Indian Wind Potential Map at 150m agl

नीवे NIWE
(ISO 9001:2015)

राष्ट्रीय पवन ऊर्जा संस्थान
NATIONAL INSTITUTE OF WIND ENERGY
नवीन और नवीकरणीय ऊर्जा मंत्रालय, अनुसंधान एवं विकास स्वायत्त संस्थान, भारत सरकार
An Autonomous R & D Institution, Ministry of New and Renewable Energy, Government of India

JUNE 2023

India’s Wind Potential Atlas

at 150m agl

NATIONAL INSTITUTE OF WIND ENERGY

CHENNAI

UNDER MINISTRY OF NEW AND RENEWABLE ENERGY, GOVERNMENT OF INDIA

June 2023

India's Wind Potential Atlas

at 150m agl

नीवे NIWE

(ISO 9001:2015)

NATIONAL INSTITUTE OF WIND ENERGY

CHENNAI

UNDER MINISTRY OF NEW AND RENEWABLE ENERGY, GOVERNMENT OF INDIA

DISCLAIMER

This mapping work is a generalized study and the results can only be considered as indicative, as this includes numerical modelling inputs and various guesstimates with limited measurements. There may be scattered potential pockets available in other states and regions, which can only be identified through a detailed site specific study. Further it is to be noted that the present wind potential estimation is for planning purpose, whereas other aspects related to policy, economics, social acceptance, etc., which may facilitate / hinder the development of projects are to be studied by respective investor/developer.

FOREWORD

With its rapidly growing economy, urbanization and industrialization, India is projected to see a huge increase in its energy demand. Government of India have installed adequate capacity to meet this increasing demand and have put in place a range of power sector reforms to make the sector robust. While adding capacity India has also emerged as a leader in energy transition, adding renewable energy capacity at a rapid pace. Honorable Prime Minister of India announced a target to achieve 500GW of installed electricity capacity from non-fossil fuel sources by the year 2030. Wind Energy will be an important component in this target. The Government of India is actively working towards increased proportion of wind energy in the electricity mix.

Wind power constitutes a significant share of the country’s renewable energy capacity. The wind sector in India has achieved around 70-80% indigenization. It is also witnessing technological upgradations resulting in increased capacity of turbines upto 5.2 MW, with higher hub heights to better exploit wind conditions.

In 2019, National Institute of Wind Energy had prepared the wind potential atlas at 120m height, which indicated 695 GW wind potential of the country. The wind potential atlas now prepared by NIWE indicates that the overall wind potential of the country would be 1164 GW at 150m height. With improvements in technology, it has become feasible to utilize this increased potential.

I am confident that the atlas would be useful to all the stakeholders and will facilitate better utilization of wind resources in the country.

[R. K Singh]

FOREWORD

I am delighted to acknowledge that National Institute of Wind Energy (NIWE), Chennai is publishing wind potential atlas at 150m height considering the modernization of the wind turbine technology, which is a milestone in our pursuit of renewable energy solutions. As per the said wind atlas, our country has the installable wind power potential of 1164 GW at 150m above ground level. The 150m wind atlas will be a remarkable tool to identify and assess the wind energy potential across various regions of our country at higher hub height coverage upto 150m. This will facilitate the wind power developers & other stakeholders to take considered decisions in determining the techno-economic viability of a wind power project.

The Indian wind industry is nearly three decades old and now holds the 4th position in the world with installations of about 43 GW as on 31st May 2023. Wind power has contributed in a substantial way in the development of renewable energy in the country. With the joint efforts of State Nodal Agencies, NIWE, Manufacturers, Developers, Technical Consultants and the Financial Institutions, the wind energy sector is firmly on track to achieve the RE targets as envisaged by Government of India.

[Bhupinder S. Bhalla]

PREFACE

The 150m Wind Potential Atlas is prepared at a spatial resolution of 500m, using the advanced meso-micro coupled numerical wind flow model with the corroboration from 155 actual measurement sites spread across the country to cater the need of increased hub heights of wind turbines in the country. It gives an updated overview of the wind climatological situations of India based on numerical meso scale model and reliable measured wind data. The indicative wind potential at 150m agl is estimated by excluding unsuitable area / land features. The potential is further stated in terms of CUF and land categories for effective decision making by all stakeholders.

Based on the estimation, it is noted that the high CUF potential regions are distributed in the states of Andhra Pradesh, Gujarat, Karnataka, Maharashtra and Tamil Nadu with scattered potential in Kerala, Madhya Pradesh, Telangana and Rajasthan. However, there may be few pockets in the country where wind could be strong due to local effects and the same could not be captured in the report in the absence of measurements in those pockets. The wind potential map given in the report is indicative and should not to be referred for detailed financial analysis for any site in general.

The Wind Potential Atlas at 150m agl has compiled together with high resolution wind potential map as hard copy for reference. This report has six chapters. Chapter 1 gives a brief history of wind resource assessment program and previous estimations done at 50m, 80m, 100m and 120m height. Chapter 2 explains the methodology adopted for the 120m high wind mapping and potential estimation. Chapter 3 summarizes the numerical modelling and Chapter 4 details about the data sources utilized in mapping. Chapter 5 gives results of the study and Chapter 6 gives map validation details.

This report is expected to serve as the basis for preliminary site assessment during the prospecting phase of wind project developments in the country. Further, the information will be useful for all stakeholders of the sector including the policy makers, private players, government agencies in their efforts towards achieving the country's ambitious RE goals.

Dr. Rajesh Katyal,
Director General (Addl. Charge), NIWE

Acknowledgements

The 150m Indian Wind Potential Atlas would not have been possible without the involvement and contribution of numerous individuals, groups and organizations. This report is one of the outcomes of the project, "Integrated Wind and Solar Resource Assessment through Mapping and Measurements" approved by R&D Sectoral Project Appraisal Committee (RDSPAC) of Ministry of New and Renewable Energy (MNRE), Government of India. The project team thanks the Ministry for sponsoring this ambitious project and their support.

At the outset, we would like to express our sincere gratitude to Shri. Bhupinder Singh Bhalla, Secretary, MNRE for providing all the necessary support to undertake the study for the preparation of this report. The project team places on record their sincere acknowledgement to Shri. Dinesh Dayanand Jagdale, Joint Secretary (Wind), MNRE for his support throughout the project's duration and his inputs on the document. The support and guidance provided by Dr. Prabir Dash, Scientist 'D', MNRE, Dr. Rahul Rawat, Scientist 'C', MNRE and other Ministry officials who have supported in finalizing and publishing the Wind Potential Atlas report is gratefully acknowledged.

We thank M/s. Vortex Factoria De Calculs S L, Spain, National Remote Sensing Centre (NRSC / ISRO), Space Application Centre (SAC / ISRO) and all the relevant national and international bodies, who have enabled the required inputs for the work. We acknowledge the excellent and inspiring cooperation of all the NIWE staff, particularly the regular, project staff and the GIS team in bringing the 150m Wind Potential Atlas to this shape through their sincere efforts in data collection, analysis and review.

We also wish to extend our sincere gratitude to all the stakeholders whom we consulted during the course of this study for their cooperation and relevant inputs which were very valuable for this study.

Authors & Contributors

Dr. Rajesh Katyal, Director General (Addl. Charge), NIWE

Shri. J. C. David Solomon, Director, NIWE

Dr. K. Boopathi, Director, NIWE

Smt. Deepa Kurup, Addl. Director, NIWE

Shri. A. Hari Bhaskaran, Deputy Director (Technical), NIWE

Shri. A.G. Rangaraj, Deputy Director (Technical), NIWE

Shri. J. Bastin, Deputy Director (Technical), NIWE

Shri. B. Krishnan, Assistant Director (Technical), NIWE

Shri. Yelchuri Srinath, Assistant Director (Technical), NIWE

Shri. R. Vinod Kumar, Junior Engineer, NIWE

Shri. Sankara Rao Tamada, Junior Engineer, NIWE

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

India is blessed with abundant sources of renewable energy and by April 2023 about 125.7 GW RE based capacity has already been installed in the country along with 46.8 GW of large hydro capacity. Out of total RE capacity wind energy represents a significant share of renewable energy portfolio. Wind energy sector is more than two decades old with manufacturing more than 80% of the components under 'Make in India'. Wind energy is also water smart electricity sources with the least water consumption. India is not only committed to refine and strengthen the business and regulatory framework governing wind power in India, but also to provide the necessary and reliable information on wind resources across the entire country.

Wind Turbine technology has evolved significantly over the last decade with emphasis on greater energy capture and improved capacity utilization factor. Modern turbines have larger rotor diameter and higher hub heights. Hence, it became necessary to identify areas which have wind potential at higher heights. Considering this and using advancements of mapping techniques, wind potential assessment of the country at 150m hub height was undertaken. Earlier, NIWE had prepared Indian Wind Atlas at 50m and indicative values at 80m hub heights with 5km resolution in April 2010. In 2015, mapping was revised by corroborating meso-scale derived wind maps and micro-scale measurements and the Indian Wind Potential Map at 100m agl was published. In 2019, the potential estimation was revisited at 120m agl and report was published.

The present 150m high potential assessment is carried out in similar lines at a spatial resolution of 500m, using the advanced meso-micro coupled numerical wind flow model with the corroboration from 155 actual measurement sites spread across the country. The indicative wind potential at 150m agl is estimated by excluding unsuitable area / land features. The potential is further stated in terms of CUF and land categories for effective decision making by all stakeholders.

This report is expected to serve as the basis for preliminary site assessment during the prospecting phase of wind project developments in the country. Further, the information will be useful for all stakeholders of the sector including the policy makers, private players, government agencies in their efforts towards achieving the country's ambitious RE goals.

Based on the study, the installable wind potential of the country is estimated as 1164 GW at 150m agl (above ground level) with 5D x 7D micro-siting configuration. Out of the total estimated 1164 GW potential, 544 GW is possible in wasteland, 607 GW in cultivable land and 12 GW in forest land. It is noted that wind potential to the extent of 164 GW is possible in high potential area with CUF greater than 35%. While areas with high wind potential and high CUF can be developed into large wind farms, those with lower CUF could be considered for distributed generation and also for wind solar hybrid for better utilization of the RE resources.

It is noted that the high CUF potential regions are distributed in the states of Andhra Pradesh, Gujarat, Karnataka, Maharashtra and Tamil Nadu with scattered potential in Kerala, Madhya Pradesh, Telangana and Rajasthan. Pockets of medium wind potential are located in states of Himachal Pradesh, Uttarakhand, Bihar, West Bengal and Odisha. For better planning and development of wind rich areas of the country, a high resolution map of the country is attached with this report.

Total wind power potential at 150m agl	1164 GW
Total wind power potential at 150m agl for waste land	544 GW
Total wind power potential at 150m agl for cultivable land	607 GW
Total wind power potential at 150m agl for forest areas	12 GW

Table E.1: State-wise detailed Wind Potential at 150m agl

% CUF State	25-30% (MW)	30-32% (MW)	32-35% (MW)	35-38% (MW)	38-40% (MW)	>40% (MW)	Total (MW)
Andhra Pradesh	65409	19143	19184	12297	4670	2632	123336
Arunachal Pradesh	121	57	57	12	0	0	246
Assam	451	7	0	0	0	0	459
Bihar	4023	0	0	0	0	0	4023
Chhattisgarh	2670	79	0	0	0	0	2749
Goa*	9	4	1	0	0	0	14
Gujarat	59392	16800	32275	34629	16589	21104	180790
Haryana	593	0	0	0	0	0	593
Himachal Pradesh	239	0	0	0	0	0	239
J & K*	0	0	0	0	0	0	0
Jharkhand*	16	0	0	0	0	0	16
Karnataka	65638	32200	40194	21696	5686	3836	169251
Kerala	663	247	277	323	144	968	2621
Madhya Pradesh	47861	5452	2016	94	0	0	55423
Maharashtra	104551	25650	25168	14258	3273	968	173868
Manipur*	0	0	0	0	0	0	0
Meghalaya*	55	0	0	0	0	0	55
Mizoram*	0	0	0	0	0	0	0
Nagaland*	0	0	0	0	0	0	0
Odisha	11072	945	112	0	0	0	12129
Punjab	428	0	0	0	0	0	428
Rajasthan	230414	44852	8958	27	0	0	284250
Sikkim*	0	0	0	0	0	0	0
Tamil Nadu	38859	17876	18207	8182	4266	7717	95107
Telangana	38279	10160	5617	609	52	0	54717
Tripura*	0	0	0	0	0	0	0
Uttar Pradesh	510	0	0	0	0	0	510
Uttarakhand*	30	12	6	2	0	0	49
West Bengal	1281	0	0	0	0	0	1281
A & N Islands	229	343	491	167	13	2	1245
Chandigarh*	0	0	0	0	0	0	0
DNH*	17	0	0	0	0	0	17
Daman and Diu*	0	0	0	0	0	0	0
Delhi*	0	0	0	0	0	0	0
Ladakh*	0	0	0	0	0	1	1
Lakshadweep	7	16	8	0	0	0	31
Puducherry	76	116	57	160	0	0	408
Total in MW	**672893**	**173958**	**152628**	**92455**	**34694**	**37228**	**1163856**

** In these states, even though the wind potential is indicated as negligible based on the applied methodology and land suitability analysis, there can be scattered potential pockets available for wind farm development due to the localized wind flows and such pockets can only be identified through in-situ measurements.*

1. INTRODUCTION

1.1. Background

India is blessed with abundant renewable energy resources like solar, wind, hydropower, biomass, etc., and has taken a leap in RE capacity additions in last few years as part of country's commitment towards sustainability. With more than two decades of experience, the wind sector occupies an important place in our RE portfolio.

