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Reassessing Wind Potential Estimates for India: Economic and Policy Implications

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Reassessing Wind Potential Estimates for India: Economic and Policy Implications

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Abstract

We assess the techno-economic on-shore wind potential in India at three hub-heights – 80m, 100m, and 120m. Assuming a turbine density of 9 MW/km^2, the total wind potential in India with a minimum capacity factor of 20 percent ranges from 2,006 GW at 80m hub-height to 3,121 GW at 120m hub-height. This techno-economic potential excludes the potential on lands that are difficult to use for wind power development such as low quality wind areas (wind power density < 200 W/m^2), areas with slopes greater than 20 degrees, areas with elevation greater than 1,500m, forests, snow-covered areas, water bodies, urban areas, and protected areas. These estimates are approximately 20 times the current official estimate of wind energy potential in India (estimated at 80m hub height). The total land footprint of developing 543 GW of this wind potential (with capacity factor > 25% at 80m) is likely to be approximately, 1,629 km^2 *or 0.05% of the total land area in India since, typically, only 3% of the land required for wind power development is its footprint on the ground and the rest of the land can be used for other purposes.*

Executive Summary

Motivation

Wind potential estimates in India need to be reassessed for three reasons. First, two recent studies – one conducted by experts from Harvard University and the Technical Research Center of Finland (published in the Proceedings of the National Academy of Sciences) and the other by experts from The Energy Resources Institute (India) – estimate on-shore wind potential in India to be >1,000 GW (estimated at hub-heights >= 80m).[1] In sharp contrast, the official wind energy potential estimate (by the Center for Wind Energy Technologies (CWET), India) used by the Indian government in its policy-making process is only 103 GW (estimated at a hub height of 80m).[2] Second, recent reassessments conducted in various countries such as the U.S. and China have found much higher wind energy potential due to better technology in the form of higher efficiency, hub heights, and sizes of wind turbines. The official wind potential estimates (expressed in capacity terms) used by China have recently increased by 800% and those of the U.S. by 50% (see Figure ES 1). Wind potential estimates for the US expressed in terms of energy have increased almost 400%. Third, systematic analysis based on Geographic Information System (GIS) data provides an accurate way to identify land with wind power development potential. The potential estimate by CWET presented in the 2010 Indian Wind Atlas, arbitrarily, assumes that just two percent of the windy land is available for wind energy development. All three reasons taken together suggest that a transparent and systematic reassessment of the wind resource in India could also reveal a substantially higher potential than previously estimated and could potentially have major implications of Indian power sector policy.

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[1] Hossain J, et al., 2011. A GIS based Assessment of Potential for Wind Farms in India, Renewable Energy (2011), doi:10.1016/j.renene.2011.04.017 and Xi Lu et al. (2010). Global Potential for Wind Generated Electricity. Proceedings of the National Academy of Sciences, April.

[2] Center for Wind Energy Technology and Riso DTU National Laboratory for Technology, 2010. Indian Wind Atlas, Chennai, India. (URL: http://www.cwet.tn.nic.in/html/departments_ewpp.html; Accessed on 24 February 2012)

Methodology

In this study, wind energy potential for turbines at 80m, 100m, and 120m hub-heights was estimated at varying levels of capacity utilization factors. The hub-height of the most commonly sold wind turbines today is 80m.[3] In general, the trend is toward steadily increasing hub-heights, with most major wind turbine manufacturers now offering turbines with hub-heights >100m and some as high as 150m.

Annual average wind power density (WPD) and wind speed data at an elevation of 80m, 100m, and 120m for each 5 km by 5 km cell in India was procured from 3Tier.[4] Publicly available GIS data on topography and land use and cover (LULC) was used to exclude areas where development of wind facilities would be technically and economically unviable. The excluded sites included low quality wind areas (WPD < 200 W/m^2), areas with slopes greater than 20 degrees, elevation greater than 1,500m, forests, snow-covered areas, water bodies, urban areas, and protected areas.

