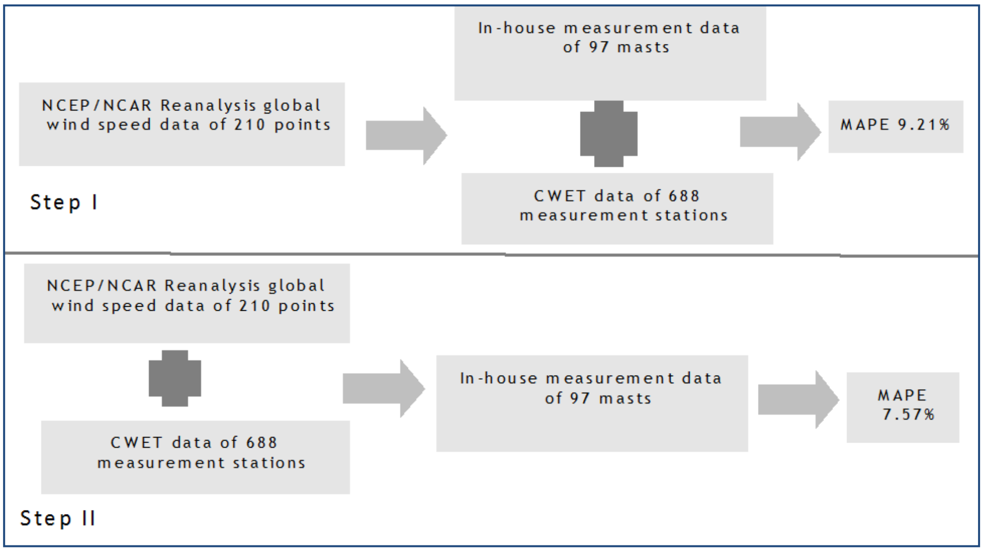


Figure 14: Boundary Layer Model and final MAPE

2.3.4. WFMS Meso-scale Model

In this task, BLW is mapped on to every cell in the RoI grid to arrive at the mean wind speeds at specified heights (100 m and 120 m) in each cell. WFMS takes into account information on areas marked out for urban expansion and densely populated regions in the RoI so that these areas are appropriately treated (masked out) in the maps. The areas identified as not suitable for wind farms are also masked out in the analysis and an exercise of 'ground truthing' is carried out through site visits. At this stage, mean annual wind speed maps at 100 m and 120 m above ground level (m.a.g.l.) are estimated.

2.3.5. Estimation of Wind Energy Potential

In this task, the wind speeds assessed for each grid element through meso-scale model was used as input in estimation of energy yield so as to assess the annual yield from a particular model for each grid element. It takes into account mean annual wind speed and specified weibull parameters. A particular model of WTG for power curve was chosen, which is representative of the technologies available in the market.

2.3.5.1. Uncertainty Analysis

This report makes an assessment of the realisable potential for wind farms in India with the predominant technology types. An important aspect of this exercise is the information on LULC i.e. how much land under what category could be considered for setting up wind farms. To make this assessment we have followed a principle of high conservatism. While there are some aspects of land that can be captured in our modelling approach on GIS platform such as the buffers around networks[4], in a macro exercise such as this, one cannot be absolutely precise and there can be uncertainties and errors that creep in either because of our assumptions or because of inherent variations emerging from data capture, instrumentation, and assimilation of satellite data. We are aware of some of these uncertainties and can account for them, but there may be uncertain uncertainties that we are not aware of. An uncertainty can either lead to under estimation or also over estimation, both are equally probable. However, in routine wind resource assessment, it is industry practice to examine the downside i.e., an assessment of how much of the estimated value could probably be an overestimate. Based on the uncertainty assessed, a probability analysis is carried out to come to values that are 75% likely, 90% likely etc. In the assessment of the potential in this report, we arrived at a value of about 40% uncertainty. However, there are certain factors that can be accounted for quantitatively but there may be other factors that we can possibly think of, but which may be difficult to account for. This could be related to different type of terrains, local settlements and how they relate to land, land ownerships – both, in terms of legal and social contexts, right of ways, size of land holdings etc. Therefore, in keeping with the principle of high conservatism, instead of carrying out a probability analysis, we have sliced off entire 40% from our assessments.

WFMS has assumed the following uncertainties corresponding to different parameters as stated in Table 6 below.

Table 6: Model Parameters and Uncertainties

Model Parameters and Uncertainties	(%)
Shape Parameter (k)	10
NIWE Measurement	15
Uncertainty of data measured over different timeframes	15
Modelling uncertainty on energy	25
Terrain uncertainty	20
Total Uncertainty	40

2.3.5.2. Other considerations

It is a known fact that even after assigning a given parcel of land for setting up wind farm, not all of the land can be used in setting up arrays of wind turbines. We hence need to account towards land for additional components for transmission of power such as sub stations, transmission line corridors, areas for carrying out in situ performance tests that

[4] Such as roads, railways, rivers, urban centres and settlements, fresh water bodies, reserved forests, national parks, heritage areas

require undisturbed wind flow in accordance with international standards, control rooms, warehouses, corridors for movement of heavy equipment, servicing set up etc. In the future, there may be areas needed for battery storage or other kinds of storages or to develop energy facilities that are a mix of solar and wind (hybrid). Also, it may be required for mitigation of any negative environmental and ecological externalities, safety to local people and their cattle and unrestricted movement and right of way. These factors may emanate even in case of absolutely barren lands, where marginal communities, who may not own the land, yet may be living off it. In assessment such as this, one needs to account for these aspects. We have therefore assigned an additional 20% of the land areas to such unforeseen considerations over and above the uncertainty that we have considered in the analysis.

The methodology has been implemented on the GIS platform Arc Editor 9.3, where the high wind energy zones were identified. The methodology has followed an iterative mode, where results were revisited after applying each filter criteria.

3. Results

The total area under the three types of land categories (wasteland, agricultural land, and forest) for the states considered for estimating the wind potential is shown in this section. A minimum cut-off wind speed has been applied by both WFMS and CSTEP to select areas which are suitable for estimating the technical wind potential.

As mentioned in the Methodology section, the installable MW capacity has been estimated based on the area available after applying the required elimination criteria, and a pre-determined layout for spacing a standardised turbine. This is referred to as capacity density. Capacity density represents wind power capacity that can be installed in a given parcel of land. It depends on the choice of turbine as well as the layout or configuration of the wind farm.

The study considers a representative 2 MW turbine with a 100 m rotor diameter, based on the average of a set of turbines in a similar nameplate capacity range. The spacing between the turbines is based on a 5D x 7D array configuration, where D represents the rotor diameter of the turbine under consideration. This configuration has shown to cause the least array of losses due to interference between the turbines. It results in a capacity density of 5.7 MW per sq. km. Further, a potential estimate based on a more optimal configuration of 3D x 5D layout is presented as part of the results, which represents a more optimistic estimate of the technical potential in the areas considered. The latter layout results in a capacity density of 13.3 MW per sq. km. In actual projects, the layout of the turbines may differ from the one assumed in this study, depending on what is suitable for the region-specific terrain. For instance, in regions with gradual hillocks, the turbines may be spaced on top of the hillocks and spaced as a linear string. Since the assessment of region-specific terrains is out of the scope of this analysis, we have considered the above two layouts to represent the range of possible layouts for turbines.

3.3. WFMS Results

This section summarises the results obtained from the wind speed dataset used by WFMS for the analysis. State-wise results are presented for the area under the three ranks of LULC categories i.e. waste land, agricultural land, and forest land, for two hub heights of 100 m and 120 m. A minimum cut-off speed of 5 m/s has been applied to estimate the potential.

3.3.5. Wind Potential - 100 m

Table 7 below presents the estimated wind potential (GW) in the 14 states with most potential, for 100 m hub height.

Table 7: Wind Potential at 100 m (GW)

	Area (sq.km)			5D x 7D Potential (GW)				3D x 5D Potential (GW)			
STATES	**Rank 1 (R1)**	**Rank 2 (R2)**	**Rank 3 (R3)**	**R1**	**R2**	**R3**	**Total**	**R1**	**R2**	**R3**	**Total**
Maharashtra	40,552	1,00,135	27,618	92	228	63	384	216	533	147	895
Karnataka	34,785	85,109	30,807	79	194	70	344	185	453	164	802
Madhya Pradesh	16,220	1,03,690	9,360	37	236	21	295	86	552	50	688
Gujarat	36,039	72,914	11,709	82	166	27	275	192	388	62	642
Rajasthan	51,541	41,011	11,507	118	94	26	237	274	218	61	554
Andhra Pradesh	42,174	39,565	21,561	96	90	49	236	224	210	115	550
Telangana	18,439	43,113	9,237	42	98	21	161	98	229	49	377
Tamil Nadu	13,542	34,292	14,780	31	78	34	143	72	182	79	333
Kerala	2,751	5,006	12,946	6	11	30	47	15	27	69	110
Orissa	2,615	6,865	2,399	6	16	5	27	14	37	13	63
Uttar Pradesh	170	3,008	549	0	7	1	8	1	16	3	20
Chhattisgarh	88	575	521	0	1	1	3	0	3	3	6
West Bengal	53	450	77	0	1	0	1	0	2	0	3
Haryana	75	119	15	0	0	0	0	0	1	0	1
TOTAL	**2,59,043**	**5,35,855**	**1,53,085**	**591**	**1,222**	**349**	**2,161**	**1,378**	**2,851**	**814**	**5,043**

3.3.6. Wind Speed Map of India – 100 m

Figure 15 below represents the wind speed of the Indian states considered for estimating the potential, at a 100 m hub height, without reference to land availability.

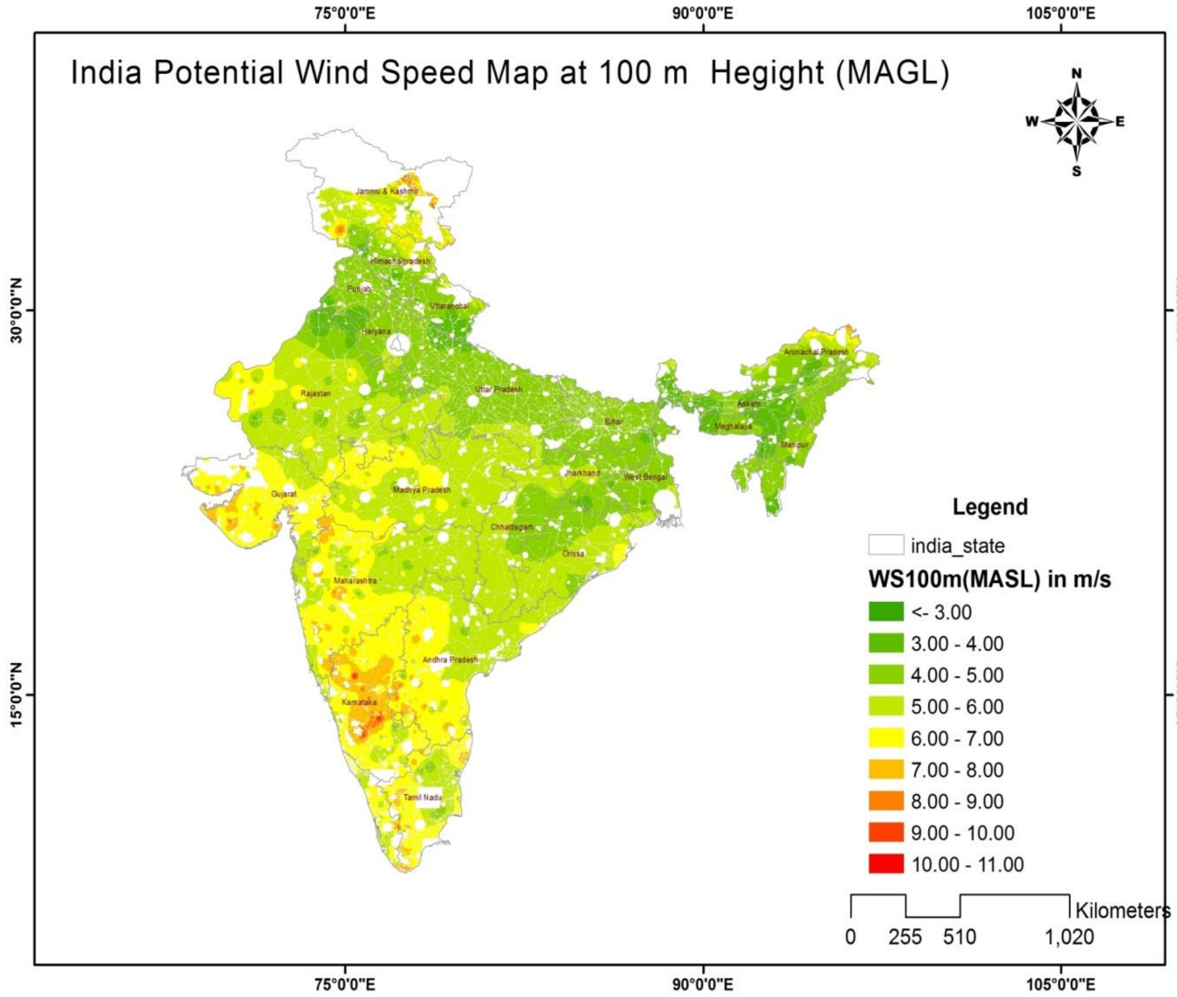


Figure 15: India Wind Speeds at 100 m Hub Height

3.3.7. CUF Map of India – 100 m

Figure 16 below represents the CUFs in the Indian states at a 100 m hub height, without reference to land availability.