Wind industry represents successful 'Make in India' narrative with all wind turbines being made in India and over 80% of the components manufactured indigenously. The year-wise installed wind power capacity upto FY 2022-23 is shown in Figure 1. As on 30.04.2023, wind power has contributed more than 42.8 GW (42868.08 MW)[1] of India's installed capacity. Wind energy also represents water smart electricity resource with least water consuming source of energy where the water requirement is negligible after commissioning as against other forms of electricity generation.

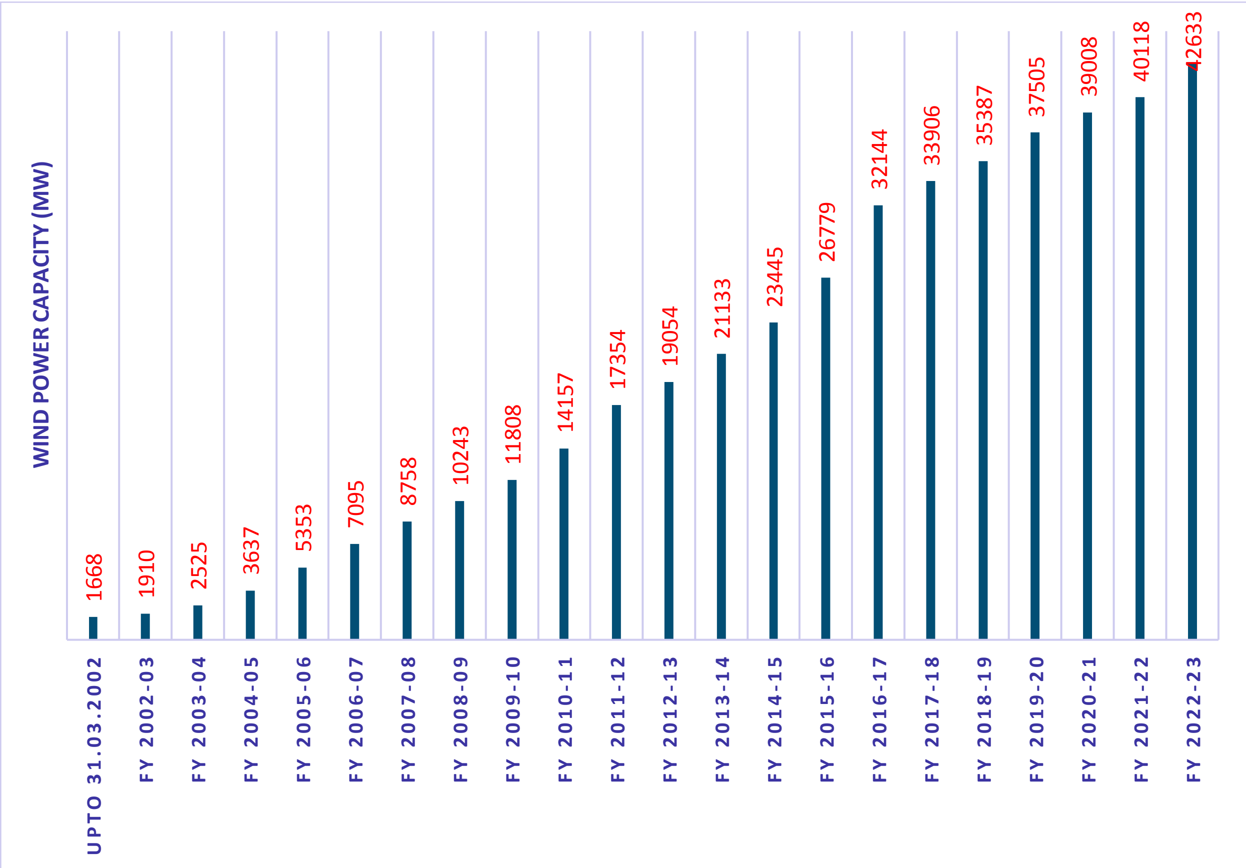


Figure 1: Cumulative Growth of Wind Power in India

[1] https://niwe.res.in

The government's ambitious goal of achieving 500 GW Non-fossil energy capacity by 2030 highlights the country's commitment towards sustainable development. In order to meet the ambitious goal, it is necessary to not only refine and strengthen the business and regulatory framework for wind power in India, but also to provide the reliable and updated information on the Indian wind resources.

The report is organised as under:

Chapter 1 gives a brief history of wind resource assessment program and previous estimations done at 50m, 80m, 100m and 120m height.

Chapter 2 explains the methodology adopted for the 150m high wind mapping and potential estimation.

Chapter 3 summarizes the numerical modelling and downscaling technique.

Chapter 4 details about the data sources utilized in mapping.

Chapter 5 gives results of the study.

Chapter 6, the final chapter of this report gives the map validation details.

The present report is expected to serve for prospecting new wind project developments in the country and also for repowering existing wind farms. This report is also expected to serve the needs of policy makers, investors, developers, manufacturers and other government agencies in their efforts to achieve the country's ambitious RE goals.

1.2. Indian Wind Potential Maps – A Recap

The Wind Power development program in India was initiated towards the last year of the Sixth Five Year Plan i.e., in 1983-84. In order to identify wind potential sites in the country, the Government of India launched 'national wind resource assessment program' in 1985. The program was designed for the selection of windy sites, procurement of suitable instruments, design and fabrication of 20m tall masts, their installation at the selected sites and collection & processing of the data. Nodal agency of each state also participated in the implementation of the program. After the establishment of the National Institute of Wind Energy (formerly, C-WET) in Chennai in 1998, the National Wind Resource Assessment Program was transferred to NIWE. Under the program, 50m, 80m, 100m and 120m height masts have been commissioned to collect dedicated wind resource data at multi-levels. As on May 2023, cumulatively 913 stations have been established under the national wind resource assessment program, which resulted in one of the largest wind power specific in-situ data bank in the world. The Ministry has been continuously supporting this programme. The following map depicts wind monitoring stations commissioned in the country till May 2023.

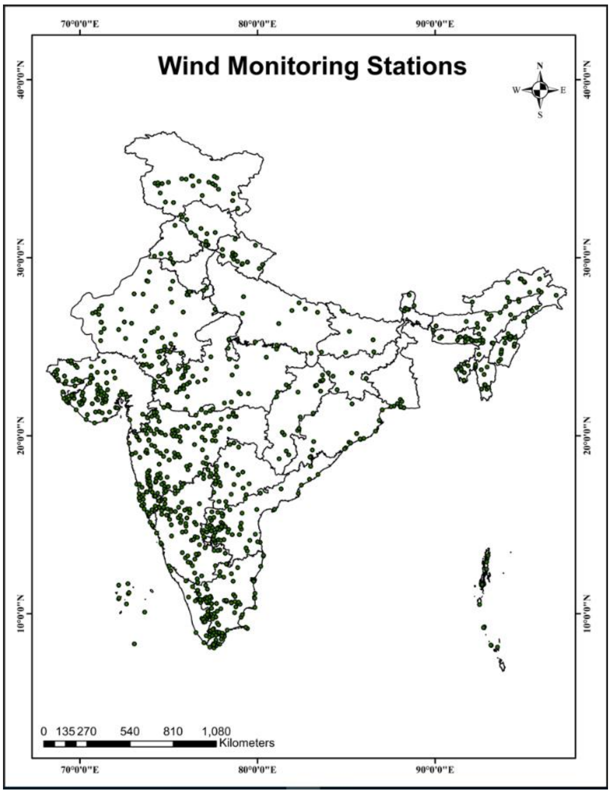


Figure 2: Wind Monitoring Stations in India

As outcome of this program, wind power density maps were also being prepared to indicate the wind potential in the country. In 2005, the wind power potential for 10 states at 50m was estimated. Further, NIWE carried out the potential estimation study at 50m and indicative study at 80m hub heights with 5 km resolution in 2010 in collaboration with RISO-DTU National Laboratory for Sustainable Energy, Roskilde, Denmark using sophisticated meso-scale modelling technique called Karlsruhe Atmospheric Meso-scale Model (KAMM).

In order to estimate the installable potential of the country, the KAMM generated meso-scale wind power density map of 50 m level was integrated with the wind power density map generated with actual measurements and the final wind power density maps were re-plotted using GIS tools. Weightage was given for the topographical features of the area. A uniform 2% land availability was considered for all states except for Himalayan states, North Eastern states and Andaman Nicobar Islands where it was assumed as 0.5%. The installable wind power potential was calculated for each wind power density range by assuming that 9 MW could be installed in each square kilometer area.

The potential in the country at 50m level with these stated assumptions was estimated as 49 GW[2]. Similar exercise carried out for 80m level with the KAMM generated meso scale map gave estimated installable potential as 103 GW[2]. The wind power density maps at 50m and 80m level are given in Figure 3 and Figure 4.