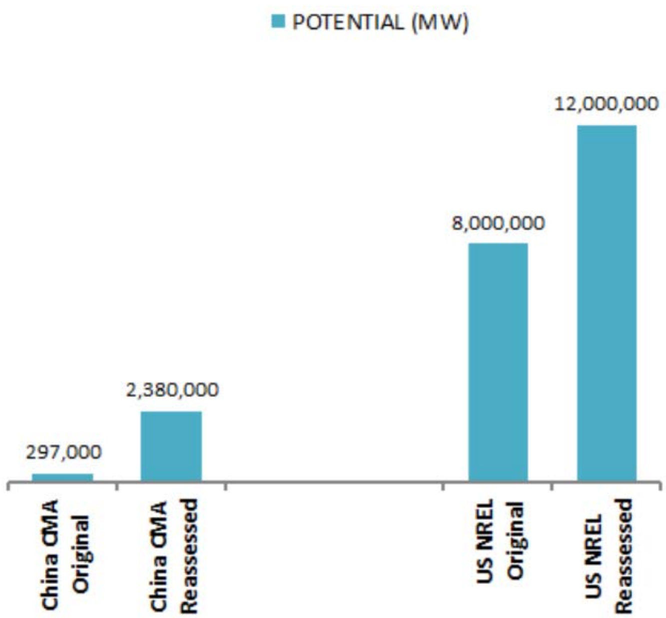

Figure ES 1. Results of Wind Potential Reassessments in US and China

Source

US Original: Described in Black & Veatch, "20 Percent Wind Energy Penetration in the United States: A Technical Analysis of the Energy Resource." Retrieved 7 August, 2011 from: http://www.20percentwind.org/Black_Veatch_20_Percent_Report.pdf. US reassessed -described in Elliott et al., 2010. *New Wind Maps and Resource Potential Estimates for the United States*. Retrieved from: http://www.nrel.gov/docs/fy11osti/50439.pdf.

China original and reassessed based on studies by China Meteorological Association (CMA) described in Li Junfeng et al., 2010 China Wind Power Outlook, October 2010, downloaded on 27/06/2011 from http://www.gwec.net/fileadmin/documents/test2/wind%20report0919.pdf

As observed in locations around the world, land can be used simultaneously for wind energy production and for agriculture (for example, farming, cattle-raising, etc.). Hence, wind energy

[3] Out of the 35 wind turbine models certified by CWET, as of June 2011, almost half have a hub-height of at least 80m.

[4] http://www.3tier.com/en/package_detail/wind-speed-gis-data-layer/

potential estimates are transparently presented by LULC type without applying any subjective criteria for development.

Key Findings

Assuming a turbine density of 9 MW/km^2, Figure ES 2 shows the techno-economically viable on-shore wind potential at three different hub-heights. The total wind potential in India with a minimum capacity factor of 20 percent ranges from 2,006 GW at 80m hub-height to 3,121 GW at 120m hub-height.

More than 95 percent of the wind energy potential is concentrated in just five states in southern and western India – Tamil Nadu, Andhra Pradesh, Karnataka, Maharashtra, and Gujarat. The state with the overall largest resource is Karnataka while the state with largest best-quality resource is Tamil Nadu. From a cost-effective perspective, the full development of best-quality wind resources in Tamil Nadu – which already leads all states in installed wind capacity – would yield a capacity of 65 GW at 80m hub-height and a minimum capacity factor of 32%. This is more than four times the total installed wind capacity in India.

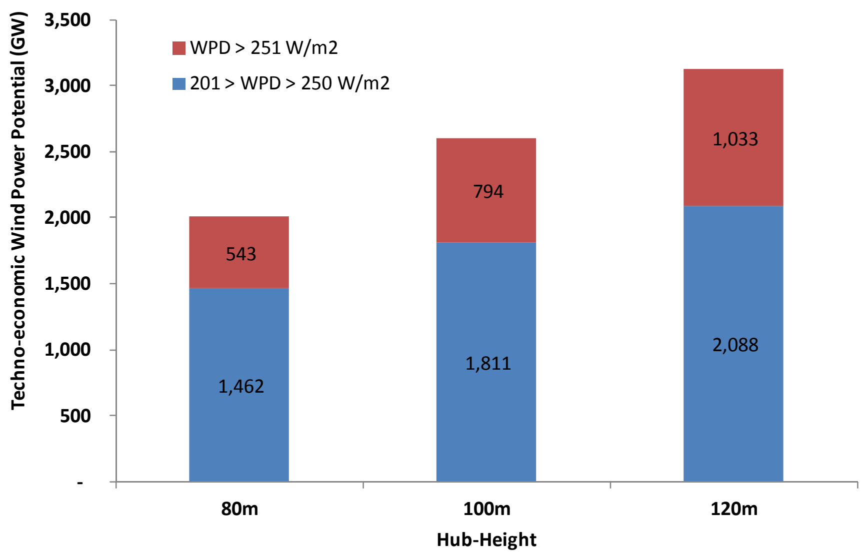

Figure ES 2. On-Shore Developable Wind Potential in India

It is unlikely that all of the wind potential identified will be developed. The land requirement for developing 543 GW (with WPD > 250 W/m^2 and CF > 25%) will be about 60,362 km^2 (based on a turbine density of 9 MW/km^2), about 2% of the total land area of India. Out of this land requirement, only a small percentage (typically about 3%) is disturbed permanently, primarily due to towers and roads, and the rest of the land can be used for other purposes. For example, based on the study of 93 wind farms totaling 13,897 MW in the US, Denholm, P. et al. (2009) found that the permanently impacted land due to wind power development is about 0.3 Hectare/MW. Hence, the actual land footprint of developing 543 GW of wind power is likely to be approximately 1,629 km^2, about 40 km by 40 km area, or 0.05% of the total land area of India.