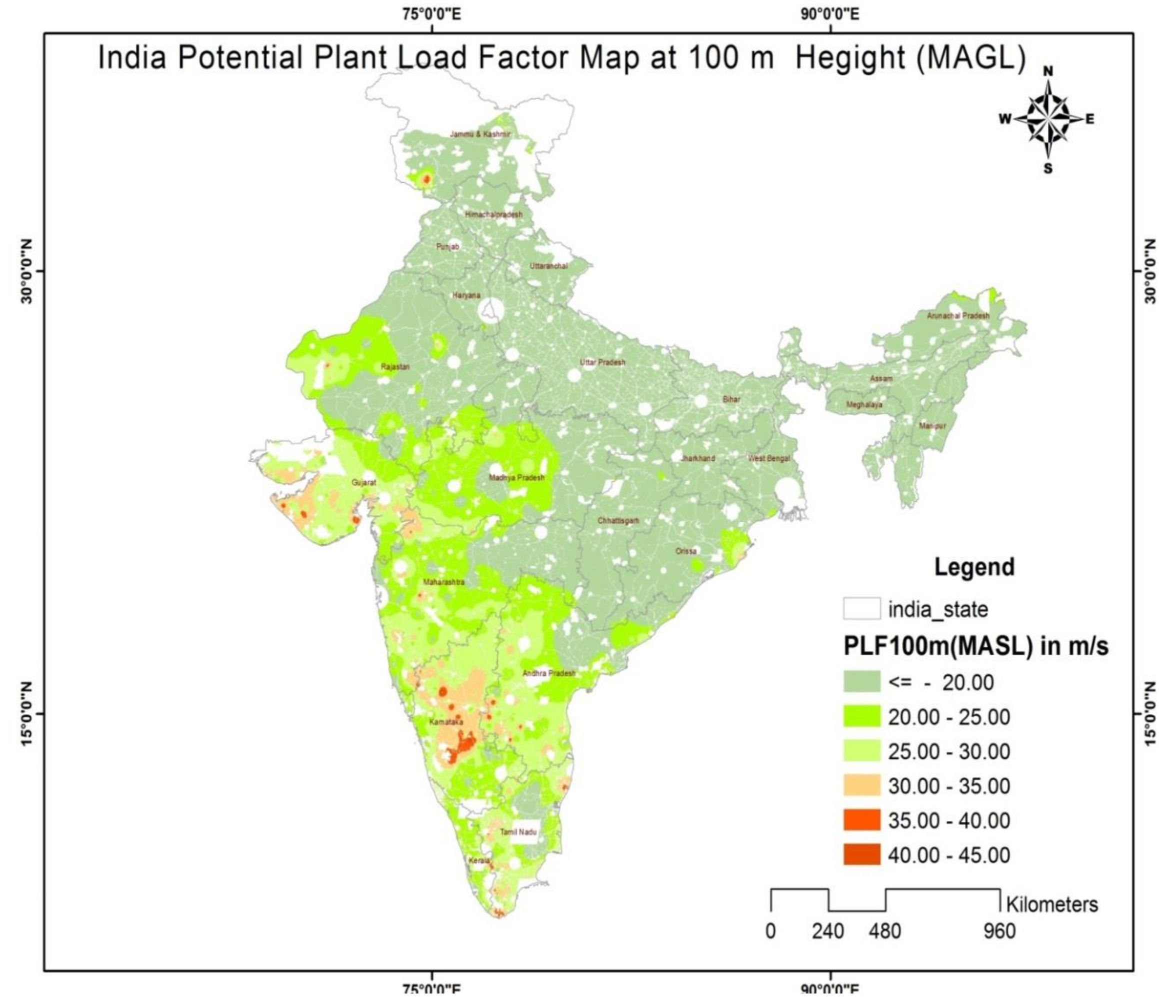


Figure 16: India Capacity Utilisation Factors (CUFs) at 100 m Hub Height

3.3.8. Wind Potential – 120 m

Table 8 below presents the estimated wind potential (GW) in the 16 states with most potential, for 120 m hub height.

Table 8: Wind Potential at 120 m (GW)

	Area (sq.km)			5D x 7D Potential (GW)				3D x 5D Potential (GW)			
STATES	**Rank 1 (R1)**	**Rank 2 (R2)**	**Rank 3 (R3)**	**R1**	**R2**	**R3**	**Total**	**R1**	**R2**	**R3**	**Total**
Maharashtra	44,515	1,14,697	36,272	101	262	83	446	237	610	193	1,040
Madhya Pradesh	21,372	1,26,208	13,748	49	288	31	368	114	671	73	858
Karnataka	36,340	88,508	31,612	83	202	72	357	193	471	168	832
Rajasthan	60,098	59,389	14,505	137	135	33	306	320	316	77	713
Gujarat	36,725	75,923	12,553	84	173	29	285	195	404	67	666
Andhra Pradesh	43,550	46,783	25,382	99	107	58	264	232	249	135	616
Telangana	19,845	48,514	14,864	45	111	34	190	106	258	79	443
Tamil Nadu	14,443	37,896	16,204	33	86	37	156	77	202	86	365
Chhattisgarh	1,524	9,312	13,821	3	21	32	56	8	50	74	131
Kerala	2,778	5,077	13,160	6	12	30	48	15	27	70	112
Orissa	4,017	10,858	5,475	9	25	12	46	21	58	29	108
Uttar Pradesh	561	4,609	843	1	11	2	14	3	25	4	32
West Bengal	87	943	135	0	2	0	3	0	5	1	6
Haryana	137	285	23	0	1	0	1	1	2	0	2
Jharkhand	59	237	95	0	1	0	1	0	1	1	2
Himachal Pradesh	149	52	0	0	0	0	0	1	0	0	1
TOTAL	**2,86,200**	**6,29,291**	**1,98,691**	**653**	**1,435**	**453**	**2,540**	**1,523**	**3,348**	**1,057**	**5,927**

3.3.9. Wind Speed Map of India – 120 m

Figure 17 below represents the wind speed of the Indian states considered for estimating the potential, at a 120 m hub height, without reference to land availability.

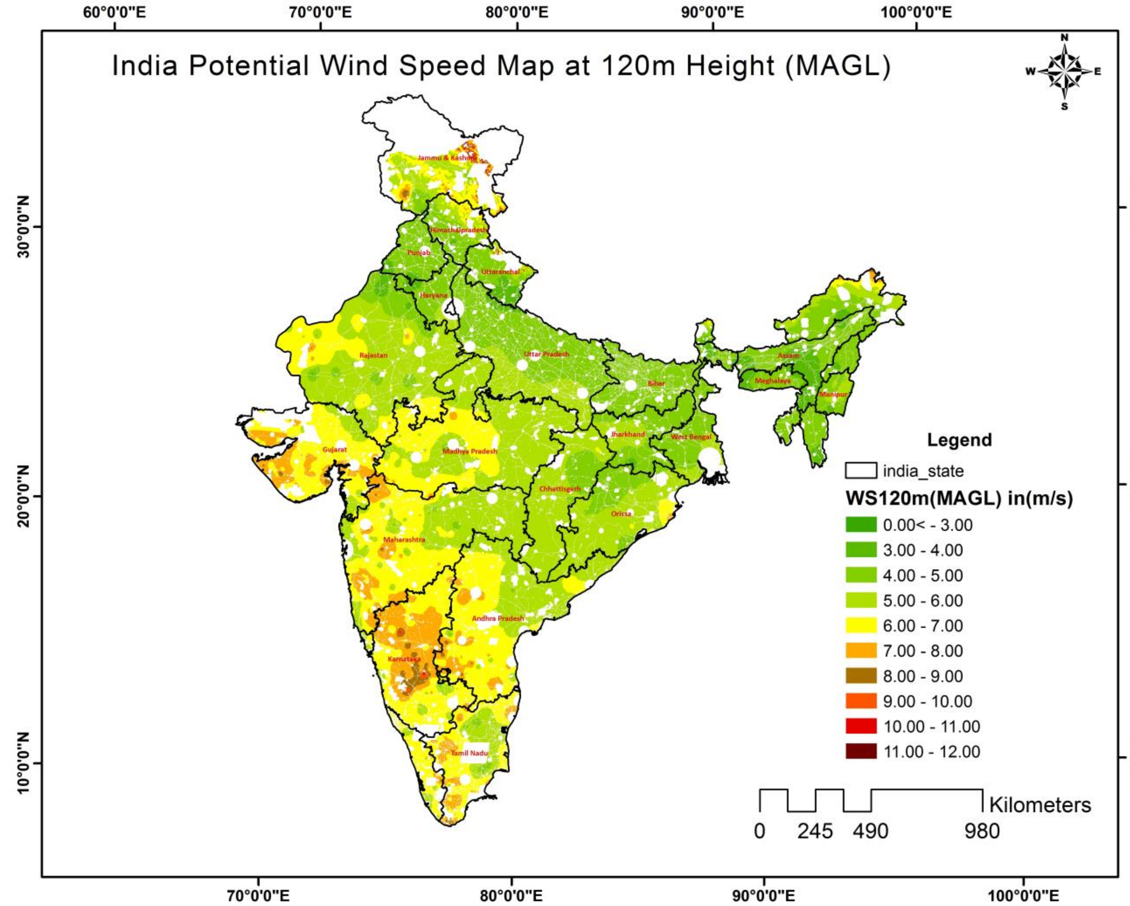


Figure 17: India Wind Speeds at 120 m Hub Height

3.3.10. CUF Map of India – 120 m

Figure 18 below represents the CUFs in the Indian states at a 120 m hub height, without reference to land availability.

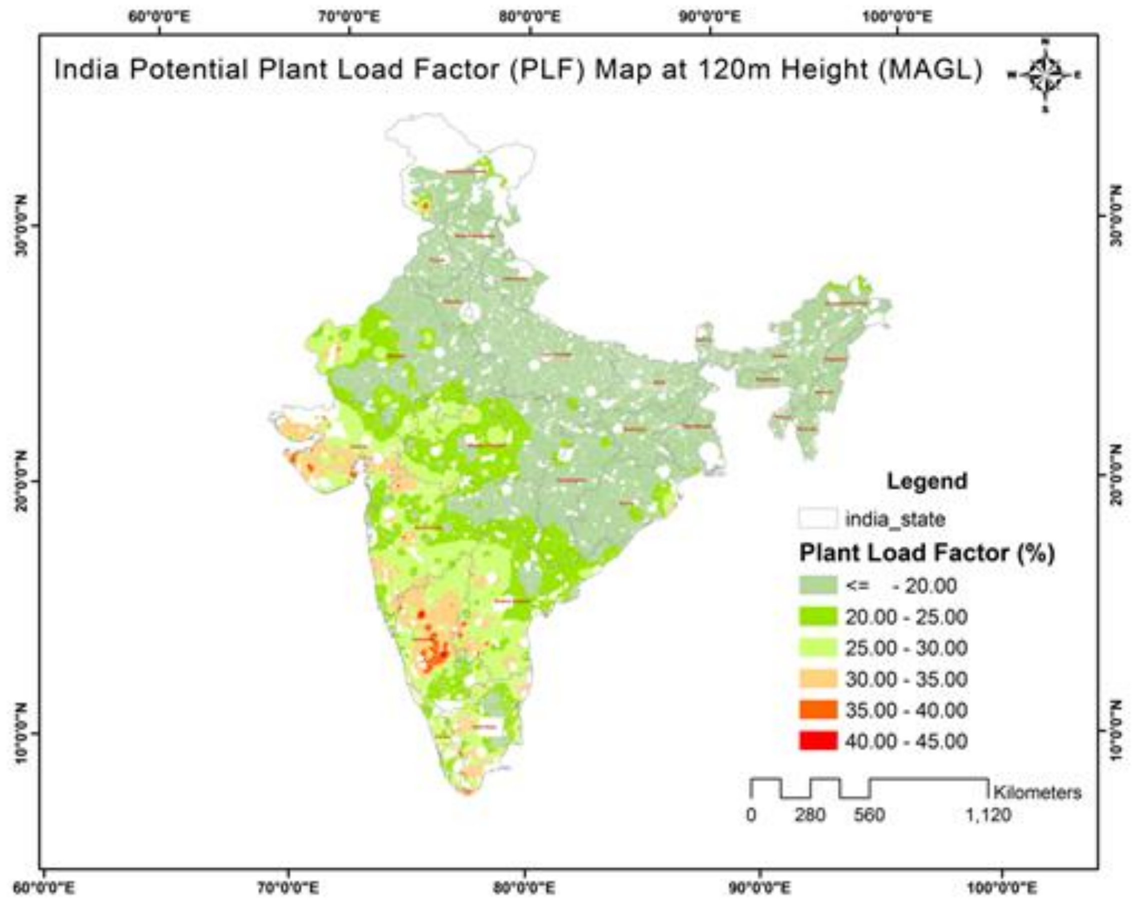


Figure 18: India Plant Load Factor or CUF at 120 m Hub Height

3.3.11. Wind Speed Maps of States – 100 m

Figure 19 below represents the wind speeds in the Indian states with maximum potential, at a 100 m hub height, without reference to land availability.