[2] Indian Wind Atlas, 2010 by C-WET, ISBN 978-81-909823-0-6

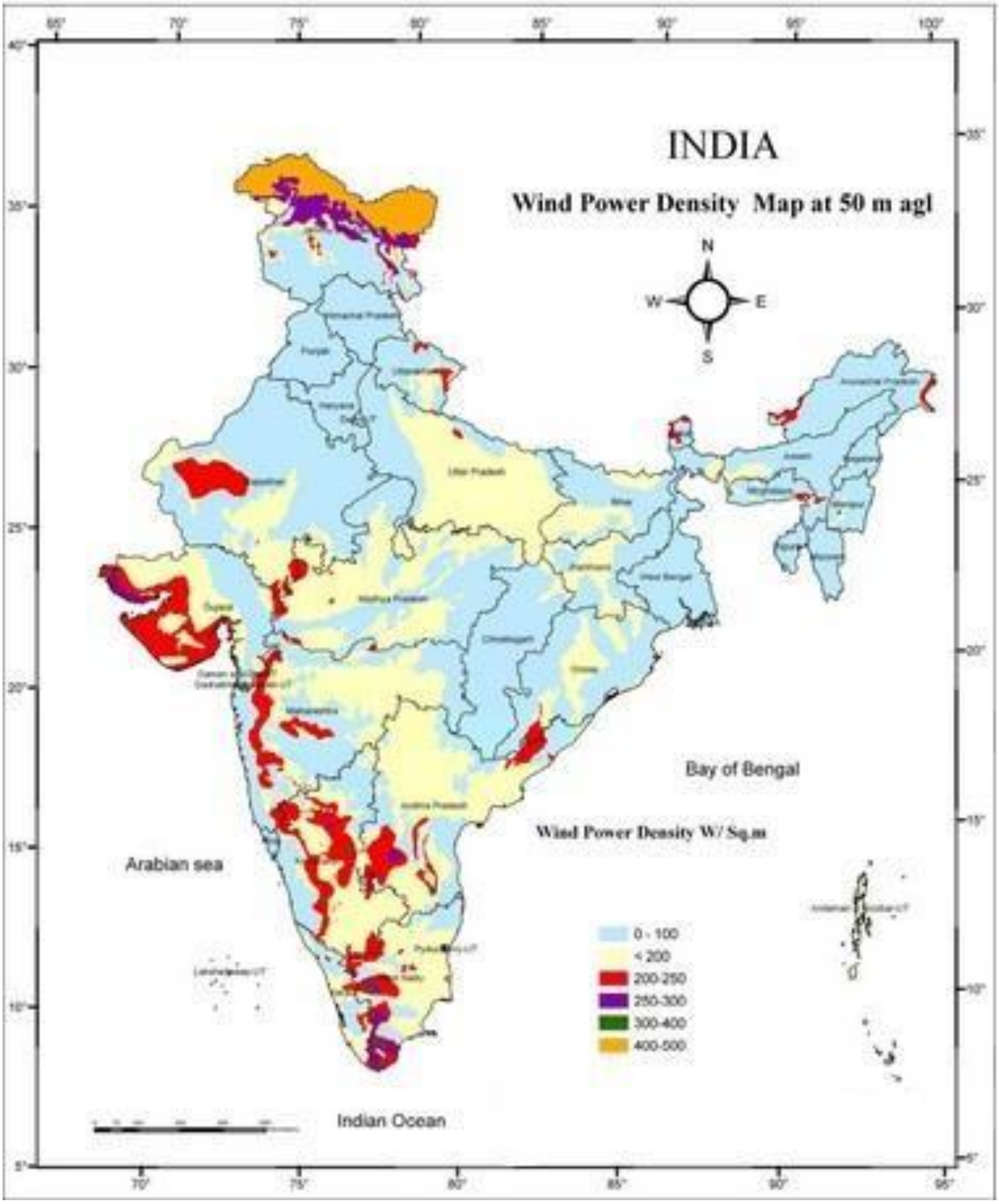


Figure 3: Wind Power Density Map of India at 50m agl

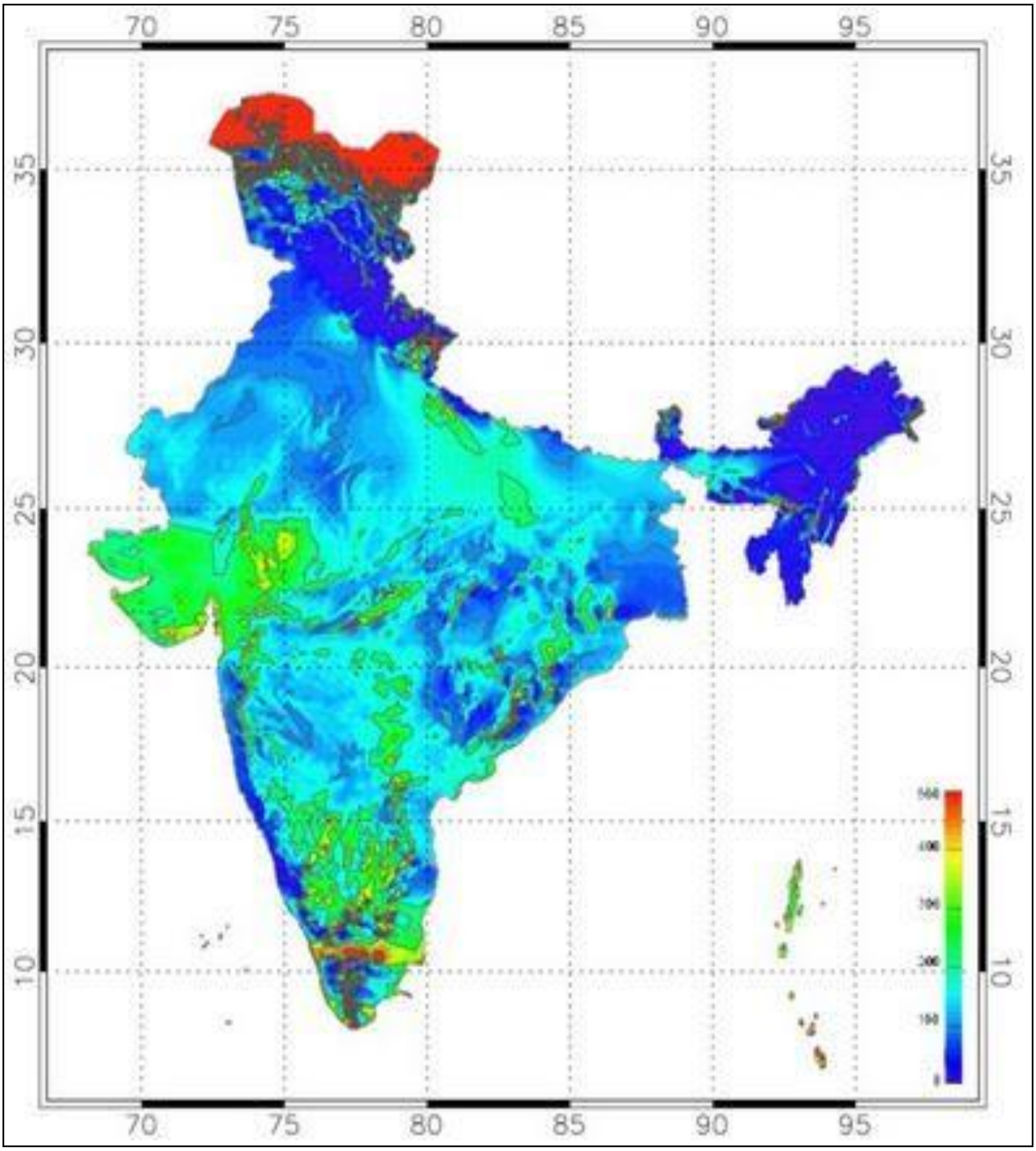


Figure 4: Wind Power Density Map of India at 80m agl

With advancing hub heights, this study was revisited at 100m agl in 2015 and wind power potential at 100m height was estimated as 302 GW[3]. Similar study performed in 2019 shows the indicative installable wind potential of India as 695 GW[4] at 120m agl.

[3] http://niwe.res.in/department_wra_100m%20agl.php

[4] https://niwe.res.in/assets/Docu/India's_Wind_Potential_Atlas_at_120m_agl.pdf

Both 100m and 120m maps were prepared at a higher spatial resolution of 500m (as compared to 5 km earlier), using the advanced meso-micro coupled numerical wind flow model and with the corroboration from actual measurement sites spread all over India. In addition, the study was performed with actual land availability estimation using National Remote Sensing Centre (NRSC) 56m resolution Land Use Land Cover (LULC) Data and with consideration of 6MW and 5MW per sq.km respectively. Land features which are not suitable for wind farming were excluded from the potential map with appropriate buffer / set-off. In addition, other developments such as roads, railways, protected areas, airports, etc., were excluded along with land area with elevation more than 1500m and slope more than 20 degree. The suitable land features were grouped into three categories- Wasteland, Cultivable Land and Forest Land and weightage of 80%, 30% and 5% was assigned respectively to these categories. The 100m wind potential map is shown in Figure 5 and Figure 6 displays the 120m wind potential map.

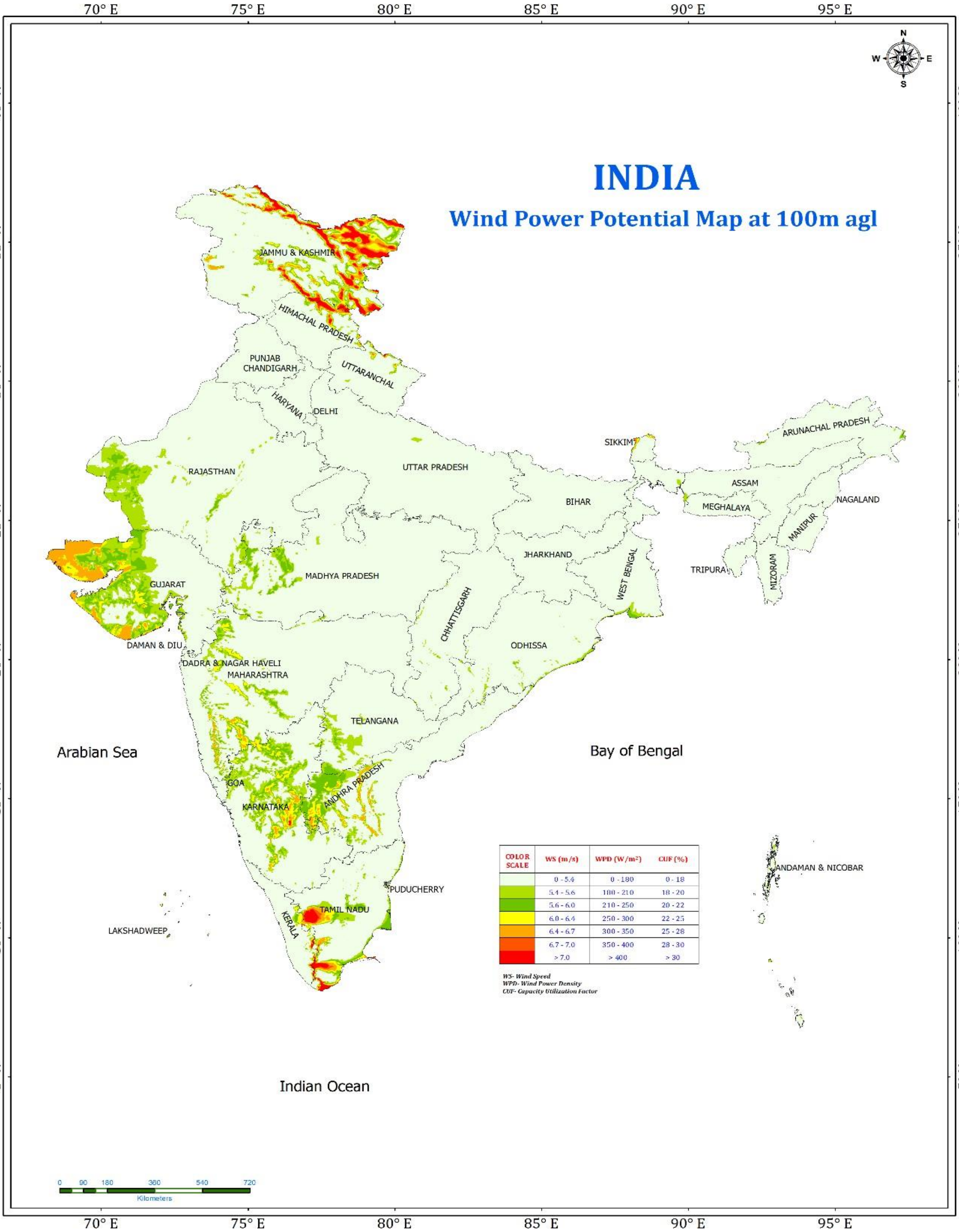


Figure 5: Wind Power Potential Map of India at 100m agl

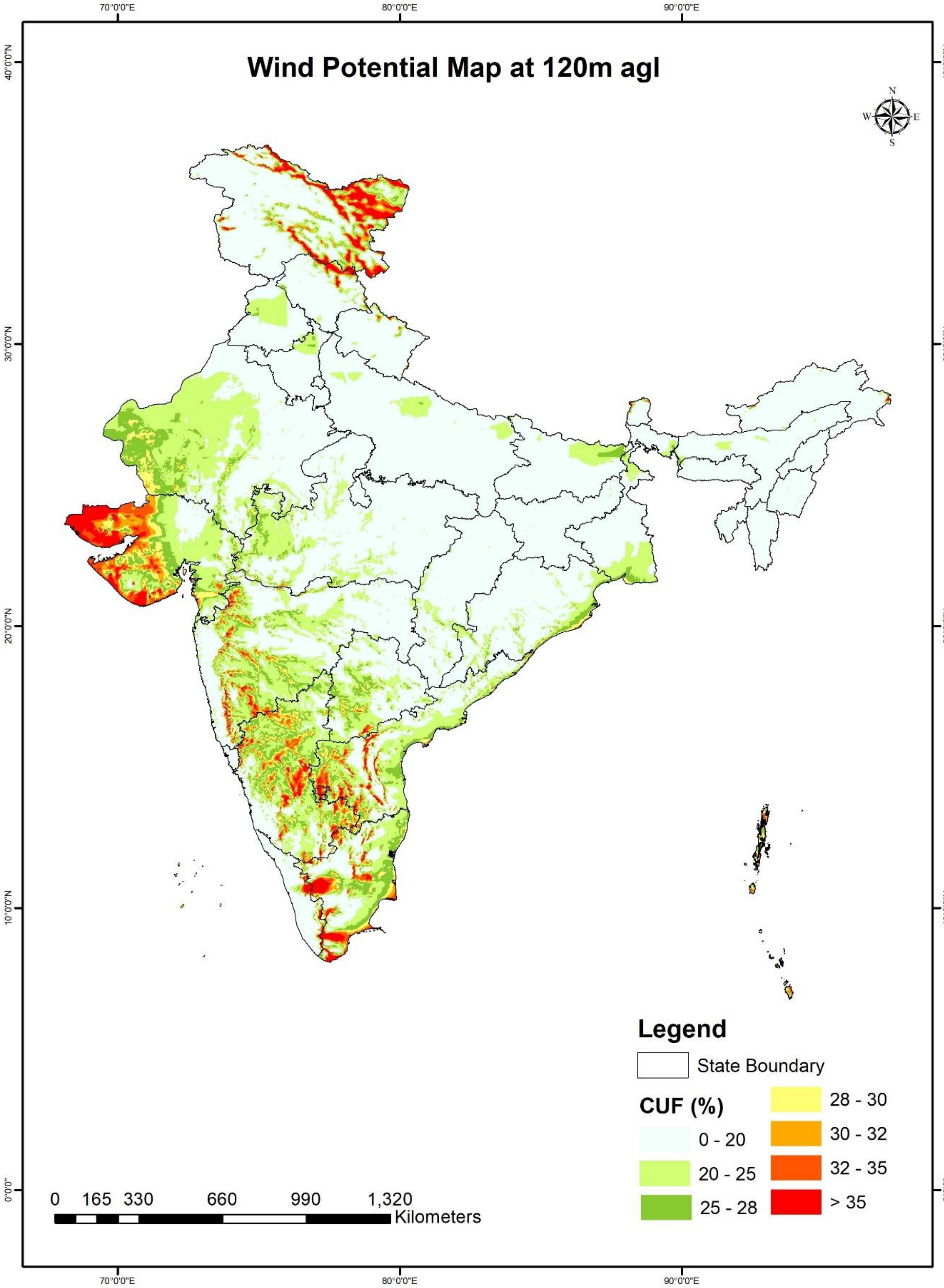


Figure 6: Wind Potential Map of India at 120m agl

The present 150m high wind potential map is prepared to cater to increased hub heights of wind turbines. The map has been prepared on similar lines with the 100m & 120m wind potential maps, incorporating all the advanced mapping techniques. The important features of the Indian Wind Potential Map at 150m agl are as follows:

- The resultant layers are at the resolution of 500m.
- Joint frequency tables have also been derived for the entire country at 500m resolution.
- High-resolution Re-analysis data set has been used for the study – NCEP/CFSR (0.5^0 latitude x 0.5^0 longitude resolution), which enhanced the accuracy of the mapping.
- Dynamic meso-micro coupled WRF modelling technique was used.
- Around 150 met-mast results were utilized for validation.
- Potential arrived through actual land availability using authentic data sources of Land Use Land Cover (LULC) in GIS format.

The methodology of mapping is detailed in the next chapter.

2. METHODOLOGY

The methodology for the preparation of the 150m wind potential map is represented as under. Subsequent sections explain each of these components.

Deriving basic wind parameters

- Generation of Basic Wind Parameter Layers for the country at 500m resolution using dynamic meso - micro coupled multiscale WRF modelling.
- 10 years of NCEP/CFSR (0.5^0 latitude x 0.5^0 longitude resolution) Re-analysis data set is used for initiation of the model.
- Wind Speed, WPD, Weibull A & k, Air Density, Temperature, Joint frequency distribution have been derived.
- Uncertainty estimation.

Processing of data sets

- Processing model output - wind parameter layers.
- Processing of NRSC Land Use Land Cover (LULC) layers.
- National Natural Resources Management System (NNRMS) Layers.
- SRTM (1 arc resolution) DEM is also processed for elevation and slope details

Capacity Utilization Factor (%CUF) map preparation

- Preparing frequency distribution for each 500m grid point using Weibull A & k parameters.
- 2.7 MW Normalized power curve derivation.
- Preparing Capacity Utilization Factor grid layer for the country at 500m resolution using frequency distribution and normalized power curve (air density corrected at each grid point).
- Arriving P50 %CUF value with standard corrections.
- Validation of the resultant GIS layer using available actual measurements.