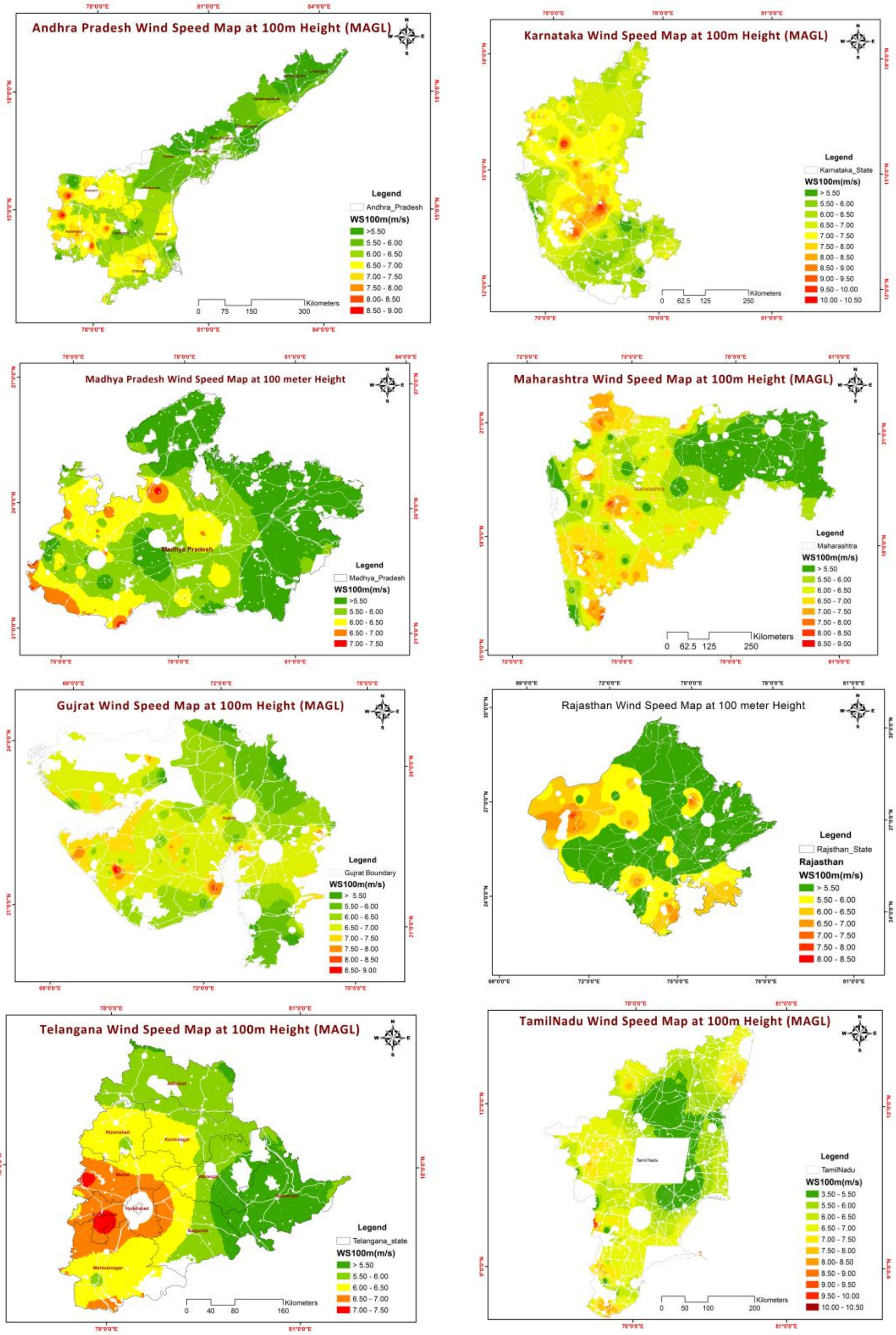


Figure 19: Wind Speeds in States with Maximum Potential - 100 m Hub Height

3.3.12. Wind Speed Maps of States – 120 m

Figure 20 below represents the wind speeds in the Indian states with maximum potential, at a 120 m hub height, without reference to land availability.

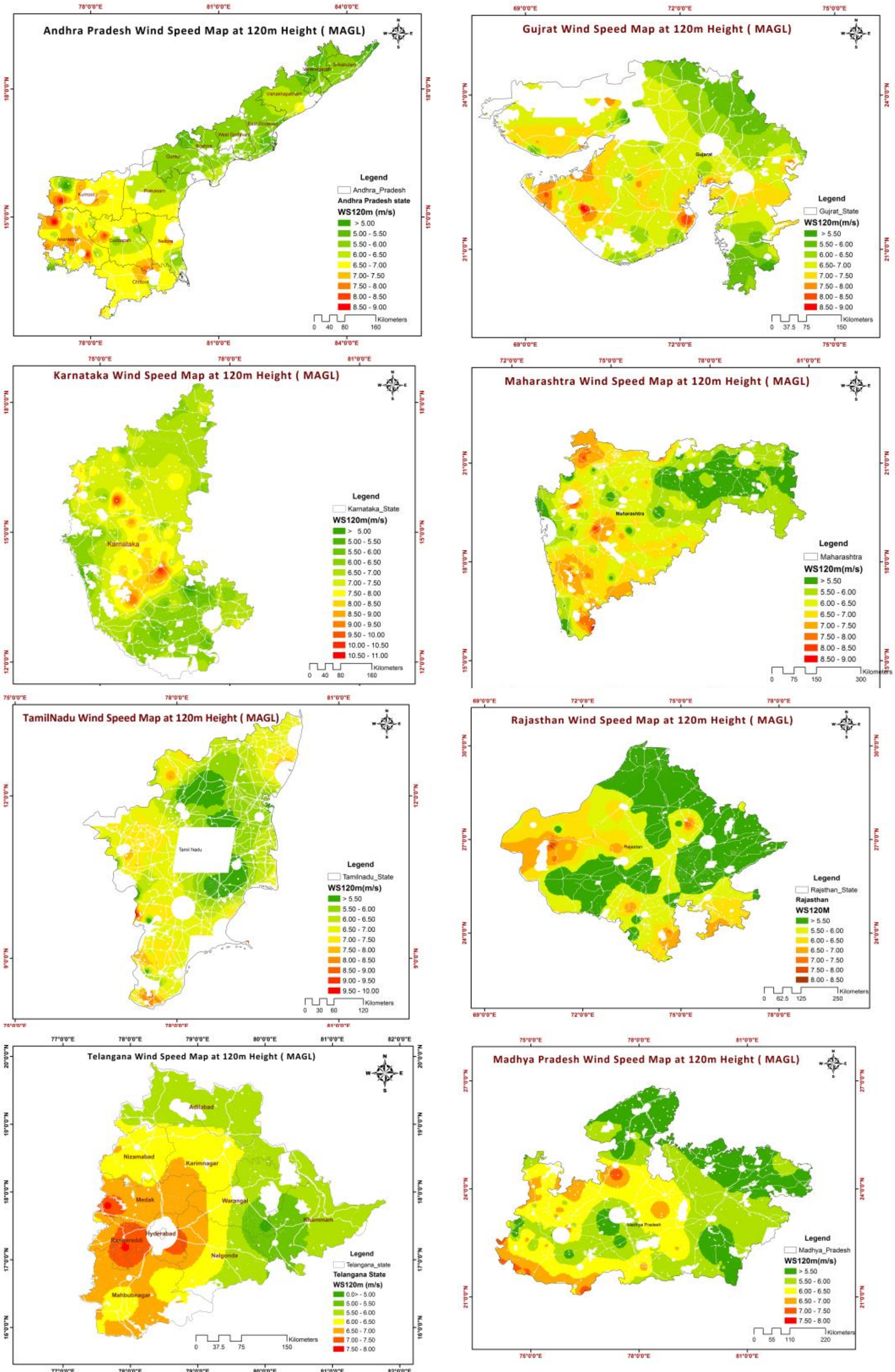


Figure 20: Wind Speeds in States with Maximum Potential - 120 m Hub Height

3.4. CSTEP Results

This section summarises the results obtained from the 3-Tier wind speed dataset used by CSTEP for the analysis. State-wise results are presented for the areas under the three ranks of LULC categories, for two hub heights of 100 m and 120 m. A minimum cut-off speed of 6 m/s has been applied to estimate the potential.

3.4.5. Wind Potential at 100 m

Based on the above capacity configurations, the estimated potential for the 14 states with most potential is as follows (Table 11) for 100 m hub height. The potential for remaining states is presented in Appendix 2.

Table 9: Wind Potential at 100 m (GW)[5]

	Area (sq.km)			Wind Energy Potential (GW) (5D x 7D)				Wind Energy Potential (GW) (3D x 5D)			
STATES	**Rank 1 (R1)**	**Rank 2 (R2)**	**Rank 3 (R3)**	**R1**	**R2**	**R3**	**Total**	**R1**	**R2**	**R3**	**Total**
Tamil Nadu	10,317	23,729	9,941	59	135	57	251	137	316	132	585
Karnataka	31,725	49,374	15,362	181	281	88	550	422	657	204	1283
Andhra Pradesh	24,053	14,685	10,152	137	84	58	279	320	195	135	650
Telangana	6,424	13,409	2,218	37	76	13	126	85	178	29	293
Maharashtra	32,253	45,131	12,378	184	257	71	512	429	600	165	1194
Gujarat	17,017	19,882	2,140	97	113	12	223	226	264	28	519
Rajasthan	41,641	25,197	2,256	237	144	13	394	554	335	30	919
Arunachal Pradesh	7	1	0	0	0	0	0	0	0	0	0
Chhattisgarh	598	3,464	3,089	3	20	18	41	8	46	41	95
Kerala	456	2,662	7,036	3	15	40	58	6	35	94	135
Madhya Pradesh	4,335	18,785	653	25	107	4	136	58	250	9	316
Orissa	6,012	7,023	13,923	34	40	79	154	80	93	185	359
Uttar Pradesh	0	287	1	0	2	0	2	0	4	0	4
West Bengal	3	71	26	0	0	0	1	0	1	0	1
TOTAL	**1,74,834**	**2,23,699**	**79,175**	**997**	**1,274**	**453**	**2,727**	**2,325**	**2,974**	**1,052**	**6,353**

3.4.6. Wind Speed Maps, by Land Type - 100 m

Figure 21 below shows the All India wind speeds over the various land categories, at a 100 m hub height.

[5] Values are rounded up for ease of readability

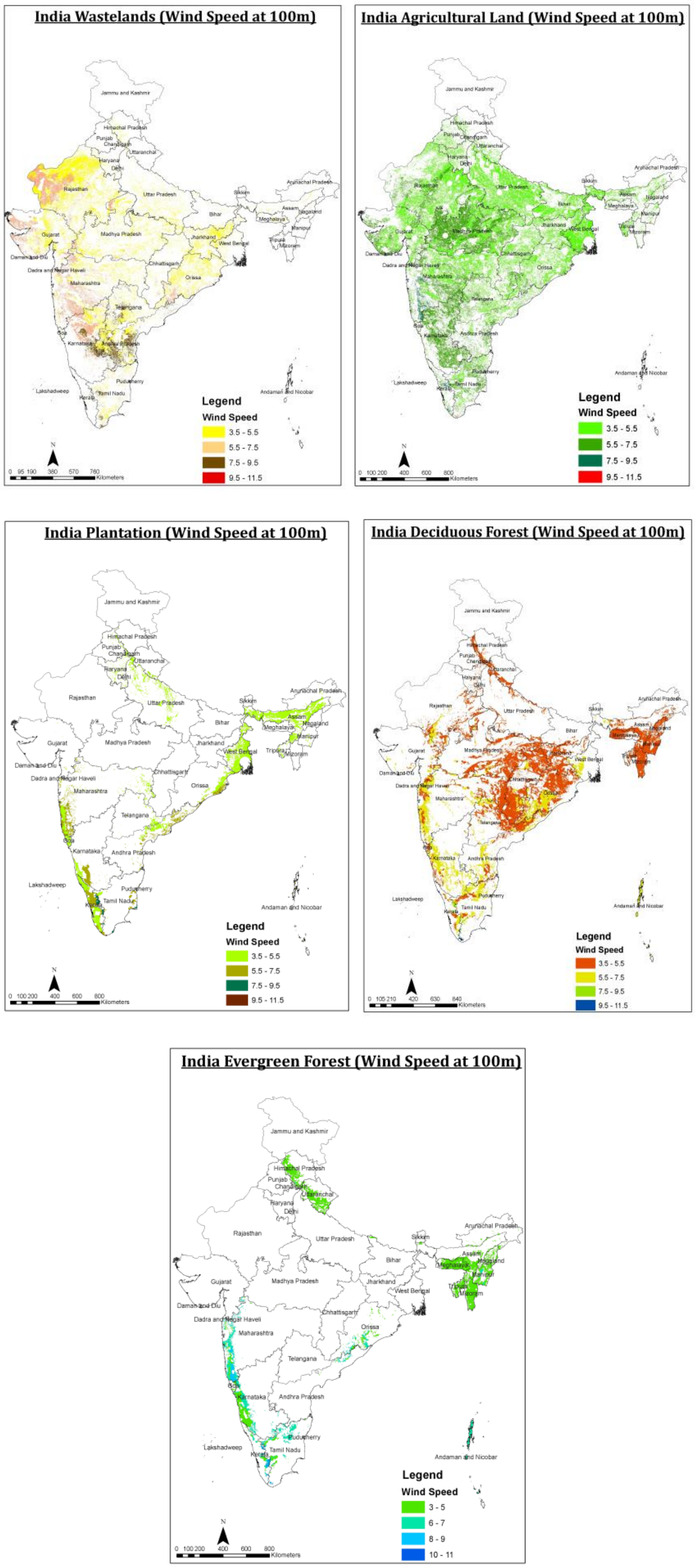


Figure 21: All India Wind Speeds by Land Type, at 100 m Hub Height

3.4.7. All India CUF Map - 100 m

Figure 22 below shows the range All India CUFs at a 100 m hub height, without any reference to land availability.

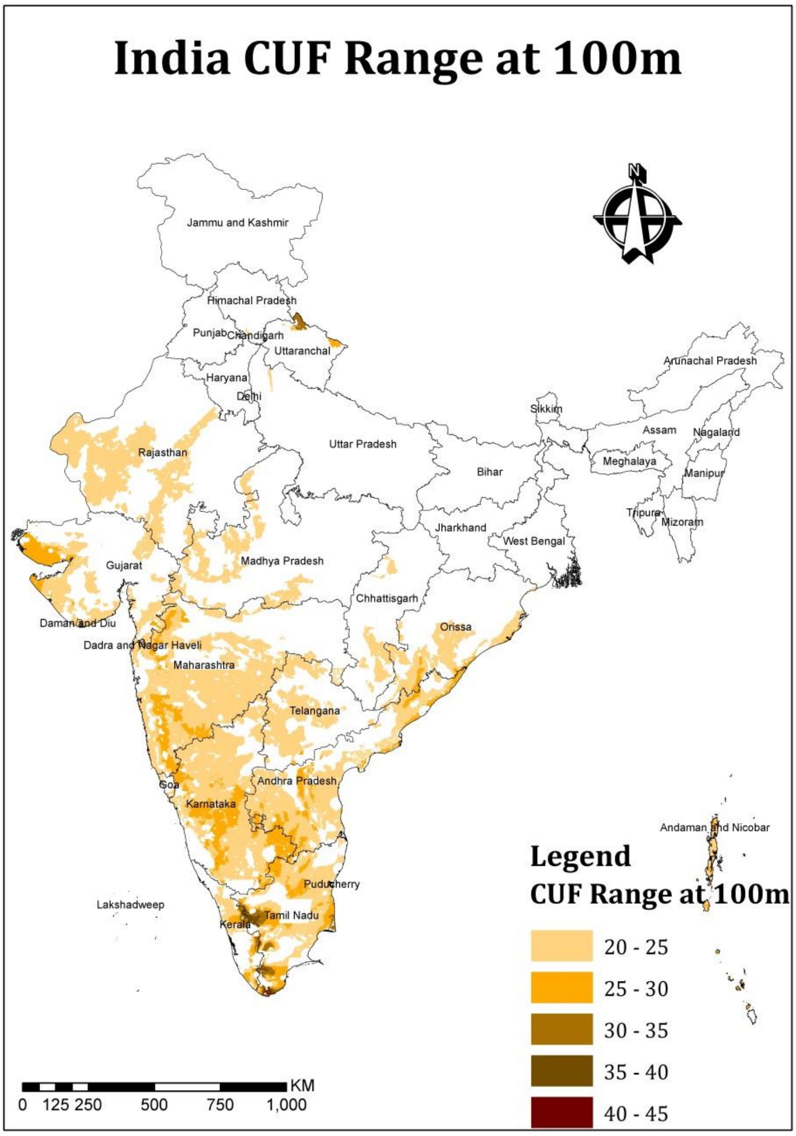


Figure 22: All India Wind CUFs, at 100 m Hub Height

3.4.8. Wind Potential at 120 m

Table 10 below presents the estimated wind potential (GW) for 16 states with the most potential at 120 m hub height. The potential for remaining states is presented in Appendix 3.

Table 10: Wind Potential at 120 m (GW)[6]

	Area (sq.km)			Wind Energy Potential (GW) (5D x 7D)				Wind Energy Potential (GW) (3D x 5D)			
STATES	**Rank 1 (R1)**	**Rank 2 (R2)**	**Rank 3 (R3)**	**R1**	**R2**	**R3**	**Total**	**R1**	**R2**	**R3**	**Total**
Tamil Nadu	10,915	24,395	10,762	62	139	61	263	145	324	143	613
Karnataka	36,830	56,847	11,582	210	324	66	600	490	756	154	1400
Andhra Pradesh	33,681	15,949	9,183	192	91	52	335	448	212	122	782
Telangana	7,864	7,390	2,935	45	42	17	104	105	98	39	242
Maharashtra	33,086	45,550	12,235	189	260	70	518	440	606	163	1209
Gujarat	18,974	23,410	1,969	108	133	11	253	252	311	26	590
Rajasthan	46,820	32,459	2,939	267	185	17	469	623	432	39	1093
Arunachal Pradesh	7	1	0	0	0	0	0	0	0	0	0
Assam	0	0	30	0	0	0	0	0	0	0	0
Chhattisgarh	819	4,516	3,278	5	26	19	49	11	60	44	115
Himachal Pradesh	5	32	10	0	0	0	0	0	0	0	1
Kerala	462	2,716	7,143	3	15	41	59	6	36	95	137
Madhya Pradesh	5,224	25,134	1,553	30	143	9	182	69	334	21	424
Orissa	6,731	7,599	5,606	38	43	32	114	90	101	75	265
Uttar Pradesh	0	693	6	0	4	0	4	0	9	0	9
West Bengal	3	78	30	0	0	0	1	0	1	0	1
TOTAL	**2,01,412**	**2,46,767**	**69,262**	**1,149**	**1,405**	**395**	**2,951**	**2,679**	**3,280**	**921**	**6,881**

[6] Values are rounded up for ease of readability

3.4.9. Wind Speed Maps, by Land Type - 120 m

Figure 23 below shows the All India wind speeds over the various land categories, at a 120 m hub height.

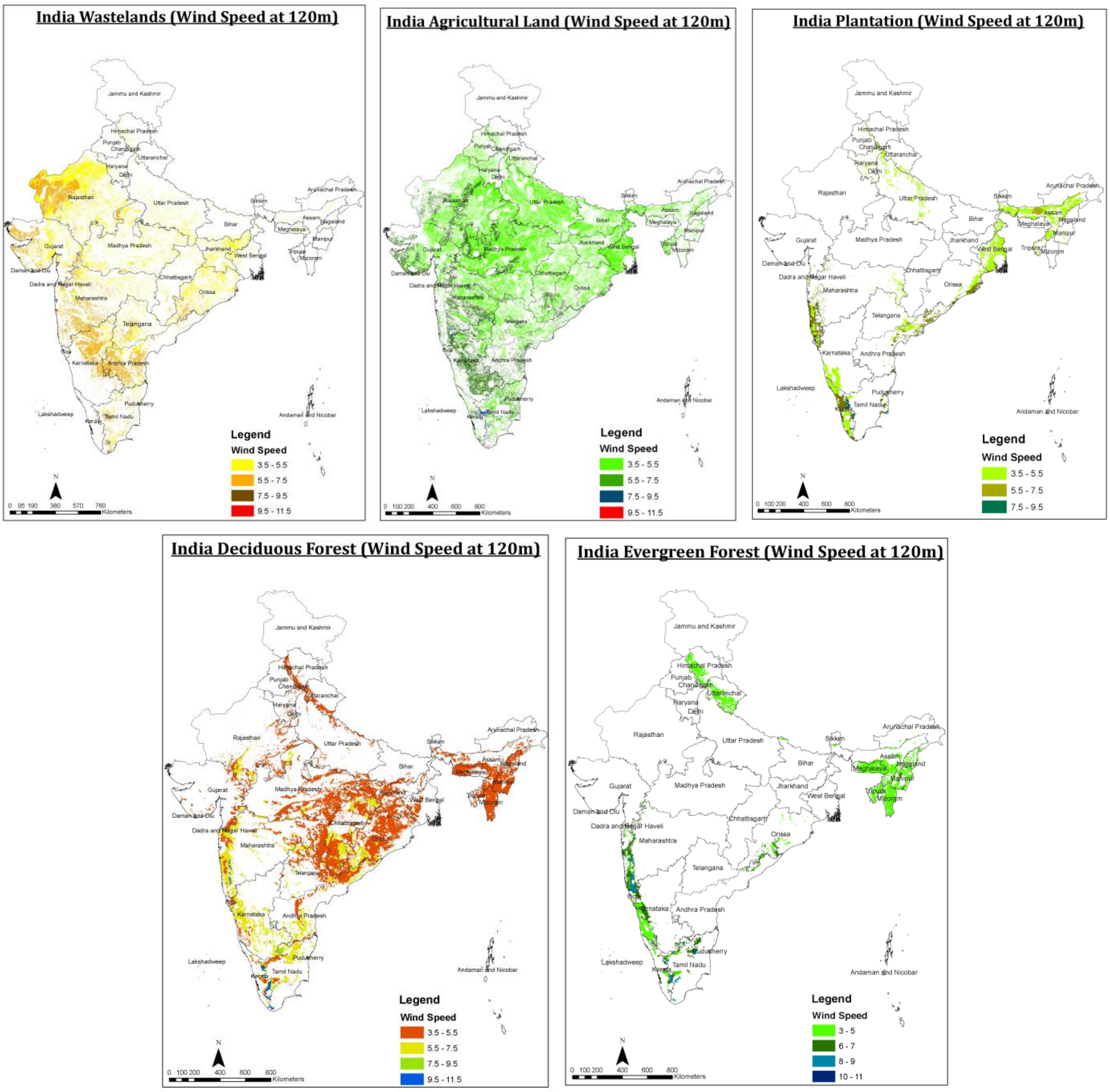


Figure 23: All India Wind Speeds by Land Type, at 120 m Hub Height

3.4.10. All India CUF Map - 120 m

Figure 24 below shows the range All India CUFs at a 120 m hub height, without any reference to land availability.

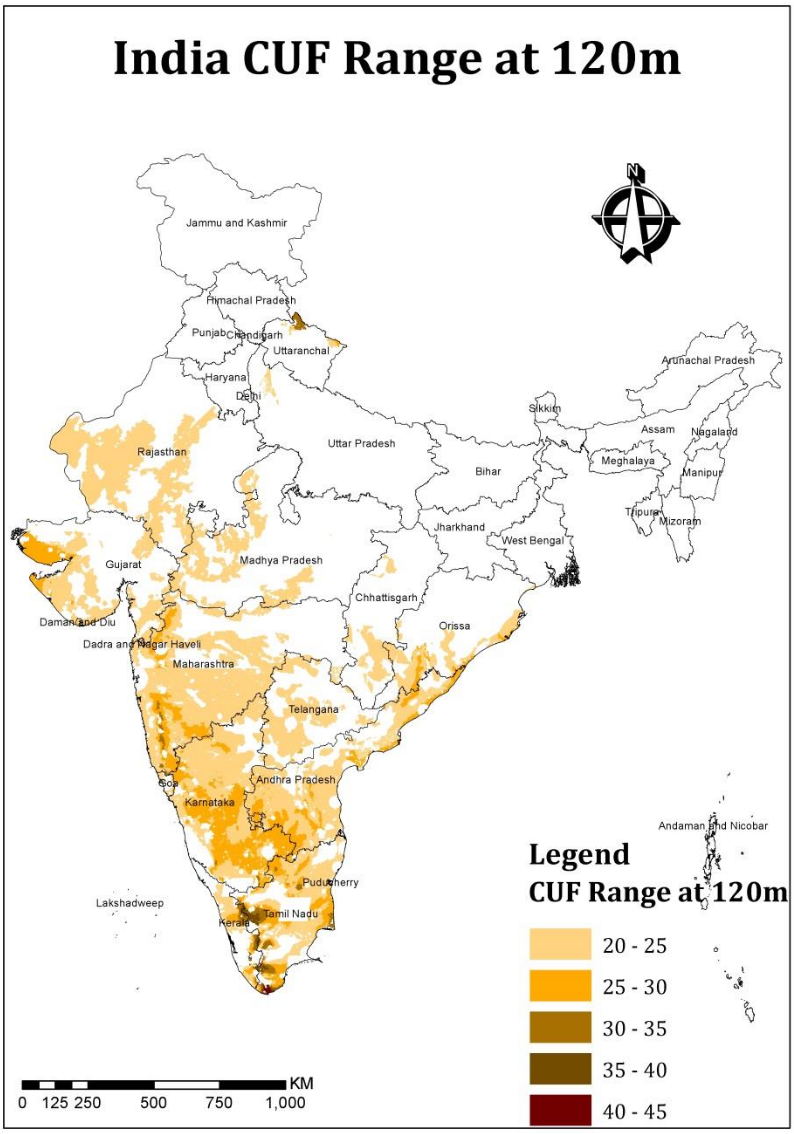
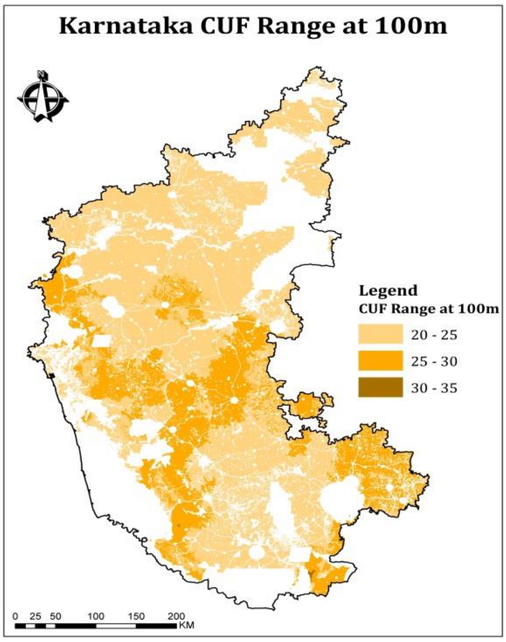


Figure 24: All India Wind CUFs, at 120 m Hub Height

3.4.11. CUF Maps of States - 100 m

Figure 25 below shows the CUFs in a few Indian states with maximum potential, at a 100 m hub height, without reference to land availability.