Area exclusion

- Land features which are not suitable for wind farming has been excluded from the potential map with appropriate buffer / set-off.
- In addition, other developments such as roads, railways, protected areas, airports, etc., are excluded.
- Land area with elevation more than 1500m and slope more than 20 degree are also excluded.

Estimation of installable wind power potential

- Zones with CUF (%) more than 25% are considered for wind potential estimation.
- The suitable land features have been grouped into 3 groups (WA150-WL: Wasteland, WA150-CL: Cultivable Land, WA150-FL: Forest Land) and appropriate weightage has been assumed.
- Installable wind power capacity is estimated by considering 4.5 MW per sq.km in each CUF range with assumption of 5D x 7D micro-siting configuration.

Figure 7: Outline of the Methodology

2.1. Deriving Basic Wind Parameters

Basic wind parameters for the country including its islands has been derived at 150m height with 500m resolution using advanced meso-micro coupled modelling / downscaling techniques. For each 500m grid point the following parameters have been derived.

- Mean Wind Speed (m/s)
- Weibull Shape factor – k
- Weibull Scale factor – A (m/s)
- Mean Wind Power Density (W/m^2)
- Mean Temperature (^{0}C)
- Mean Atmospheric Pressure (KPa)
- Mean Air Density (Kg/m^3)
- Wind Direction
- Joint Frequency Distribution

With long-term wind variation and advancements in assimilation re-analysis data sets into consideration, 10 years of data (2005 – 2014) from high-resolution re-analysis data set, NCEP CFS/CFSR was used to initiate the flow modelling. In the methodology, Weather Research and Forecasting System (WRF) atmospheric model developed by NCAR/NCEP was used. Meso to micro-scale coupling was solved within the modelling chain by seamless simulations of WRF down to 500m resolution.

The Planetary Boundary Layer (PBL) is parameterized by using the Turbulent Kinetic Energy or Mellor Yamada Janic scheme, which makes use of the TKE in order to characterize the turbulent aspects of the wind flow. For the surface layer, NOAH land surface model and Monin Obukov similarity theory options in the WRF model were used. In relation to the characteristics of the modelling domains setup, a large buffer region was used so that any possible issue arising from domain-border numerical problems are cut out of the output for desired accuracy.

2.2. Processing of Data Sets

The study considers various data sets accessed / procured from different sources and were scrutinized to bring them into a common format, so that the processing could be easier and error free.

The wind parameter layers from M/s. Vortex have been validated with actual met-mast measurements towards understanding the uncertainty in the modelling. Land Use Land Cover (LULC) data were obtained from NRSC, Hyderabad which were in raster format, with 19 classifications. For convenience and to maintain a common format, the data set for the whole country was converted into vector format using GIS tools, without any smoothening to reproduce the same 56m resolution data set. Buffer analysis of the land features such as settlements, water bodies was carried out based on the pixel count. After classification, the same was converted into vector layer.

National Natural Resources Management System (NNRMS) data sets were accessed through their online portal with dedicated user-link. The layers were already in vector format and the same were utilized in the study as such. In NNRMS data set, separate Telangana and Andhra Pradesh state boundary was not defined. Similarly Jammu & Kashmir and Ladakh boundary bifurcation was not provided. In both the cases, Survey of India (SoI) political boundary was referred for splitting the map boundary.

In this study, the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model data with 1arcsec (~30m resolution) interval was used for both elevation and slope exclusion. The SRTM pixels with more than 1500m elevation are excluded in the potential area calculation in the study. Similarly, using ArcGIS, the slope values are calculated using SRTM DEM and slopes more than 20 degrees were considered as non-suitable for wind farming and were also excluded in the study.

2.3. Preparation of Wind Power Capacity Utilization Factor (% CUF) Map

The methodology adopted for the derivation of CUF and its mapping is as follows:

- Wind speed frequency distribution at each grid point were calculated by using the wind speed and Weibull shape parameter 'k' for 0 – 25 m/s.
- A normalized 2.7 MW power curve was derived from nine modern wind turbines used in the country with above 2 MW capacity. The normalized machine was corrected for air density (IEC method) at each grid point.
- By utilizing both air density corrected power curve and wind speed distribution, gross CUF was estimated for each grid point.
- Standard correction factors as per practice (95% - Grid availability, 95% - Machine Availability, 3% - Transmission Loss and 10% - Array Loss) was applied to the gross estimates to find out the net values of each grid point at P50 (50% probability of exceedance) confidence level.
- Thematic map for P50 capacity utilization factor (%CUF) was prepared with classifications of less than 25%, 25-30%, 30-32%, 32-35%, 35-38%, 38-40% and greater than 40% ranges.
- As meso-scale models do not reflect the local wind variations perfectly at the complex sites, the model based resultant map was validated with 155 numbers of on-site measurements to understand the map error.

2.4. Area Exclusion

Land features which are not suitable for wind farming were excluded from the potential map with appropriate buffer range.

- NRSC Land Use Land Cover (LULC) data set with Level – II classification (AWiFS – 56m resolution) was utilized for the land suitability analysis in this work.
- In addition, areas covering other land features such as Roads, Railways, Protected Areas, Airports, etc., have been removed (with / without buffers).

- Areas with elevation more than 1500m and slope more than 20 degree have also been removed in the base case studies. The exclusion layers with the appropriate set-off / buffer is shown in Table 1.
- This information was converted into vector layers and excluded from the potential map.

Table 1: Area Exclusion Criteria

S. No.	Land Feature / Development	Function	Range
1	Build Up		
	Build Up - up to 1sq.km	BE	200m
	Build Up - up to 10sq.km	BE	1000m
	Build Up - up to 50sq.km	BE	3000m
	Build Up - up to 100sq.km	BE	5000m
	Build Up - more than 100sq.km	BE	10000m
2	Water Bodies		
	Water Bodies - up to 2sq.km	E	
	Water Bodies - more than 2sq.km	BE	500m
3	Snow Covered	E	
4	Gullied	E	
5	Littoral Swamp	BE	500m
6	Elevation more than 1500m	E	
7	Slope more than 20 degree	E	
8	Golden Quadrilateral Road	BE	500m
9	NH Roads	BE	500m
10	District Roads	BE	200m
11	Rural Roads	BE	2m
12	Railway track	BE	500m
13	Reservoir	BE	500m
14	Rivers	BE	500m
15	Airports	CM	10000m
16	Protected Areas	BE	1000m

BE – Buffered Exclusion, E – Exclusion, CM – Circular Mask

2.5. Potential Estimation

The methodology adopted for the indicative wind potential estimation is as follows:

- Zones only with more than 25% Capacity utilization factor (P50) are considered for wind potential estimation.
- After removing exclusion layers from the potential map, the remaining potential zones are calculated in sq.km.
- Potential area calculation and segregation performed with respect to CUF ranges.
- The suitable land features of NRSC LULC data sets are grouped into three categories as WA150-WL: Wasteland, WA150-CL: Cultivable Land and WA150-FL: Forest Land and the same are detailed in Table 2.
- Appropriate weightage viz., WA150-WL: 80%, WA150-CL: 30%, WA150-FL: 5%, was assumed to estimate the potential.
- Installable wind power capacity is estimated by considering 4.5 MW per sq.km in each CUF range with the assumption of 5D x 7D micro-siting configuration (calculated based on the rotor diameter of the normalized turbine).

Table 2: Grouping of NRSC Land Use Features

WA150-WL: Wasteland	WA150-CL: Cultivable Land	WA150-FL: Forest Land
Grass Land	Kharif	Plantation/Orchard
Other Waste Land	Rabi	Evergreen Forest
Scrub Land	Zaid	Deciduous Forest
Rann	Double/Triple	
	Current Fallow	
	Shifting Cultivation	
	Scrub/Deg. Forest	

3. ATMOSPHERIC MODELLING

High-resolution numerical modelling of weather conditions provides sensitive information of good quality, which is crucial for the development of any wind project and are useful from the early stages of prospecting the wind farm design to long-term adjustments. In particular, the use of meso and micro-scale coupled wind resource products has gained widespread acceptance by the wind industry, offering reliable long term reference data for wind condition characterization and the same has been utilized in this work. Under this study, Meso to micro-scale coupling is solved within the modelling chain by seamless simulations of WRF down to 500m resolution.

The core of the technical modelling approach used for this work is the atmospheric model Weather Research and Forecasting System (WRF) developed by NCAR/NCEP. The WRF-system is a community based, open-source model, where the latest advances in physics and numerics are incorporated in a modular way. The WRF model has been employed largely for research, climate analysis and operational weather forecasting. More information about the modelling core and the methodology to derive the parameters are provided in Annexure 2.

In this project, the model was driven by the latest generation of re-analysis data - NCEP CFS/CFSR, Re-gridded versions of SRTM (no-void) altimetry data and ESA Globcover (300m) land use database. The WRF model was used in order to downscale Reanalysis datasets to the final 500m x 500m resolution. In this downscaling process, several nested domains from coarser to finer resolution grids were used, starting at 27km and ending at 0.5km.

4. DATA SOURCES

Considering importance of the outcome, efforts were made to use most of the data sets from authentic sources. However, some of the on-line / private sources have also been used in this study after validation. The data sources are listed in following table.

Table 3: Data Sources

Sl. No.	Data Set	Source
1	WRF Model Inputs	• NCEP CFS/CFSR[5] • SRTM[6] (Shuttle Radar Topography Mission) three arc-sec • ESA Globcover (300m)[7]
2	Land Use Land Cover Data Set for Land Suitability Estimation	NRSC[8]/ISRO, Hyderabad 56m resolution (AWiFS)
3	Road, Railway lines, Administrative Boundary (except Telangana, Andhra Pradesh, Jammu & Kashmir and Ladakh*), Reservoir, River details	NNRMS[9] (National Natural Resource Management System)
4	Elevation and Slope information	SRTM (Shuttle Radar Topography Mission) one arc-sec
5	Airports	Google Earth / GSR 751(E)[10] / Online Sources
6	Protected Areas	WDPA[11] (World Database on Protected Areas) – Polygons with Google Earth verification

**Survey of India (SoI) political boundary was referred for splitting the administrative map of Andhra Pradesh and Telangana and Jammu & Kashmir and Ladakh.*

[5] https://climatedataguide.ucar.edu/
[6] https://earthexplorer.usgs.gov/
[7] http://due.esrin.esa.int/page_globcover.php
[8] https://www.nrsc.gov.in/
[9] http://www.moef.gov.in/envis/nnrms.html
[10] https://www.civilaviation.gov.in/
[11] https://www.iucn.org/theme/protected-areas/our-work/world-database- protected-areas

4.1. Normalized Power Curve

The normalized power curve for the CUF estimation in this study was derived from nine modern wind turbine power curves. The machines which were chosen are above 2 MW capacity and are having higher hub heights & rotor diameter. The rotor diameter was considered as 131m by averaging the rotor diameters of these nine turbines and hub height of the normalized turbine was assumed as 150m. All these nine numbers of power curves have been normalized into a 2.7 MW power curve. Then the power values against each wind speed has been averaged to obtain the normalized power curve. Figure 8 represents the power curves used in the study after normalization to 2.7 MW. The 2.7 MW normalized power curve used for the analysis is represented in Figure 9.

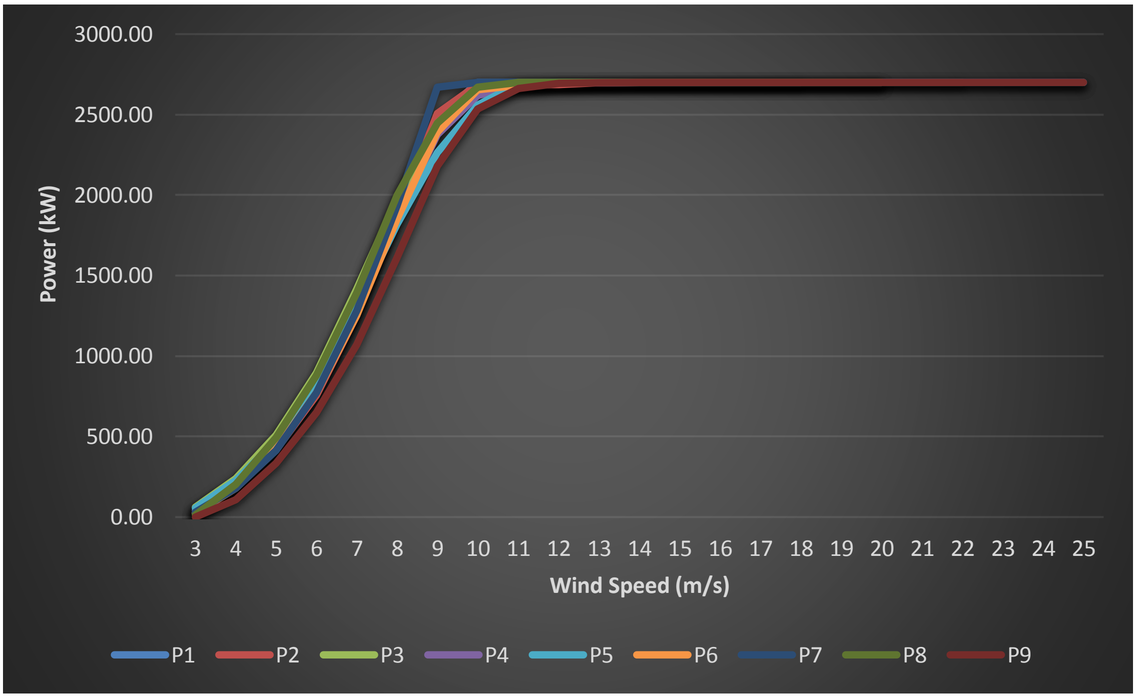


Figure 8: Power Curves considered for the study (normalized to 2.7MW)