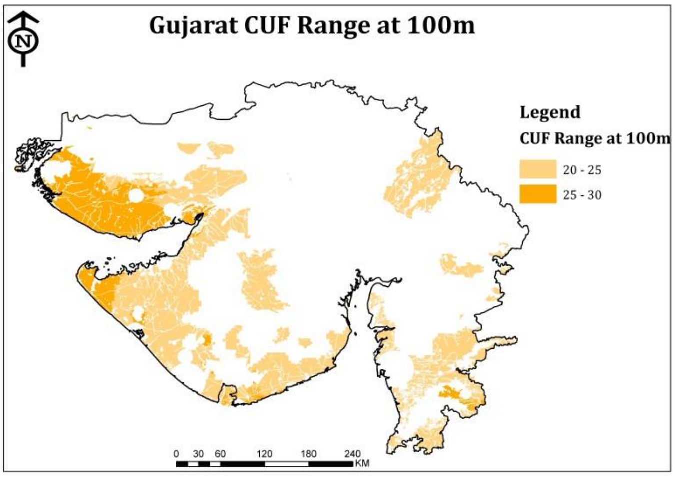


Figure 25: CUF Maps of Select States with Maximum Potential, at 100 m Hub Height

3.4.12. CUF Maps of States - 120 m

Figure 26 below shows the CUFs in a few Indian states with maximum potential, at a 120 m hub height, without reference to land availability.

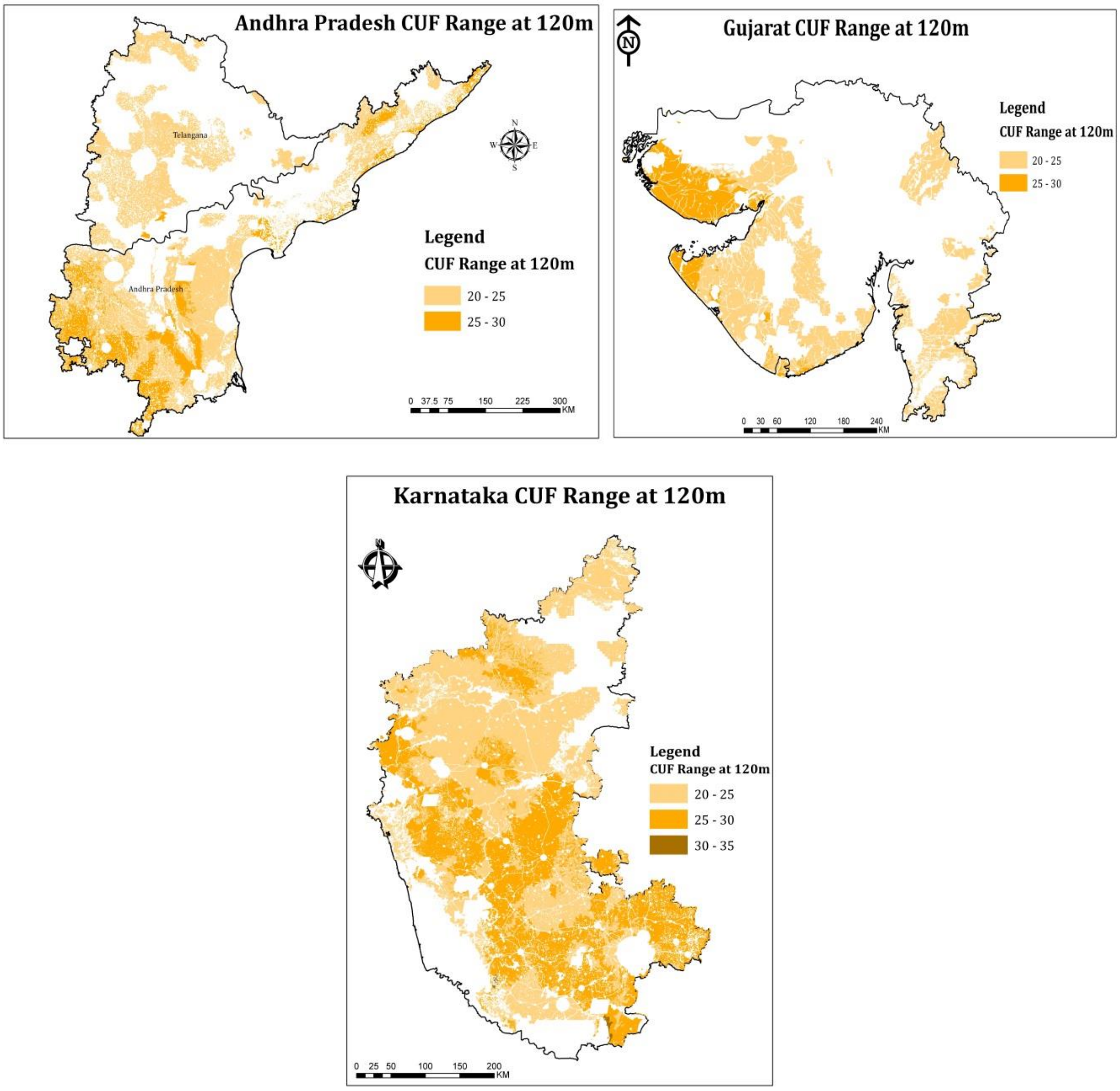


Figure 26: CUF Maps of Select States with Maximum Potential, at 120 m Hub Height

4. Wind Power Potential in Wastelands

The areas shaded in 'green' in Figure 27 signify wastelands (Rank 1). Wastelands may be considered as most suitable type of land for the deployment wind projects. The following results (Table 11) show the wind power potential corresponding to CUF>20%.

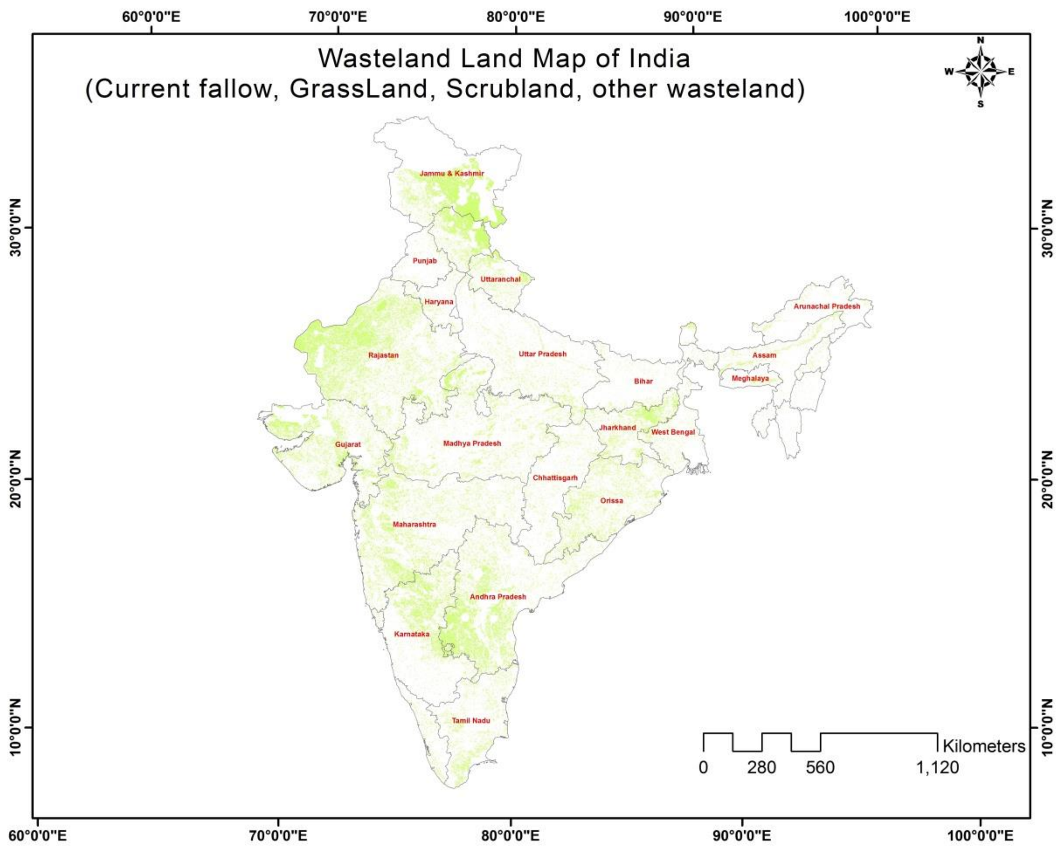


Figure 27: All India Wastelands

Table 11: Wind Power Potential with CUF > 20%

	WFMS			CSTEP		
Hub Height (m)	**Area (sq. km)**	**Potential with 5D x 7D (GW)**	**Potential with 3D x 5D (GW)**	**Area (sq. km)**	**Potential with 5D x 7D (GW)**	**Potential with 3D x 5D (GW)**
80 m	-	-	-	133,710	762	1,778
100 m	259,043	591	1,378	175,692	1,001	2,337
120 m	286,200	653	1,523	201,568	1,149	2,681

5. Solar-Wind Potential

This chapter presents the results of the solar-wind potential in India, as per CSTEP's geo-spatial analysis

5.3. Aim and Scope

The aim of this section is to assess the potential of and identify sites suitable for solar Photovoltaic (PV) plus wind hybrid installations in India. A report on the GIS approach for land planning by Lehman (Lehman, 2011) explains that several factors play a crucial role in selecting a site. Availability of land is the primary factor. In addition, information about electrical infrastructure, topography, insolation, flood information, environmentally sensitive areas, federal lands and land conservation units are all critical factors when considering a potential site. GIS offers the ability to take these and other layers of information into account when searching for optimal regions for solar development.

5.4. Data Sources for GIS Analysis

Table 12 shows the various data sources that have been used for the GIS study of solar power potential in Karnataka, as an illustration. This methodology has been applied across the country to identify locations and potential.

Table 12: Data Sources Used in GIS Analysis

Name	Data Type	Resolution	Source	Available For	Comments
GHI map	Vector	10km x 10km cell size	NREL	India	• Free • Satellite derived data
Land use/Land cover data	Vector	NA	KSRSAC	Specific to Karnataka	• Commercial data
	Raster	300m	Bhuvan, NRSC	India	• Free • Satellite derived data
Sub stations (66,110,220 kV)	Vector	NA	KSRSAC	Only for Karnataka	Commercial data
Sub stations (132 kV and above)	AutoCAD + PDF	NA	PGCIL/ MNRE	India	Free
Water bodies	Vector	NA	KSRSAC	Only for Karnataka	• Commercial data
	Raster	300m	Bhuvan, NRSC	India	• Free • Satellite derived data
Roads	Vector	NA	KSRSAC	Only for Karnataka	Commercial data
Roads	Vector	NA	DIVA-GIS	India	Free

5.4.5. National Renewable Energy Laboratory (NREL)

The US-based NREL develops solar resource maps based on satellite data. In 2010, NREL released Global Horizontal Irradiation (GHI) resource maps at a resolution of 10 km for India. The high-resolution (10 km) solar resource data was developed using weather satellite data. The data is available in GIS format and as static maps.

5.4.6. Land Use Land Cover Data

The Karnataka State Remote Sensing Application Centre (KSRSAC) has developed a detailed LULC map of Karnataka. This mapping is done at a scale of 1:50000.

Land-use GIS data for Karnataka was sourced from both KSRSAC and Bhuvan (NRSC).

5.4.7. Roads

The road data was available from KSRSAC and DIVA-GIS. For the purpose of this analysis, state highways, national highways and metalled (tar) roads were considered.

5.4.8. Transmission Lines

The transmission lines data was available from Power Grid Corporation of India Ltd. (PGCIL) (for India) and KSRSAC (for Karnataka) for different types of substations and power lines. Only the available substation data was considered while conducting the proximity analysis.

5.5. Methodology Framework

5.5.5. Suitable Sites for Solar Photovoltaic Assessment

The methodology used for the site suitability assessment was decided based on a literature survey which suggested that it is important to include constraints such as distance to roads and the nearest sub-station in a potential assessment. The flowchart in Figure 28 shows the methodology used for a generic estimation of the potential of PV technologies, using GIS.

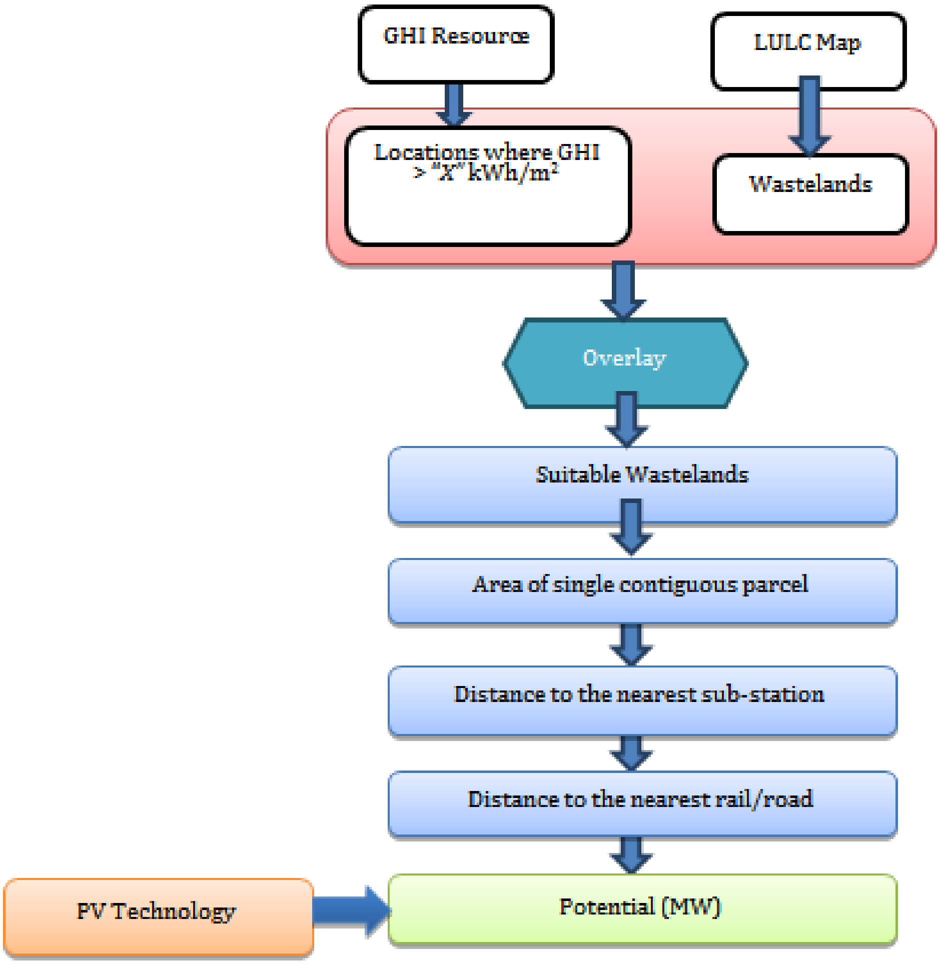


Figure 28: Methodological Framework for Site Suitability and Potential Assessment of Photovoltaic (PV) Technologies

This analysis takes into consideration multiple criteria to select a suitable site. Depending on whether the site meets the various criteria listed, one can decide if the site is suitable or not.

As an illustration, locations with Global Horizontal Radiation (GHI) greater than or equal to 4.5 kWh/m^2/day were first chosen for analysis. This was intersected with the wastelands in Karnataka. Then the wastelands which have a contiguous parcel size of less than 0.02 sq. km (for PV) were filtered out. Then proximity criteria like distance to the nearest sub-station and the nearest road was applied.

5.5.6. Assessment of Solar Potential

Once the total area (sq. km) of suitable wastelands was calculated, it was converted into potential (MW). For this, the methodology depicted in Figure 29 was followed.

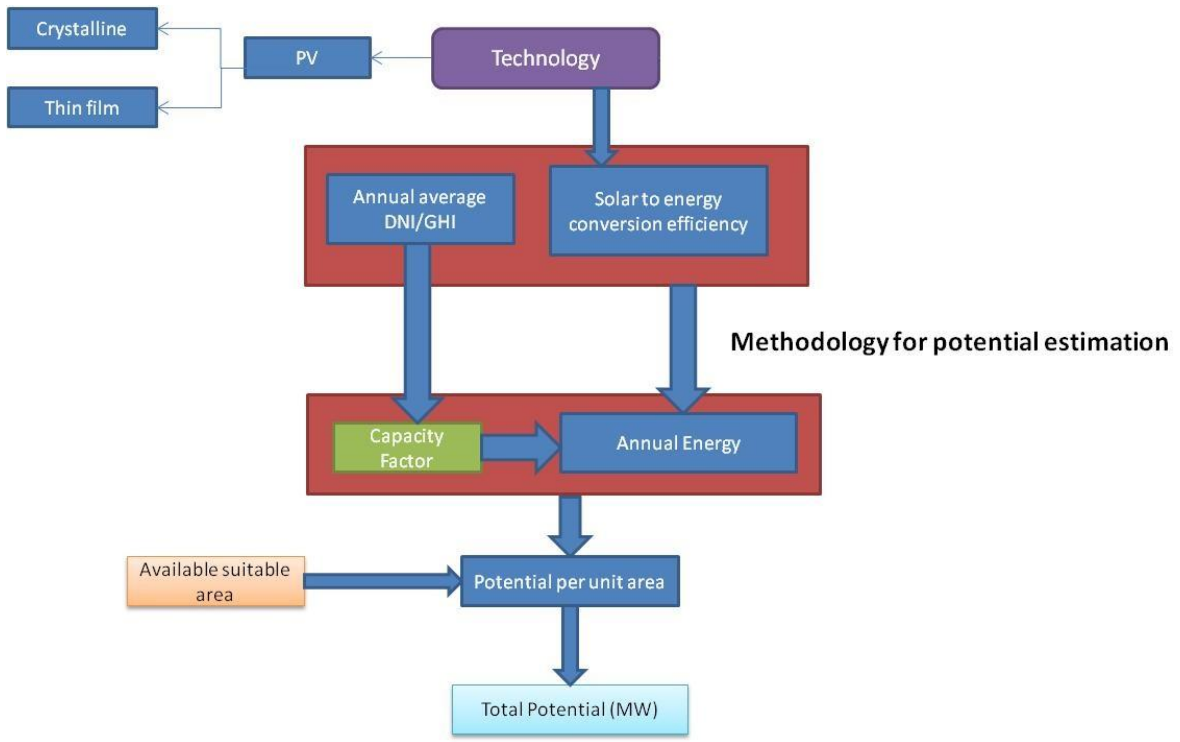


Figure 29: Methodology for Solar PV Potential Estimation

Different solar technologies were selected and the solar to energy conversion efficiency of each solar technology was noted. It was assumed that there will be 300 days of sunshine and an annual average GHI greater than or equal to 4.5 kWh/m2/day. For different PV technologies, the efficiencies mentioned in Table 13 were considered.

Table 13: Efficiencies of PV Technologies

PV Technologies	Efficiency
Poly Crystalline Silicon (c-Si)	14%
Mono Crystalline Silicon	18%
Copper Indium Gallium Diselenide (CIGS)	11%
Cadmium Telluride (CdTe)	9%

Based on these assumptions and factors, the potential per unit area was calculated and then the suitable area (from GIS analysis) was used to calculate the total potential in MW.

5.5.7. Assessment of Wind Potential

Only wastelands that have an average wind speed greater than 6 m/s at 120 m hub height were considered for wind potential calculations. The wind potential of a land parcel was calculated by multiplying the area by 5.7 (assuming a capacity density factor resulting from a 5D x 7D configuration, where D represents the rotor diameter of the turbine).

5.5.8. Methodology for Solar PV and Wind Hybrid Site Selection

Using the wind and solar resource availability data, the solar PV potential at land parcels in each state (based on GHI received in those parcels) was identified. The identified sites were then ranked in order of solar PV potential, proximity to sub-stations and proximity to rail/road networks. This method can be repeated for every parcel of land in the nation. The solar PV potential is calculated using the standard methods with parameters as specified in Table 9.

5.5.9. Methodology for Solar PV and Wind Hybrid Potential Calculation

Due to the irregular shape of land parcels, the hybrid potential was approximated using the fact that the footprint of a wind-based installation is much smaller than that of a solar installation. First the highest wind speed for every parcel was identified. Second, the PV technology with the highest potential was identified. Finally, the total potential was calculated as the sum of 90% of solar potential and 10% of wind potential[7].

5.5.10. Results of GIS Analysis

Figure 30 shows the wasteland locations in Karnataka that have wind speeds more than 6 m/s at 120 m hub height, and GHI values more than 5.7 kWh/m2/day.

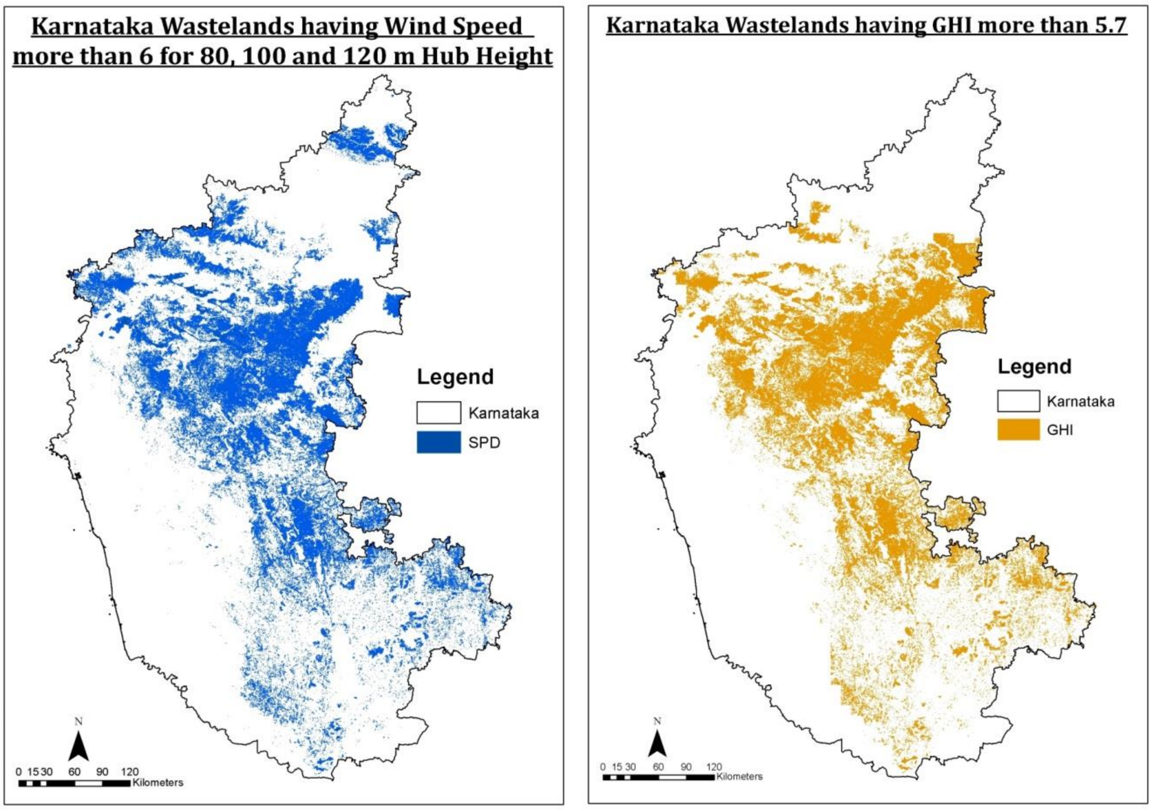


Figure 30: Karnataka Wastelands having Wind Speeds greater than 6 m/s

[7] Note that this potential is the maximum possible. In an actual installation, potential may vary from 20%-80% of the maximum.

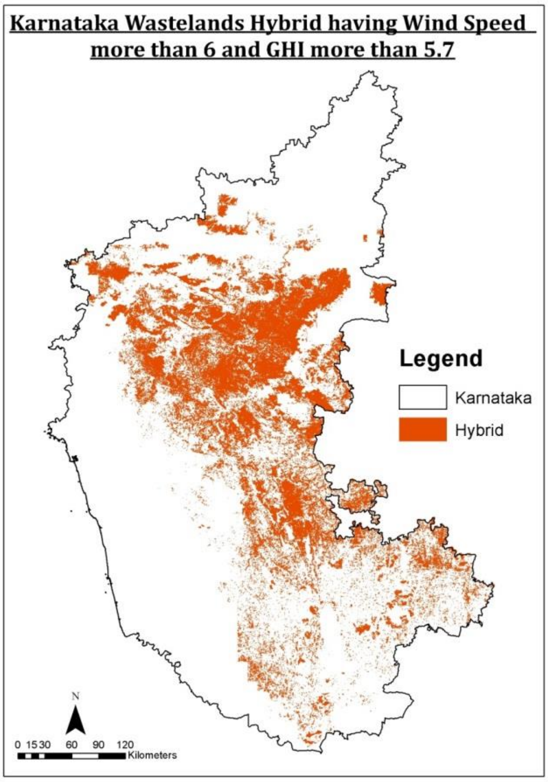


Figure 31: Karnataka Hybrid Potential Sites

Figure 31 above shows the area formed by the intersection of the land masses shown in Figure 30.