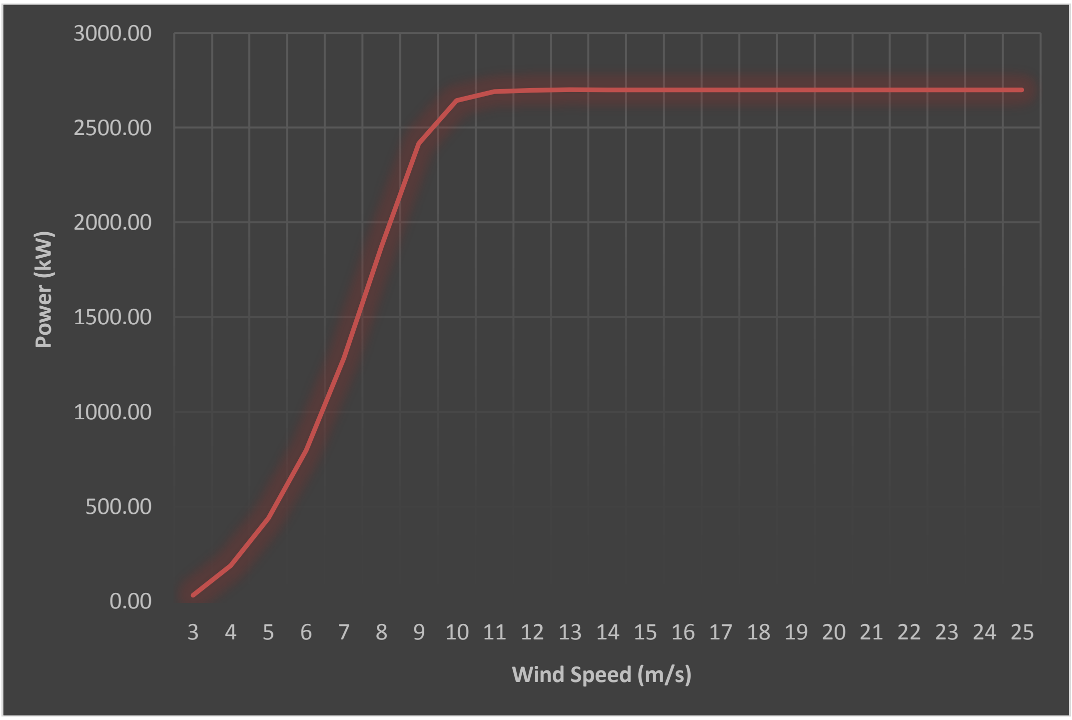


Figure 9: Normalized Power Curve (Average)

5. RESULTS

Based on the above methodology, the state-wise wind power installable capacity has been estimated and the details are shown in Table 4. In order to calculate the installable wind potential, land availability was assumed as under:

- WA150-WL (Wasteland) : 80% potential land is available
- WA150-CL (Cultivable Land) : 30% potential land is available
- WA150-FL (Forest Land) : 5% potential land is available

Table 4 shows the resultant state-wise installable wind potential with respect to the above Land features categorization i.e., WA150-80:30:5.

Table 4: State-wise Installable Wind Potential (> 25% CUF) at 150m (with respect to Land Categorization)

State	WA150-WL (MW)	WA150-CL (MW)	WA150-FL (MW)	Total (WA150-80:30:5) (MW)
Andhra Pradesh	58058	62926	2351	123336
Arunachal Pradesh	187	18	42	246
Assam	345	107	7	459
Bihar	225	3797	0	4023
Chhattisgarh	194	2074	482	2749
Goa*	2	2	10	14
Gujarat	87279	92944	566	180790
Haryana	34	557	3	593
Himachal Pradesh	87	144	7	239
Jammu and Kashmir*	0	0	0	0
Jharkhand*	6	9	1	16
Karnataka	35725	130821	2705	169251
Kerala	552	1649	420	2621
Madhya Pradesh	15804	39476	144	55423

State	WA150-WL (MW)	WA150-CL (MW)	WA150-FL (MW)	Total (WA150-80:30:5) (MW)
Maharashtra	85626	86660	1582	173868
Manipur*	0	0	0	0
Meghalaya*	1	52	2	55
Mizoram*	0	0	0	0
Nagaland*	0	0	0	0
Odisha	3434	8325	370	12129
Punjab	17	412	0	428
Rajasthan	206411	77516	323	284250
Sikkim*	0	0	0	0
Tamil Nadu	28368	65074	1665	95107
Telangana	21584	32386	747	54717
Tripura*	0	0	0	0
Uttar Pradesh	7	502	1	510
Uttarakhand*	31	15	3	49
West Bengal	28	1208	45	1281
A&N Islands	288	330	626	1245
Chandigarh*	0	0	0	0
D&N Haveli*	3	7	7	17
Daman and Diu*	0	0	0	0
Delhi*	0	0	0	0
Ladakh*	1	0	0	1
Lakshadweep#	27	3	1	31
Puducherry	126	272	10	408
Total in MW	**544448**	**607288**	**12120**	**1163856**

** In these states, even though the wind potential is indicated as negligible based on the applied methodology and land suitability analysis, there can be scattered potential pockets available for wind farm development due to the localized wind flows and such pockets can only be identified through in-situ measurements.*

#Estimated based on extrapolation from actual measurements

With the above-mentioned assumptions and defined protocol, the installable wind potential of the country is estimated as 1164 GW at 150m agl (above ground level).

Out of the total estimated 1164 GW potential, 544 GW is possible in wasteland, 607 GW in cultivable land and 12 GW in forest land. As was expected Southern and Western states are majorly contributing to wind potential of the country while other areas with lower wind potential have emerged in other states.

The P50 CUF wind potential map at 150m agl is shown in Figure 10, whereas the technical potential map (after exclusion of unsuitable areas) is shown in Figure 11.

A high resolution map is also given along with this report.

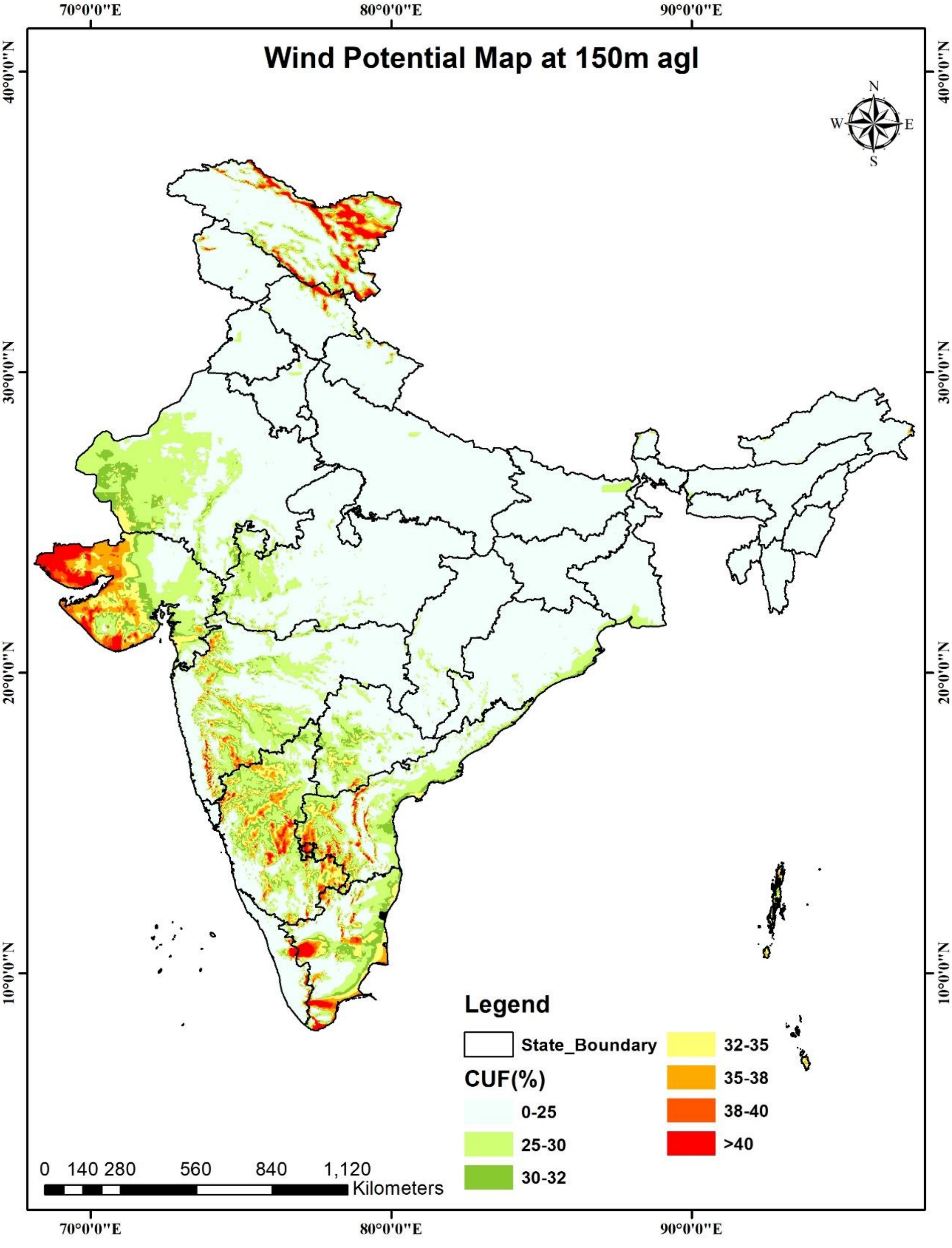


Figure 10: Wind Potential Map of India at 150m agl

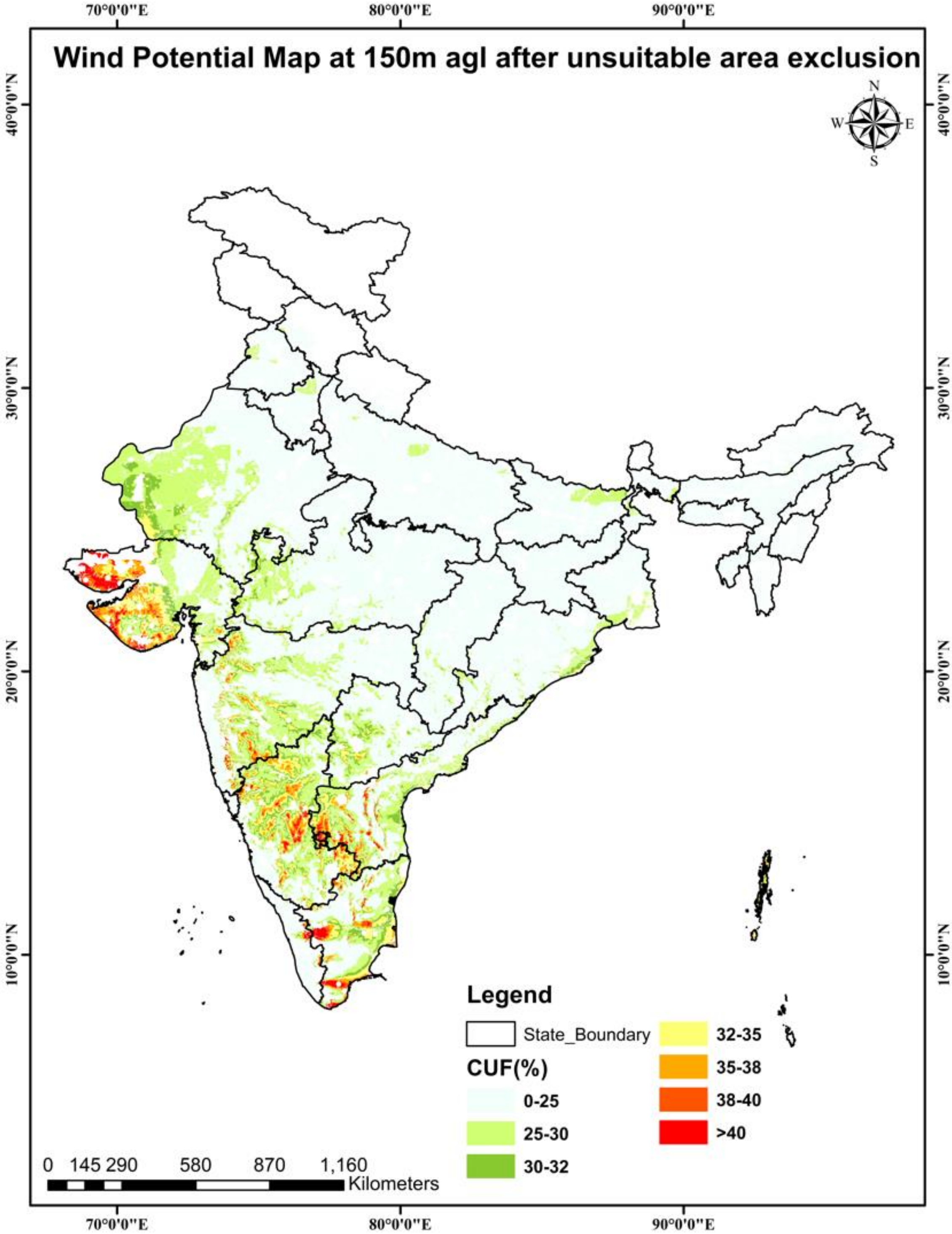


Figure 11: Wind Potential Map of India at 150m agl (after unsuitable area exclusion)

In order to better utilize the wind potential and harness to the maximum extent, state-wise wind potential based on Capacity Utilization Factor (CUF) is tabulated in table below.