Table 14 shows the requisite details for hybrid locations in Karnataka.

Table 14: Details of Hybrid Locations in Karnataka

Total Number of Parcels for Hybrid installations	**57, 206**
Total Area	8, 000 sq. km
Total Gross Solar PV (Mono) Potential	915 GW
Useful Solar PV (Mono) Potential	824 GW
Total Gross Wind Potential at 120 m	45 GW
Useful Wind Potential at 120 m	4.5 GW
Total Hybrid Potential	**828.5 GW**

The procedures described in this section were repeated for all the states in India that have adequate wind and solar resources. Table 15 shows the total potential across India for solar PV and wind hybrid installations.

Table 15: All India Hybrid Potential

State	Area (in sq. km)	Solar PV Potential (GW)	Hybrid-capable Wind Potential (GW) at 120 m Hub Height	Hybrid Potential (GW)
Andaman and Nicobar	60	6.1	0.4	5.5
Andhra Pradesh	20,000	220	112	1,987
Arunachal Pradesh	2	0.2	0.2	0.2
Chhattisgarh	102	11	0.6	9.9
Dadra and Nagar Haveli	42	4.5	0.2	4.1
Daman and Diu	13	1.5	0	1.3
Goa	36	4.0	0.2	3,605
Gujarat	27,531	3,087	157	2794
Himachal Pradesh	6	0.5	0	0.5
Jammu and Kashmir	6,361	629	36	570
Karnataka	8,000	915	45	828
Kerala	80	9	0.5	7.8
Madhya Pradesh	22	2.5	0.1	2.1
Maharashtra	18,612	2,054	106	1860
Orissa	2,653	275	15	249.5
Puducherry	19	2	0.1	2
Rajasthan	15,230	1,705	86	1545
Sikkim	6	0.6	0	0.5
Tamil Nadu	3,331	380	19	344
Uttaranchal	973	94	5.5	85.5
West Bengal	3	0.3	0	0.2
India	**1,03,082**	**11,380**	**585**	**10,300**

6. Summary

6.3. Total Potential

In this analysis, the potential calculated through the more dispersed layout of 5D x 7D can be taken as the conservative end of the range of potential. The denser layout of 3D x 5D can be visualised as the more closely packed, optimal layout, resulting in a higher deployment potential or reduced land requirement. Hence the total wind power potential for India can be presented as shown in Table 16.

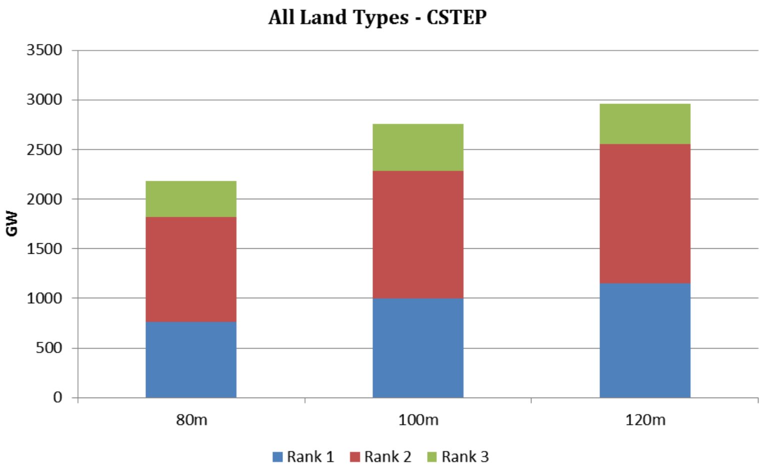
Table 16: Total Wind Power Potential

Hub Height (metres)	Estimated Wind Potential Range - CSTEP (in GW)	Estimated Wind Potential Range - WFMS (in GW)
100	2,759 – 6,439	2,161 – 5,043
120	2,959 – 6,905	2,540 – 5,927

At the conservative end of the estimated results, most of the potential lies in waste land and agricultural land, namely ranks 1 and 2 respectively. The spread of the lower end of the range of potential, among the three major land categories, is presented in Table 17 and Figure 32.

Table 17: Potential for 3 Land Categories at 80, 100, and 120 m Hub Height

	GW Potential - CSTEP		GW Potential - WFMS	
Land Rank	**100 m**	**120 m**	**100 m**	**120 m**
Rank 1	1,001	1,149	591	653
Rank 2	1,279	1,409	1,222	1,435
Rank 3	479	401	349	453
TOTAL	2,759	2,959	2,162	2,541



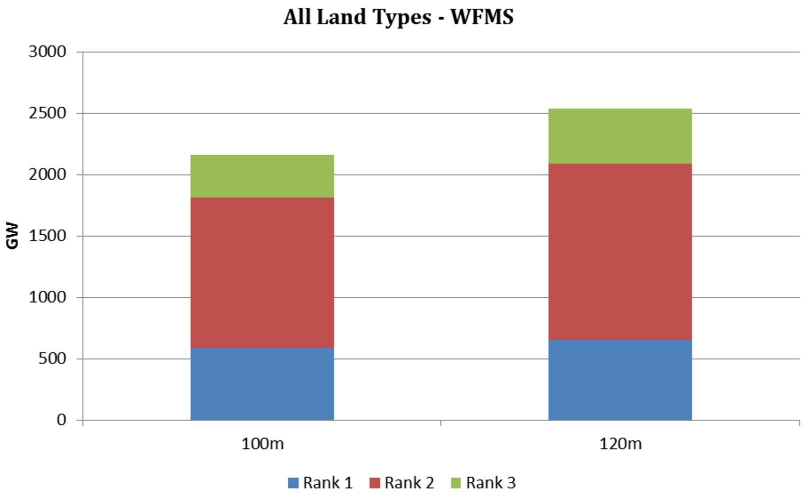


Figure 32: Distribution of Total Potential across All Land Types – CSTEP and WFMS results

At all the three hub heights, close to 50% of the estimated potential lies in agricultural land.

Of the remaining potential, most of the potential is present in waste lands, with a maximum of 17% of the potential lying in plantations, evergreen areas, and deciduous forests. These results imply that states can prioritise the development of wind potential in land categories of Rank 1 and 2, i.e. waste land and agricultural land, and implement state-level constraints on limiting the development of wind farms in forests. This would ensure faster implementation of wind projects, by avoiding long delays associated with obtaining environmental clearances and land availability hurdles faced in forests.

Even if Rank 3 category areas are removed from the conservative potential estimate, there is a substantial amount of potential (up to 2,500 GW) to be harnessed in Rank 1 and 2 categories of land. On waste land alone, there is a minimum of about 590 GW, with up to a maximum of 1,000 GW of potential estimated at a hub height of 100 m. Results are presented in Table 18.

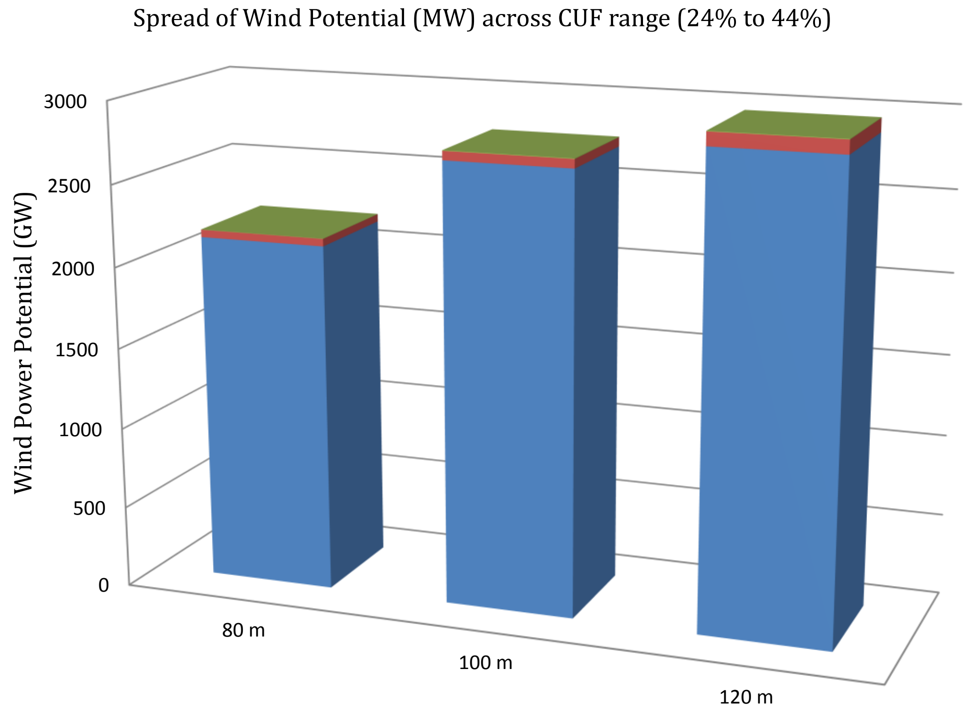
Table 18: GW Potential for Waste Land and Agricultural Land Categories at 100 m and 120 m

	GW Potential - CSTEP		GW Potential - WFMS	
Land Rank	**100 m**	**120 m**	**100 m**	**120 m**
Rank 1	1,001	1,149	591	653
Rank 2	1,279	1,409	1,222	1,435
TOTAL	2,280	2,558	1,813	2,088

6.4. Potential across Various CUF Ranges

The potential estimated in Table 18 is the installable potential across various land categories, for the set of results obtained from CSTEP. The actual electricity generated per year, from a particular site, is dependent on the resource quality and height of the turbine. For instance, a turbine which is installed at a site with higher wind speed will operate at a higher CUF in comparison to the same turbine which is installed in another site with lower wind speeds. Technology advancements have enabled installation of turbines which are designed to operate with a higher CUF at lower wind speeds that are typical of Indian sites. Similarly, a turbine of 120 m hub height installed at a location will operate at a higher CUF compared to a turbine of 100 m hub height installed at the same location.

Hence, the electricity generated at a particular site is largely dependent on the choice of turbine in addition to the resource quality at the site. For this study, a representative turbine with 2 MW capacity, and 100 m rotor diameter was chosen. The minimum CUF obtained, by intersecting the wind speed profile (with weibull shape parameter k = 2, for a minimum wind speed of 6 m/s) is 24%. In the three main land categories, most of the estimated wind potential lies between 24-34%. A very small percentage of the estimated potential has a CUF of 42-44%. The spread of the potential across the CUF ranges, for the set of results of CSTEP can be visualised as shown in Figure 33.



	80 m	100 m	120 m
42% to 44%	1	3	3
35% to 41%	45	55	84
24% to 34%	2140	2701	2873

Figure 33: CUF-wise GW Potential at 3 Hub Heights – CSTEP Results

6.5. Optimisation of Land

With advanced technologies, it is possible to obtain higher CUFs, thus economically utilising low to medium wind regime sites. Often, the increase in CUF is sufficient to offset the increase in capital cost of the wind turbine, thus reducing the LCOE of wind power.

Further, the capacity density factor determines the amount of land required for installing wind farms. Table 21[8] illustrates that even if 100% of the potential is tapped, the total land area under wind farms will be ~15% of India's total land area in case of a packing layout of 5D x 7D. The land requirement reduces to less than half if a layout of 3D x 5D is considered. In reality, the layout may vary between these two extremes depending on site-specific conditions.

[8] Seven states considered for the above analysis: Tamil Nadu, Andhra Pradesh, Telangana, Karnataka, Rajasthan, Gujarat, Maharashtra.

Table 19: Land Utilisation for Estimated Potential

		5D x 7D	3D x 5D
Capacity installed per sq. km.	**MW/sq. km**	**5.71**	**13.33**
Wind power potential at 100 m	MW	2,759,703	
Total footprint area	sq. km	27,597	
India's total land area	sq. km	3,287,263	
Total land required for tapping the full potential	sq. km	482,948	206,978
Total land required as % of India's total land	%	14.69	6.30
Footprint area as % of India's total land	%	0.84	
Potential in 7 wind-rich states	MW	2,332,912	
Potential in 7 wind-rich states as % of total potential	%	85	
Total land required in 7 wind-rich states	sq. km	408,260	174,968
Total area of these 7 wind-rich states	sq. km	1,442,870	
Total land required as % of the total area of 7 states	%	28.29	12.13
Footprint area of the capacity installed in wind-rich states	sq. km	23,329	
Footprint area as % of total area of 7 states	%	1.62	

6.6. Conclusion

There are some assumptions to be particularly noted for interpreting the results.