Table 5: State-wise Wind Potential based on Capacity Utilization Factor (CUF)

% CUF State	25-30% (MW)	30-32% (MW)	32-35% (MW)	35-38% (MW)	38-40% (MW)	>40% (MW)	Total (MW)
Andhra Pradesh	65409	19143	19184	12297	4670	2632	123336
Arunachal Pradesh	121	57	57	12	0	0	246
Assam	451	7	0	0	0	0	459
Bihar	4023	0	0	0	0	0	4023
Chhattisgarh	2670	79	0	0	0	0	2749
Goa*	9	4	1	0	0	0	14
Gujarat	59392	16800	32275	34629	16589	21104	180790
Haryana	593	0	0	0	0	0	593
Himachal Pradesh	239	0	0	0	0	0	239
J & K*	0	0	0	0	0	0	0
Jharkhand*	16	0	0	0	0	0	16
Karnataka	65638	32200	40194	21696	5686	3836	169251
Kerala	663	247	277	323	144	968	2621
Madhya Pradesh	47861	5452	2016	94	0	0	55423
Maharashtra	104551	25650	25168	14258	3273	968	173868
Manipur*	0	0	0	0	0	0	0
Meghalaya*	55	0	0	0	0	0	55
Mizoram*	0	0	0	0	0	0	0
Nagaland*	0	0	0	0	0	0	0
Odisha	11072	945	112	0	0	0	12129
Punjab	428	0	0	0	0	0	428
Rajasthan	230414	44852	8958	27	0	0	284250

% CUF State	25-30% (MW)	30-32% (MW)	32-35% (MW)	35-38% (MW)	38-40% (MW)	>40% (MW)	Total (MW)
Sikkim*	0	0	0	0	0	0	0
Tamil Nadu	38859	17876	18207	8182	4266	7717	95107
Telangana	38279	10160	5617	609	52	0	54717
Tripura*	0	0	0	0	0	0	0
Uttar Pradesh	510	0	0	0	0	0	510
Uttarakhand*	30	12	6	2	0	0	49
West Bengal	1281	0	0	0	0	0	1281
A & N Islands	229	343	491	167	13	2	1245
Chandigarh*	0	0	0	0	0	0	0
DNH*	17	0	0	0	0	0	17
Daman and Diu*	0	0	0	0	0	0	0
Delhi*	0	0	0	0	0	0	0
Ladakh*	0	0	0	0	0	1	1
Lakshadweep#	7	16	8	0	0	0	31
Puducherry	76	116	57	160	0	0	408
Total in MW	**672893**	**173958**	**152628**	**92455**	**34694**	**37228**	**1163856**

** In these states, even though the wind potential is indicated as negligible based on the applied methodology and land suitability analysis, there can be scattered potential pockets available for wind farm development due to the localized wind flows and such pockets can only be identified through in-situ measurements.*

#Estimated based on extrapolation from actual measurements

It is noted that wind potential to the extent of 164 GW is possible in high potential area with CUF greater than 35%. The high wind potential regions are distributed in the states of Andhra Pradesh, Gujarat, Karnataka, Maharashtra and Tamil Nadu with scattered potential in Kerala, Madhya Pradesh, Telangana and Rajasthan. Pockets of medium wind potential are located in states of Himachal Pradesh, Uttarakhand, Bihar, West Bengal and Odisha. While areas with high wind potential and high CUF can be developed into large wind farms, those with lower CUF could be considered for distributed generation and also for wind solar hybrid for better utilization of the RE resources.

6. VALIDATION

Validation with actual measurements is essential in any model-based mapping. Globally, wind potential maps are being prepared using the numerical downscaling techniques from atmospheric models. In general, the following three inputs are used for downscaling and mapping.

- Assimilated re-analysis data sets – which are gridded data, created through assimilating data collected from different sources at various time scale
- Generalized elevation data
- Generalized land use land cover data

Due to the nature of inputs and methodology of prediction, the results generated using atmospheric models is always interpreted with caution. Due to the accuracy level of inputs and uncertainties in the downscaling techniques, the modeled results may not predict localized wind variations accurately. Although, this issue cannot be fully resolved but the error level of the modeled map can be quantified with the help of actual measurements. In this study, physical measurements from 155 stations were used (after the removal of outliers) to validate the map result. The actual measured data has been corrected for long term variation prior to the validation process. The wind speeds at 150m was arrived at through measurement or derived with the help of power law index, after long term correction. Based on the validation study, the mean absolute percentage error of the map is found to be 5.26%. The correlation coefficient (r) between the measured wind speed and the map value is found to be 0.72. The scatter plot showing the comparison between actual measurements and model wind speeds is shown in figure 12.

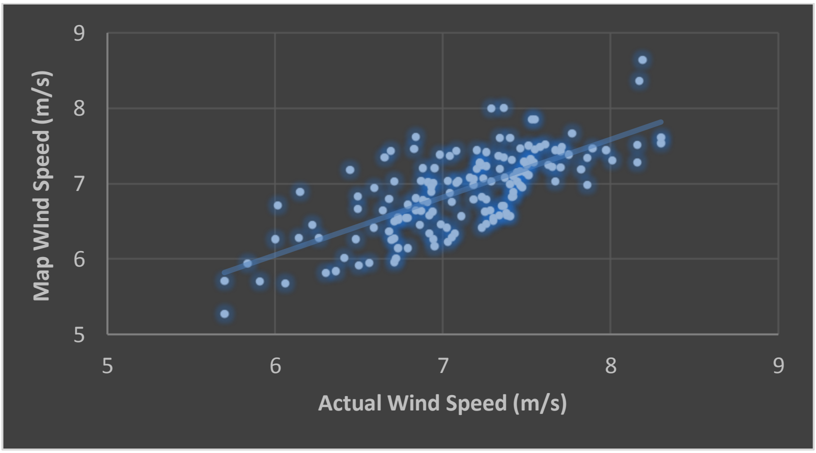


Figure 12: Scatter Plot showing the comparison between Map wind speed and Actual Wind Speed for 155 stations

ANNEXURE 1 - The History of Wind Resource Assessment Programme in India

The Wind Power development programme in India[12] was initiated towards the last year of the Sixth Five Year Plan, in 1983-84. The first grid connected modern wind turbine in the country was commissioned at Veraval, Gujarat in 1985 as a demonstration project by Gujarat Energy Development Agency and JK Synthetics Ltd. The first grid connected wind farm (10 x 55 kW- Vestas wind turbines) in the country was set up at Mullaikkadu near Tuticorin, Tamil Nadu in January 1986 under the demonstration project of Government of India. In the same year, two more wind farms of 550 kW each were established along the coast at Devgad in Maharashtra and Okha in Gujarat. Demonstration projects have helped the private sector in making an easier SWOT analysis. In addition, the Government initiatives and promotional policies have supported and motivated the entrepreneurs to invest in the wind power projects.

In order to identify wind farmable sites in the country, the Government of India launched a national wind resource assessment programme in 1985. India faced a serious problem on information on wind resources of the country while windmills were making a comeback during the late 1970s. In fact, the first attempt of preparing the Indian Wind Map from the wind energy point of view was made by the National Aerospace Laboratories (NAL), Bangalore in 1960s based on the India Meteorological Department (IMD) data. As there was a need for detailed and more accurate data on winds for the wind energy estimation, the Commission for Additional Sources of Energy (Department of Science & Technology), had decided to compile the IMD data and the Field Research Unit, Bangalore of Indian Institute of Tropical Meteorology, Pune (IITM FRU) was engaged to carry out the work. Under the leadership of Ms. Anna Mani, Wind Energy Data for India was prepared and published in 1983. In this volume compilation of surface wind data recorded at 343 observatories and 65 upper wind stations with a detailed analysis of hourly wind speed and wind power at 37 stations of IMD was made. The compiled data was found useful in identifying regions where good wind energy potential was available.

[12] Indian Wind Atlas, 2010 by C-WET, ISBN 978-81-909823-0-6

Based on the data published in Wind Energy Data for India, four demonstration wind farms were established by the Ministry of New and Renewable Energy (MNRE, the then Department / Ministry of Non–Conventional Energy Sources (DNES/MNES)) in 1986 at Tuticorin (Tamil Nadu), Devgad (Maharashtra), Okha (Gujarat) and Puri (Odisha). The performance of the four-demonstration wind farms had indicated that wind data collected at meteorological observatories cannot provide an actual representation of the wind energy potential in the country. Moreover, large wind farms for the generation of power from wind are not expected to be near meteorological observatories. Realizing these facts the Department / Ministry of Non- Conventional Energy Sources (now Ministry of New and Renewable Energy, MNRE) decided to venture a National Wind Resource Assessment programme with dedicated wind monitoring stations to identify windy locations in the country. The task was assigned to the Field Research Unit, Bangalore of Indian Institute of Tropical Meteorology, Pune, (IITM-FRU) in mid 1980s in association with the National Aerospace Laboratories (NAL), Bangalore.

The National Wind Resource Assessment Programme was designed for the selection of windy sites, procurement of suitable instruments, design and fabrication of 20m tall masts, their installation at the selected sites and collection & processing of data. Nodal agency of each state also actively participated in the implementation of the programme. The programme was initially taken up in the states of Tamil Nadu, Maharashtra, Gujarat and Odisha. The surface and upper wind data collected by IMD in conjunction with the study of contour maps of scale 1:50000 published by Survey of India was of immense help in identifying the locations during field visits. The first wind monitoring station of the country was established at Sultanpet in the exit region of Palghat gap, Coimbatore district, Tamil Nadu in 1986. Subsequently the programme was extended to other states like Andhra Pradesh, Rajasthan, Karnataka, Madhya Pradesh, etc. Under the programme, 20m tall tubular guyed masts (tilt-up design) with instrumentation at two levels viz. at 10 and 20m above ground levels were commissioned at carefully chosen locations. All types of terrain viz-inland plains, coastal plains, smooth or rugged hills / ridge tops, mountain tops, valleys, foothills, deserts, plateaus, islands, etc. were considered. Based on the data collected under the exclusive wind-monitoring programme, potential locations were identified even in the interior parts of the country. As the wind monitoring is a continuous programme since 1985, the programme is extended to almost all the states, union territories of India including islands. Commissioning and closure of wind monitoring stations has been a continuous process under the national programme. The FRU of IITM Bangalore had collected wind data from 448 stations in various states and Union Territories. After the establishment of the National Institute of Wind Energy (formerly, C-WET) in Chennai, the National Wind Resource Assessment Programme has been transferred to NIWE and the activities of FRU-IITM was terminated. Since 2001, the National Wind Resource Assessment Programme is being executed by NIWE on behalf of MNRE. Over the period, the height of wind turbines have seen upward trend and thus it was also necessary to increase the height of wind monitoring masts to measure the wind close to the hub height. Hence, in order to fulfill the industry need, NIWE started to install taller masts. Initially the wind monitoring was carried out only in known windy areas. Now it is extended to any area, which is not covered in earlier projects to complete the Indian Wind Power Mapping.

Under the programme 50m, 80m, 100m and 120m height masts have been commissioned to collect dedicated wind resource data at multi-level. The basic data that are being collected is 10 minutes (averaged), the industry standard, based on 2 seconds samples of wind speed and direction data at multi-level. The data collected under the programme is being used widely to establish wind farms in the country and most of the wind farms established in the country till now is based on the reference data collected under this National Programme of wind resource assessment directly or indirectly.

All the states and the major union territories are covered under this programme. More stations are being added every year so that more uncovered areas in all the states are studied scientifically. The data collected also serves as data bank for the preparation of national wind potential maps and other research purposes. Under the programme, cumulatively 913 stations have been established as on May 2023. The Ministry is continuing this project through NIWE in association with State Nodal Agencies.

As a part of the programme, in order to provide the authentic knowledge of the wind energy availability in a region of interest to the stakeholders, the Ministry decided to publish the data in a book form. Nine volumes of Wind Energy data books, which provide extensive information of the sites where actual wind measurements carried out, have been published so far. The first volume of Wind Energy Resource Survey in India was published in 1990 and the latest one in this series is the Wind Energy Resource Survey in India Volume IX in 2017. M/s. Allied Publishers, New Delhi brought out the first four volumes, during the period 1990 to 1996 and the volumes V to IX were directly published by IITM-FRU / NIWE (formerly, C-WET) respectively in 1998, 2001, 2005, 2012 and in 2017. The continuous and reliable data availability for one or more year from a given station was the main consideration for the inclusion of the monitoring stations in these volumes.

As a part of outcome of this study, wind power density maps have been prepared based on the measurements and meso-scale models. In 2005, the wind power potential for 10 states at 50m has been estimated with relevant assumptions. From the discrete values of WPD at individual locations, the wind power potential over an extended area of land have been estimated. In the year 2010, Indian wind atlas was prepared with a combined effort from RISO-DTU, Denmark using sophisticated meso-scale modelling technique called Karlsruhe Atmospheric Meso-scale Model (KAMM). Subsequently, in 2015 and 2019 the Indian Wind potential map at 100m agl and 120m agl were prepared respectively.

ANNEXURE 2 - Numerical Modelling

The core of the technical modelling approach for this work is the atmospheric model Weather Research and Forecasting System (WRF) developed by NCAR/NCEP. The WRF-system is a community-based, open-source model, where the latest advances in physics and numerics are incorporated in a modular way. It represents a cutting-edge modelling technology as well as optimized dynamic and physical cores. It includes a nest domain, allowing zooming atmospheric circulation down to near wind-farm resolution.

The effort to develop WRF has been a collaborative partnership, principally involving the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the National Centers for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). WRF allows researchers to conduct simulations reflecting either real data or idealized configurations. WRF provides operational forecasting a model that is flexible and efficient computationally, while unlocking the advances in physics, numeric and data assimilation contributed by the research community.

WRF model has a long record on usage and it is employed operational in many weather services, cutting-edge research activities and different industry applications. WRF development has engaged a wide community of users, which meant large peer- review validations analysis, and upgrading of advances in the different components of the weather & climate modelling science.

WRF model is now the first generation of multi-scale chain modelling that can seamlessly go from regional to wind farm scales. Regarding, micro-scale backed, WRF incorporates innovation planetary boundary layer sub model (PBL) that can handle effectively turbulence and flow adjustments due to high-resolution orographic effects. Moreover, WRF is a unique solution to provide dynamic representation of wind flow at wind farm resolution including mechanical and thermal turbulence.

WRF model includes a set of sub-models to treat dynamically and physically flow regime at very high resolution. These modules employ non-linear representations of different topography induced mechanisms.

Experience acquired from the studies of Vortex in more than 24,000 simulations completed with thousands of them checked against measurements has proven that the WRF model at a 500m resolution produces a realistic representation of flow circulation induced by high-resolution topography effects such as valleys, sea-land transition, hills, etc. By preserving the continuity of the WRF modelling chain, a more consistent site- specific assessment of wind energy parameters can be obtained, minimizing the impact of any artificial interpolation or adequation between different atmospheric scales.

Model Run

Under this study, the model has been driven by large-scale conditions prescribed by the latest generation of re-analysis projects for the satellite period: NCEP CFS/CFSR. Further, the re-gridded versions of SRTM (no-void) altimetry data were employed to prescribe altimetry conditions. The ESA Globcover (300m) land use database was employed to characterize land-use classes. Seasonal variation data from ESA Globcover will be included to better prescribe albedo effects during winter periods. WRF (Weather & Research Forecast) model is used in order to downscale Reanalysis datasets to the final 500m x 500m resolution through nested domains. Nesting is performed at 27km, 3km, 1km and 500m, each resolution adequate for different scales and characteristic phenomena included in the WRF model. Thus, the WRF model provides output variables at each of the 500m x 500m grid points and therefore no interpolation methods are applied for generating the results. Each of the grid points is directly written to the final files avoiding any error or truncation issues deriving from interpolation techniques. In relation to the complex terrain treatment, no different code is applied. The WRF model is capable of modelling the wind at different resolutions and each of the scales is treated accordingly with the Navier-Stokes equations and the corresponding PBL & Surface Layer schemes parameterizations available in the model, which are widely accepted by the wind industry community. The modelling flow chart is shown in Figure A.1.

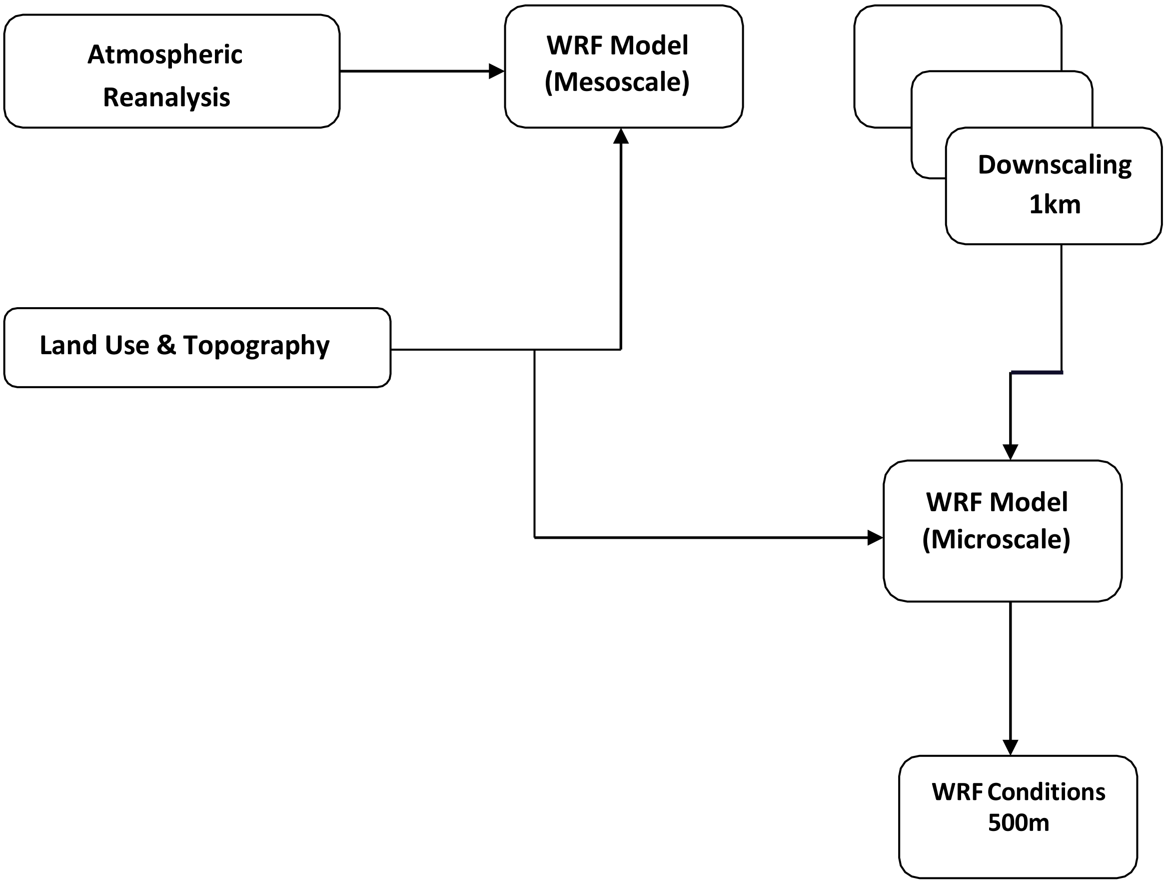


Figure A.1 Atmospheric Modelling Flow Chart

Methodology to derive Main Variables

The WRF model provides Wind Speed, Temperature & Pressure among other variables at each of the 500m x 500m grid points and any height between ground level and the troposphere. This allows us to estimate the wind power density by making use of the wind speed and density on an hourly basis - a general gas law for air is used for deriving density values from pressure & temperature.

Joint frequency distribution is obtained by binning the wind speed in 1m/s bins from 0 to 1, 1 to 2 and so on, and binning the wind direction in 30 degrees sectors north centered, that is from -15 to 15, 15 to 45 and so on. The joint frequency distribution can be presented in percentage or number of hours per year. Weibull Parameters are computed by using the WAsP assumption, which emphasizes the most energetic part of the histogram in the Weibull fitting.

Uncertainty of the results is estimated by running some different configurations of WRF model that is different turbulent schemes and slightly different initial conditions, which perturb the model and give an indication on how sensitive the studied region is to some changes in the model. The generated results by the different configurations are then post processed and mixed up in order to have an idea of how wide / uncertain the wind distribution.

ANNEXURE 3 - Data Sources

Macro-scale meteorological inputs come from the latest NCEP version of reanalysis: Climate Forecast System Reanalysis (CFSR) that was completed over the 31- year period of 1979 to 2009 in January 2010. The CFSR was designed and executed as a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system to provide the best estimate of the state of these coupled domains over this period. The current CFSR will be extended as an operational, real time product into the future. The CFSR relative to most, if not all, previous reanalysis include coupling of atmosphere and ocean during the generation of the 6 hour guess field, an interactive sea-ice model, and assimilation of satellite radiances by the Grid-point Statistical Interpolation scheme over the entire period. The CFSR global atmosphere resolution is ~38km (T382) with 64 levels extending from the surface to 0.26hPa. The global ocean is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels to a depth of 4737m. The global land surface model has 4 soil levels and the global sea ice model has 3 levels. With these variable parameters, the analyzed state will include estimates of changes in the Earth system climate. All available conventional and satellite observations were included in the CFSR. Satellite observations were used in radiance form and were bias corrected with "spin up" runs at full resolution, taking into account variable CO_2 concentrations. This procedure enabled smooth transition of the climate record due to evolutionary changes in the satellite observing system. CFSR atmospheric, oceanic and land surface output products are available at an hourly time resolution and 0.5° horizontal resolution. This reanalysis will serve many purposes, including, providing the basis for most of NCEP Climate Prediction Center's operational climate products by defining the mean states of the atmosphere, ocean, land surface and sea ice over the next 30-year climate normal (1981- 2010); provide initial conditions for historical forecasts required to calibrate operational NCEP climate forecasts and provide estimates and diagnoses of the earth's climate state, over the satellite data period, for community climate research. Preliminary analysis of the CFSR output indicates a product far superior in most respects to the reanalysis of the mid-1990s. The previous NCEP reanalysis have been one of the most used NCEP products in history, there is every reason to believe the CFSR will supersede these older products both in scope and quality, because it is higher in time and space resolution, covers the atmosphere, ocean, sea ice and land, and was executed in a coupled mode with more modern assimilation system and forecast model.

SRTM (Shuttle Radar Topography Mission)

Topography data comes from the Shuttle Radar Topography Mission (SRTM), which obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. The Shuttle Radar Topography Mission (SRTM) was flown aboard the space shuttle Endeavour February 11-22, 2000. The National Aeronautics and Space Administration (NASA) and the National Geospatial- Intelligence Agency (NGA) participated in an international project to acquire radar data, which were used to create the first near-global set of land elevations. The radars used during the SRTM mission were actually developed and flown on two Endeavour missions in 1994. The C-band Space borne Imaging Radar and the X-Band Synthetic Aperture Radar (X-SAR) hardware were used on board the space shuttle in April and October 1994 to gather data about Earth's environment. The technology was modified for the SRTM mission to collect interferometric radar, which compared two radar images or signals taken at slightly different angles. This mission used single-pass interferometer, which acquired two signals at the same time by using two different radar antennas. An antenna located on board the space shuttle collected one data set and the other data set was collected by an antenna located at the end of a 60-meter mast that extended from the shuttle. Differences between the two signals allowed for the calculation of surface elevation.

Endeavour orbited Earth 16 times each day during the 11-day mission, completing 176 orbits. SRTM successfully collected radar data over 80% of the Earth's land surface between 60° north and 56° south latitude with data points posted every 1 arc-second (approximately 30 meters).

SRTM Non-Void Filled elevation data (used for WRF modelling) were processed from raw C-band radar signals spaced at intervals of 1 arc-second (approximately 30 meters) at NASA's Jet Propulsion Laboratory (JPL). This version was then edited or finished by the NGA to delineate and flatten water bodies, better define coastlines, remove spikes and wells, and fill small voids. Data for regions outside the United States were sampled at 3 arc-seconds (approximately 90 meters) using a cubic convolution re-sampling technique for open distribution.

SRTM 1 Arc-Second Global elevation data (used for Elevation & Slope suitability analysis in the study) offer worldwide coverage of void filled data at a resolution of 1 arc-second (30 meters) and provide open distribution of this high-resolution global data set.

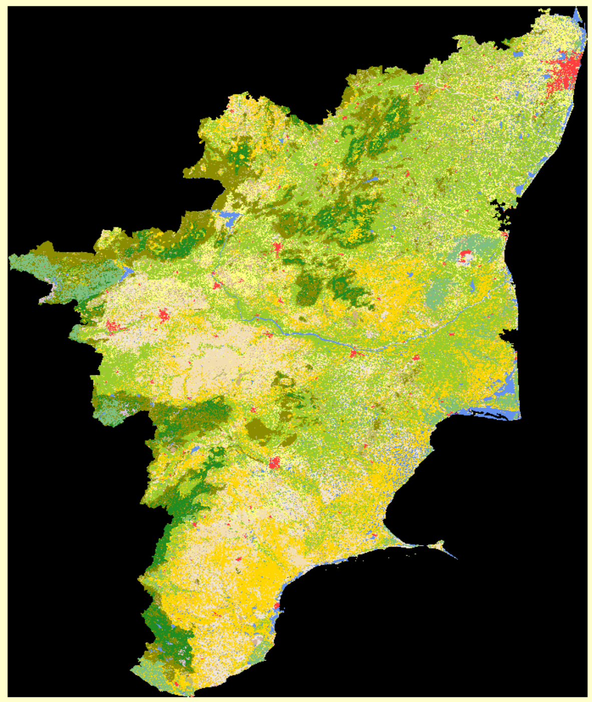
ESA Globcover

Land cover data for the WRF model comes from ESA GlobCover Land Cover I product derived by an automatic and regionally tuned classification of a time series of MERIS FR mosaics. Its 22 land cover global classes are defined with the UN Land Cover Classification System (LCCS). Each mosaic product is available in the Hierarchical Data Format-EOS2 (HDF) and is organized on a 5° by 5° tiling without any overlap. 2592 tiles (72 horizontal tiles x 36 vertical tiles) therefore cover the entire Earth. Only tiles including land cover are processed, which reduces the number of available tiles. The GlobCover products are based on ENVISAT's Medium Resolution Imaging Spectrometer (MERIS) Level I B data acquired in Full Resolution mode with a spatial resolution of 300 meters. For the generation of the Level I B data, the raw data acquisitions have been re- sampled on a path-oriented grid, with pixel values having been calibrated to match the Top of Atmosphere (TOA), radiance.

Land Use Land Cover Data (LULC) – NRSC

National Remote Sensing Centre (NRSC) provides ortho-rectified, multi temporal land use land cover data for the entire country at different scale levels. In this project, land use land cover (LULC) data at 1:250K scale with 56m resolution obtained from NRSC/ISRO, Hyderabad has been utilized for land use identification and exclusion. The data set covers the period of July 2012 to May 2013. NRSC 'Level II' classification would be appropriate to segregate different LULC classes. There are 19 classes available in NRSC Level – II classification. The sample pictorial representation of the same for Tamil Nadu is shown in Figure A.2.