First, in order to estimate the wind power potential intersected with land-use, minimum speed criteria is applied in both sets of results. The range of CUFs which is represented pictorially in this study is positively correlated to the wind speeds used to estimate the MW potential. It is dependent on the net production of energy from a particular site, which is a product of the shape of the weibull speed profile and the power response curve of the representative turbine chosen for this analysis. Hence, in order to realise the estimated potential, careful selection of the right turbine for a particular wind speed profile is recommended while micro-siting. The turbine should ideally be chosen such that its response curve complements the wind speed distribution of the site to yield maximum energy. Technology improvements in newer turbines, designed for improved efficiency at lower wind speeds, will significantly impact the observed CUFs.

Second, the capacity density factors of 5.7 MW/ sq. km. and 13.3 MW/sq. km. which the potential is based on optimal wind farm array configurations for a fixed unit of area. In actual realisation of the potential, these configurations may be difficult to achieve due to site-specific constraints of availability of land and suitability of terrain. Similarly, the configurations can be optimised further, based on identification of contiguous parcels of that are practically available for wind farm installation.

Finally, there will be considerable operational challenges for grid operators to balance supply and demand with increasing share of wind capacity in the generation mix, due to the variability inherent in the resource. Better preparedness for managing this externality is essential for efficient utilisation of the power generated from wind.

6.6.5. Policy Implications

Every recent report that estimates India's wind power potential, including this report, suggests significant wind power potential is available in India. Although site-specific investigation is necessary for setting up projects, such macro-level analyses are widely used around the globe for the purpose of policy making and planning for the growth of the sector. Some of the major implications for policy and planning for the sector are as follows:

- There is very high potential available on wasteland alone, up to 1,000 GW. There is opportunity for nodal agencies in the states with high wind potential to identify some of the high potential wastelands and expedite clearances for them

- In order to utilise this vast potential, it is essential that the resource data regime improves. India needs to ensure public access to credible and updated onshore and offshore resource data for the country in ways that do not adversely impact potential investments in the sector. Towards this end, the Government may consider encouraging models which channelise private sector investments to accelerate the deployment of met masts and the process for data validation.

- As explained previously, choice of turbine has a significant impact on the efficient utilisation of wind potential at any site

- There is opportunity to unlock some of the high potential lands in states, which have been occupied with low-capacity and low-efficiency wind turbines from the early stages of development in wind power in the country. Appropriate incentives for repowering these sites can enhance capacity in some of the known high potential sites

- As the potential is mostly concentrated in the southern and western states, there needs to be mechanisms to enable inter-state trading of wind power, requiring coordination among load dispatchers and transmission utilities

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Appendix I: Copy of MNRE Order Constituting the Committee

No.: 58/91/2014-WE
Ministry of New and Renewable Energy
(Wind Energy Division)
***

Block-14, C.G.O. Complex
Lodhi Road, New Delhi-3

Date: 03.09.2014

Office Memorandum

Subject: Constitution of the Committee for Reassessment of Wind Power Potential of the country.

I am directed to convey that a Committee has been constituted in the Ministry for Reassessment of Wind Power Potential of the country. Composition of the Committee is as follows.

(i) Dr. Alok Srivastava, Joint Secretary, MNRE (Chairman)
(ii) Shri S.K. Shukla, Vice President, AREAS
(iii) Shri Madhusudan Khemka, Regen PowerTech or a nominated representative from IWTMA
(iv) Dr. Anshu Bharadwaj, Executive Director, C-STEP
(v) Shri Jami Hossain, Windforce Management
(vi) Shri Deepak Gupta, Shankti Sustainable Energy Foundation
(vii) Shri S.B Patil, GEDA (Representative from SNA)
(viii) Shri Dilip Nigam, Director, MNRE
(ix) Dr. S. Gomathinayagam, Director General, NIWE (Convener)

The Committee will complete its task as per the Terms of Reference mentioned below in two months' time. MNRE will facilitate the procurement of necessary data and maps required for this purpose.

2. Terms of Reference of the Committee are as follows:

(i) Review of all existing literature on India's onshore wind power potential assessment.

(ii) Preparation of a review report, which compares the methodology, assumptions, data sets used and conclusions of the above mentioned studies. Use this analysis to draw conclusions for India's onshore wind power potential.

(iii) Develop a common methodology for India's onshore wind power potential assessment using GIS based wind speed maps at 80 m and 100 m hub heights and Land Use & Land Classification (LULC) maps for various categories of lands such as Wastelands, Forest, and Agriculture.

(iv) Use the above methodology to estimate India's onshore wind potential and clearly document the assumptions.

(v) Submit a final report based analysis on the above to the Ministry, which can be peer reviewed by external experts.

(vi) The findings of the committee will be disseminated in a workshop and also in research publications.

3. Members may make it convenient to attend the meetings of the Committee.

4. This issues with approval of Secretary, MNRE.

(Shobhit Srivastava)
Scientist-B

1) The Executive Director, National Institute of Wind Energy (NIWE), Velachery-Tambaram High Road, Pallikaranai, Chennai- 601 302

2) Shri S.K. Shukla, Chief Executive Officer, Chhattisgarh State Renewable Energy Development Agency (CREDA), CSERC Building, 2nd Floor, Shanti Nagar, Raipur – 492001

3) Shri Madhusudan Khemka, Managing Director, Regen Powertech Pvt. Ltd., Samson Towers, 3rd, 4th & 5th Floor, 403L, Pantheon Road, Egmore, Chennai - 600 008 – with request to inform the nominated official, Shri T.S. Saravanan.

4) Dr. Anshu Bharadwaj, Executive Director, Center for Study of Science, Technology and Policy, Dr. Raja Ramanna Complex, Raj Bhavan Circle, High Grounds, Bangalore – 560001

5) Shri Jami Hossain, WinDForce Management Services Private Limited, Universal Trade Tower, 5th Floor, Sector 49, Sohna Road, Gurgaon - 122 001

6) Shri Deepak Gupta, Shakti Sustainable Energy Foundation, Capital Court, 104 B/2, 4th Floor, Munirka Phase –III, New Delhi 110067

7) Shri S.B. Patil, Deputy Director, Gujarat Energy Development Agency (GEDA), 4th Floor, Block No. 11 & 12, Udyog Bhawan, Sector 11, Gandhi Nagar – 382017

Copy for information to:

1) PSO to Secretary, MNRE

2) PS to Dr. Alok Srivastava, Joint Secretary, MNRE

3) Shri Dilip Nigam, Director, MNRE

Appendix 2: Wind Potential at 100 m

Table below presents the potential for 21 states for which wind speeds above 6 m/s are available, at 100 m hub height. These results are obtained from the input wind speed data set used by CSTEP.

	Area (sq.km)			Wind Energy Potential (GW) (5D x 7D)				Wind Energy Potential (GW) (3D x 5D)			
STATES	**Rank 1 (R1)**	**Rank 2 (R2)**	**Rank 3 (R3)**	**R1**	**R2**	**R3**	**Total**	**R1**	**R2**	**R3**	**Total**
Tamil Nadu	10,317	23,729	9,941	59	135	57	251	137	316	132	585
Karnataka	31,725	49,374	15,362	181	281	88	550	422	657	204	1283
Andhra Pradesh	24,053	14,685	10,152	137	84	58	279	320	195	135	650
Telangana	6,424	13,409	2,218	37	76	13	126	85	178	29	293
Maharashtra	32,253	45,131	12,378	184	257	71	512	429	600	165	1194
Gujarat	17,017	19,882	2,140	97	113	12	223	226	264	28	519
Rajasthan	41,641	25,197	2,256	237	144	13	394	554	335	30	919
Andaman & Nicobar Islands	100	292	3,717	1	2	21	23	1	4	49	55
Arunachal Pradesh	7	1	0	0	0	0	0	0	0	0	0
Assam	598	0	31	3	0	0	4	8	0	0	8
Chhattisgarh	598	3,464	3,089	3	20	18	41	8	46	41	95
Dadra & Nagar Haveli	49	52	160	0	0	1	1	1	1	2	3
Goa	50	126	250	0	1	1	2	1	2	3	6
Himachal Pradesh	18	53	36	0	0	0	1	0	1	0	1
Kerala	456	2,662	7,036	3	15	40	58	6	35	94	135
Madhya Pradesh	4,335	18,785	653	25	107	4	136	58	250	9	316
Manipur	0	127	646	0	1	4	4	0	2	9	10
Orissa	6,012	7,023	13,923	34	40	79	154	80	93	185	359
Puducherry	36	100	3	0	1	0	1	0	1	0	2
Uttar Pradesh	0	287	1	0	2	0	2	0	4	0	4
West Bengal	3	71	26	0	0	0	1	0	1	0	1
TOTAL	**1,75,691**	**2,24,450**	**84,018**	**1,001**	**1,279**	**480**	**2,760**	**2,336**	**2,985**	**1,115**	**6,439**

Appendix 3: Wind Potential at 120 m

Table below presents the potential for 20 states for which wind speeds above 6 m/s are available, at 120 m hub height. These results are obtained from the input wind speed data set used by CSTEP.

	Area (sq.km)			Wind Energy Potential (GW) (5D x 7D)				Wind Energy Potential (GW) (3D x 5D)			
STATES	**Rank 1 (R1)**	**Rank 2 (R2)**	**Rank 3 (R3)**	**R1**	**R2**	**R3**	**Total**	**R1**	**R2**	**R3**	**Total**
Tamil Nadu	10,915	24,395	10,762	62	139	61	263	145	324	143	613
Karnataka	36,830	56,847	11,582	210	324	66	600	490	756	154	1400
Andhra Pradesh	33,681	15,949	9,183	192	91	52	335	448	212	122	782
Telangana	7,864	7,390	2,935	45	42	17	104	105	98	39	242
Maharashtra	33,086	45,550	12,235	189	260	70	518	440	606	163	1209
Gujarat	18,974	23,410	1,969	108	133	11	253	252	311	26	590
Rajasthan	46,820	32,459	2,939	267	185	17	469	623	432	39	1093
Arunachal Pradesh	7	1	0	0	0	0	0	0	0	0	0
Assam	0	0	30	0	0	0	0	0	0	0	0
Chhattisgarh	819	4,516	3,278	5	26	19	49	11	60	44	115
Dadra & Nagar Haveli	49	53	160	0	0	1	1	1	1	2	3
Goa	62	171	332	0	1	2	3	1	2	4	8
Himachal Pradesh	5	32	10	0	0	0	0	0	0	0	1
Kerala	462	2,716	7,143	3	15	41	59	6	36	95	137
Madhya Pradesh	5,224	25,134	1,553	30	143	9	182	69	334	21	424
Manipur	0	143	666	0	1	4	5	0	2	9	11
Orissa	6,731	7,599	5,606	38	43	32	114	90	101	75	265
Puducherry	36	100	3	0	1	0	1	0	1	0	2
Uttar Pradesh	0	693	6	0	4	0	4	0	9	0	9
West Bengal	3	78	30	0	0	0	1	0	1	0	1
TOTAL	**2,01,566**	**2,47,234**	**70,423**	**1,149**	**1,408**	**402**	**2,960**	**2,681**	**3,286**	**936**	**6,906**

Appendix 4: Wind Potential at 80 m

Table below presents the potential for 18 states for which wind speeds above 6 m/s are available, at 80 m hub height. These results are obtained from the input wind speed data set used by CSTEP.

	Area (sq.km)			Wind Energy Potential (GW) (5D x 7D)				Wind Energy Potential (GW) (3D x 5D)			
STATES	**Rank 1 (R1)**	**Rank 2 (R2)**	**Rank 3 (R3)**	**R1**	**R2**	**R3**	**Total**	**R1**	**R2**	**R3**	**Total**
Tamil Nadu	9,786	22,290	9,207	56	127	52	235	130	296	122	549
Karnataka	22,809	44,289	12,936	130	252	74	456	303	589	172	1064
Andhra Pradesh	20,779	12,770	9,455	118	73	54	245	276	170	126	572
Telangana	4,398	13,169	2,872	25	75	16	117	58	175	38	272
Maharashtra	29,337	37,075	9,306	167	211	53	432	390	493	124	1007
Gujarat	13,670	15,046	1,494	78	86	9	172	182	200	20	402
Rajasthan	23,731	14,485	1,999	135	83	11	229	316	193	27	535
Andaman & Nicobar Islands	100	292	3,717	1	2	21	23	1	4	49	55
Chhattisgarh	372	2,187	1,123	2	12	6	21	5	29	15	49
Dadra & Nagar Haveli	23	33	7	0	0	0	0	0	0	0	1
Goa	40	100	208	0	1	1	2	1	1	3	5
Himachal Pradesh	5	26	7	0	0	0	0	0	0	0	1
Kerala	451	2,572	6,437	3	15	37	54	6	34	86	126
Madhya Pradesh	3,587	13,710	415	20	78	2	101	48	182	6	236
Manipur	0	95	33	0	1	0	1	0	1	0	2
Orissa	4,582	6,927	5,455	26	39	31	97	61	92	73	226
Puducherry	36	100	3	0	1	0	1	0	1	0	2
West Bengal	2	42	14	0	0	0	0	0	1	0	1
TOTAL	**1,33,708**	**1,85,208**	**64,688**	**762**	**1,056**	**369**	**2,187**	**1,778**	**2,463**	**860**	**5,102**

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