Value	Description	Color	Red,Green,Blue
1	Build up		255,64,64
2	Kharif only		255,255,128
3	Rabi only		255,214,0
4	Zaid only		189,143,143
5	Double / triple		153,204,43
6	Current fallow		242,222,176
7	Plantation/orchard		128,191,128
8	Evergreen forest		33,140,33
9	Deciduous forest		140,140,0
10	Scrub/Deg. forest		189,184,107
11	Littoral swamp		89,10,163
12	Grassland		214,191,214
13	Other wasteland		237,230,222
14	Gullied		128,64,64
15	Scrubland		209,176,140
16	Water bodies		99,145,237
17	Snow covered		214,191,214
18	Shifting Cultivation		237,120,64
19	Rann		230,230,247



Source: NRSC, Hyderabad

Figure A.2 RSC LULC (Land Use Land Cover) Sample for Tamil Nadu

National Natural Resources Management System (NNRMS)

The National Natural Resources Management System (NNRMS), a national level inter-agency system, set-up in 1983 and chaired by the Member, Planning Commission, Govt. of India. The National Natural Resources Management System (NNRMS) supports the national requirements of natural resources management and developmental needs by generating a proper and systematic inventory of natural resources. In doing so, NNRMS adopts various advanced technologies of satellite and aerial remote sensing; Geographical Information Systems (GIS); precise Positioning Systems; database and networking infrastructure and advanced ground-based survey techniques. NNRMS standards have been adopted to enable technologies – imaging, GIS, GPS and applications – thematic mapping, services, etc. to work together. Over the past twenty years, the National Natural Resources Management System (NNRMS) has steered the generation of spatial information using remote sensing data from various IRS missions. Through a wide variety of user driven projects, a rich base of map information for the country has been generated. An important element of the NNRMS is the task of encapsulating the entire spatial data into a Natural Resources Repository (NRR) and making it accessible to citizens, society, private enterprise and government.

To bring a systematization and "automation" in the process of mapping and GIS, ISRO had spearheaded and prepared the National (Natural) Resource Information System (NRIS) standards in 1998. Accordingly, the NRIS standards have become the de facto GIS standards for database creation and organization in the country. The spatial layers of the NRR are stored in a geo database. This database is referred to as Natural Resources Database (NRDB). The NRDB contents adhere to a naming convention and category coding as specified in the NNRMS standards document. From NRDB the following layers (Table A.1) have been extracted and utilized for this study.

Table A.1 NNRMS Layers used for the Study

S.no.	Layer Name	Code	Coordinate System
1	State Boundary	nrdb_3226	WGS84
2	Reservoir	nrdb_3232	
3	River	nrdb_3233	
4	Golden Quadrel Road	nrdb_3235	
5	National Highway	nrdb_3236	
6	Railway	nrdb_3238	
7	District Roads	nrdb_3241	
8	Rural Roads	nrdb_3242	

World Database on Protected Areas (WDPA)

The World Database on Protected Areas (WDPA) is the most comprehensive global spatial dataset on marine and terrestrial protected areas available. Protected areas are internationally recognized as major tools in conserving species and ecosystems. The WDPA is a joint project of UNEP and IUCN, produced by UNEP-WCMC and the IUCN World Commission on Protected Areas working with governments and collaborating NGOs.

Since 1981 UNEP-WCMC, through its Protected Areas Programme, has been compiling this information and making it available to the global community. The overall goal for the World Database on Protected Areas is to provide the most comprehensive and authoritative global dataset on national parks and protected areas that answers key questions about sustainable development informing decision makers and policy makers. Mandate for the assessment The WDPA includes the "UN List of Protected Areas" mandated by the UN Economic and Social Council (res. 713 XXVII 1959) to be compiled from officially delegated national authorities on protected areas. In addition to the UN List mandate, the WDPA is specifically mentioned in many decisions and recommendations of the CBD and IUCN, and serves to fulfill an even longer list of mandates on protected areas, ecosystem services and biodiversity protection as the recognized authoritative source of comprehensive information on the global protected areas network. WDPA contains the data in both point and polygon formats. In this study, protected zones, which are drawn as polygons (so that the boundary of the protected area could be properly represented) have been considered for area corrections, with intense validation with Google Earth.

Airport Details

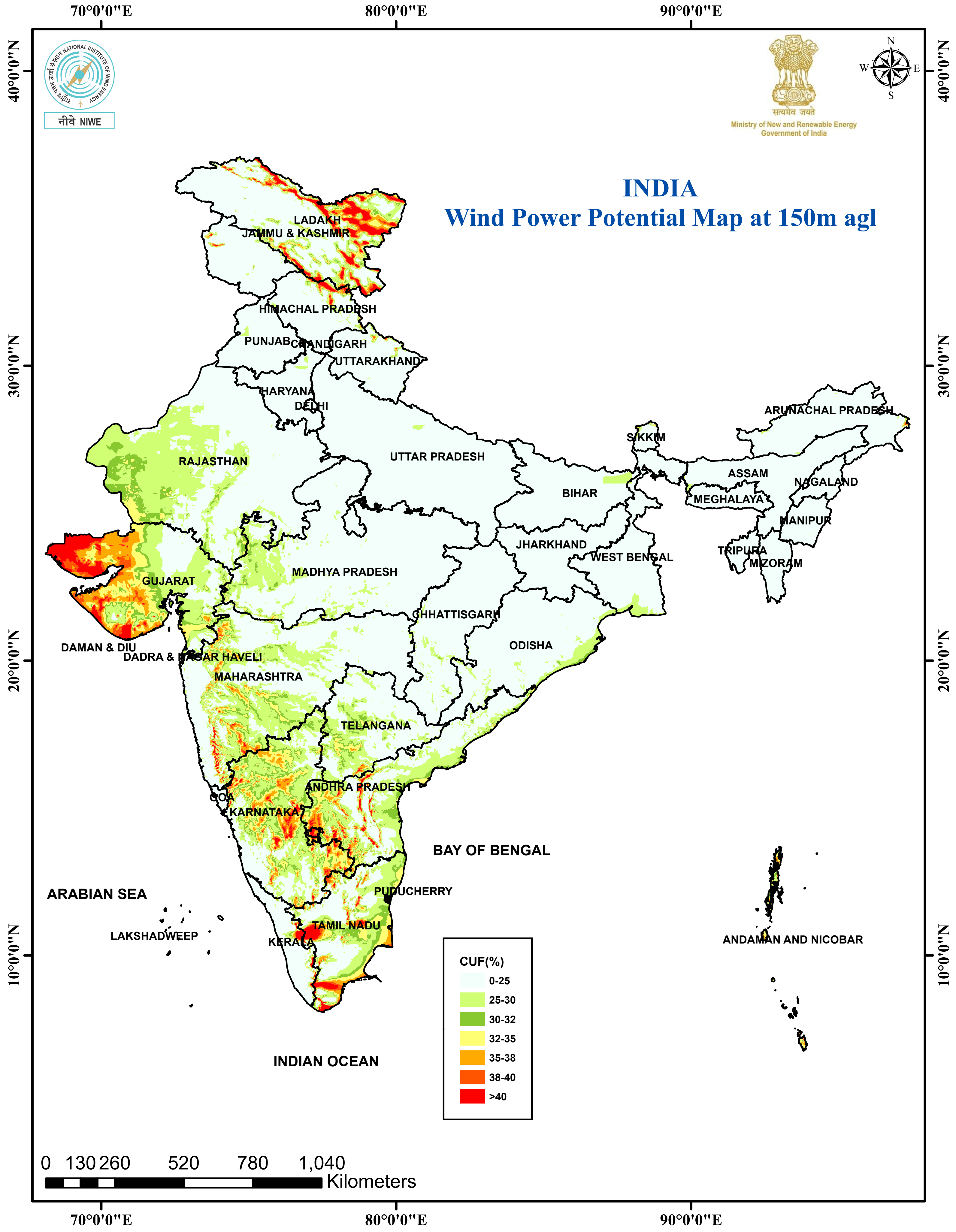
Airport details have been obtained from the MINISTRY OF CIVIL AVIATION NOTIFICATION G.S.R. 751(E). Further Airport / Helipad location details have been verified through Google Earth Pro software and with the online data sources. In addition, intense on-line review has also been performed to identify / assure the airport locations, including defense airports, under construction airports, etc. All the airport locations have been given circular buffer of 10km and the buffered zone was later removed from the wind potential map. Helipad locations are not considered for exclusion in this analysis.

SYMBOLS AND ABBREVIATIONS

Symbol	Details
D	Rotor Diameter
GW	Gigawatt
MW	Megawatt

Acronym	Details
AFWA	Air Force Weather Agency
agl	above ground level
amsl	above mean sea level
AWiFS	Advanced Wide Field Sensor
BF	Brown Field
CFSR	Climate Forecast System Reanalysis
CUF	Capacity Utilization Factor
C-WET	Centre for Wind Energy Technology
DTU	Technical University of Denmark
FAA	Federal Aviation Administration
FSL	Forecast Systems Laboratory
GF	Green Field
GIS	Geographic Information System
GPS	Global Positioning System
HDF	Hierarchical Data Format
IITM-FRU	Indian Institute of Tropical Meteorology- Field Research Unit
IMD	India Meteorological Department
ISRO	Indian Space Research Organisation
IUCN	International Union for Conservation of Nature
JPL	Jet Propulsion Laboratory
LCCS	Land Cover Classification System
LULC	Land Use Land Cover

Acronym	Details
MNRE	Ministry of New and Renewable Energy
NAL	National Aerospace Laboratories
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDC	Nationally Determined Contribution
NGA	National Geospatial-Intelligence Agency
NGO	Non-governmental Organization
NIWE	National Institute of Wind Energy
NM	Nautical Mile
NNRMS	National Natural Resources Management System
NOAA	National Oceanic and Atmospheric Administration
NRDB	Natural Resources Database
NRIS	National (Natural) Resource Information System
NRSC	National Remote Sensing Centre
PBL	Planetary Boundary Layer
RE	Renewable Energy
SOI	Survey of India
SRTM	Shuttle Radar Topography Mission
SWOT	Strengths, Weaknesses, Opportunities and Threats
UNEP	United Nations Environment Programme
WAsP	Wind Atlas Analysis and Application Programme
UNEP-WCMC	UN Environment World Conservation Monitoring Centre
WDPA	World Database on Protected Areas
WRF	Weather Research and Forecasting System
X-SAR	X-Band Synthetic Aperture Radar


70°0'0"E
80°0'0"E
90°0'0"E
40°0'0"N
30°0'0"N
20°0'0"N
10°0'0"N
नीवे NIWE
NATIONAL INSTITUTE OF WIND ENERGY
सत्यमेव जयते
Ministry of New and Renewable Energy
Government of India
N
W
E
S
INDIA
Wind Power Potential Map at 150m agl
LADAKH
JAMMU & KASHMIR
HIMACHAL PRADESH
PUNJAB
CHANDIGARH
UTTARAKHAND
HARYANA
DELHI
ARUNACHAL PRADESH
SIKKIM
RAJASTHAN
UTTAR PRADESH
ASSAM
NAGALAND
BIHAR
MEGHALAYA
MANIPUR
JHARKHAND
TRIPURA
WEST BENGAL
MIZORAM
MADHYA PRADESH
GUJARAT
CHHATTISGARH
ODISHA
DAMAN & DIU
DADRA & NAGAR HAVELI
MAHARASHTRA
TELANGANA
ANDHRA PRADESH
GOA
KARNATAKA
BAY OF BENGAL
ARABIAN SEA
PUDUCHERRY
TAMIL NADU
LAKSHADWEEP
KERALA
ANDAMAN AND NICOBAR
INDIAN OCEAN
CUF(%)
0-25
25-30
30-32
32-35
35-38
38-40
>40
0 130 260 520 780 1,040
Kilometers

ABOUT NIWE

National Institute of Wind Energy formerly Centre for Wind Energy Technology shortly known as NIWE is an autonomous R&D institution established in 1998 at Chennai by the Ministry of New and Renewable Energy (MNRE), Government of India. It is a premier institution with highly experienced professionals having expertise in all related disciplines of wind energy sector. NIWE is a forward looking and practical institution always well placed to take the next logical steps towards advancing wind technology in the right direction. With its progressive approach to all wind energy related science and technology from onshore to offshore, NIWE assures assistance from resource assessment (both wind and solar, RE forecasting for Energy production) to project implementation. As an integral part of NIWE, a world class accredited services providing Wind Turbine Test Station (WTTS) is established at Kayathar, Tamil Nadu. Perhaps, NIWE is the only Testing and Certifying agency in the country.

NIWE has been vested with the responsibility to provide complete scientific and technical backing to all stakeholders in the field of wind energy and has stated its commitment through its quality policy.

QUALITY POLICY

NIWE is committed to achieve customer satisfaction, loyalty and confidence by providing credible, prompt and complete solutions of international quality to all the stakeholders in the wind energy sector.

NIWE, strives to be technical focal point of excellence for the present and future. NIWE shall stay at the forefront of Wind Turbine Technology application by continuously improving its expertise.

नीवे NIWE

NATIONAL INSTITUTE OF WIND ENERGY

An Autonomous Research and Development Institution
Ministry of New and Renewable Energy, Government of India
Velachery – Tambaram Main Road, Pallikaranai, Chennai – 600 100, Tamil Nadu, India
Phone: +91-44-2246 3982, +91-44-2246 3983, +91-44-2246 3984 Fax: +91-44-2246 3980
E-mail: info@niwe.res.in Web: http://niwe.res.in