Using the norms specified by the Central Electricity Regulatory Commission (CERC), Figure ES 3 shows the estimated wind potential at various levels of levelized tariffs. Based on CERC norms, approximately 200 GW of wind potential is available at a levelized tariff of Rs. 4.5/kWh or less and about 100 GW is available at Rs 4.0/kWh or less at all three hub-heights.

It is necessary to note that the estimates presented here regarding yields and the extent of land most suitable for wind power development in India are not detailed enough to determine sites for an actual wind generation facility or predict its exact output. These estimates are, however, appropriate for use in high-level policy-making; estimates based on methodologies similar to the one used here serve as the basis for policy development and long-term power sector planning purposes in the U.S., China, and the European Union.

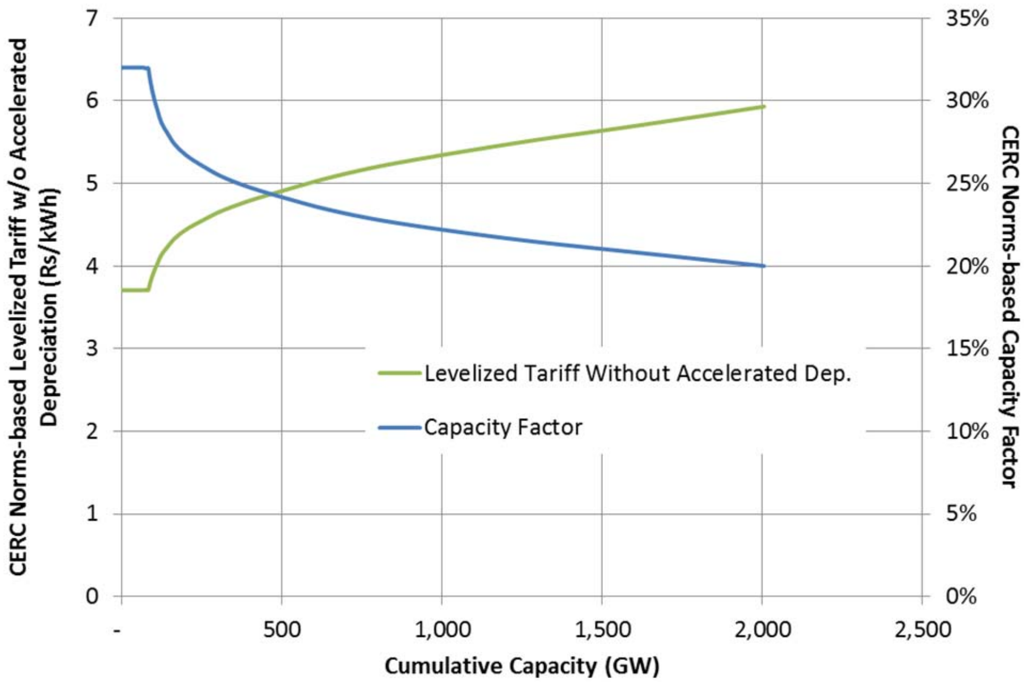

Figure ES 3. Available Wind Potential at Different Levelized Tariffs

Note: As per CERC norms, we assume that techno-economic wind-potential on sites with WPD > 400 W/m^2 would yield a capacity factor of 32% when it could be substantially higher. The levelized tariff associated with this capacity factor is Rs.3.71/kWh.

Implications and Future Work

Our findings suggest that the availability of a developable wind resource is not a constraint for wind to play a major role in India's electricity future. This is in sharp contrast with the earlier official estimate of the potential, which, if fully exploited would have provided only about eight percent of electricity demand (in energy terms) in 2022. The technical feasibility of integrating large quantities of wind energy needs to be assessed systematically. However, experience from operation of existing power systems in such places as Denmark and Germany and several studies, have indicated the techno-economic feasibility of such integration (Milligan et al., 2009 and Wiser et al., 2011). Given effective planning, policies, and programs, wind energy can be a core component of India's affordable, reliable, and clean energy portfolio.

1 Background and Motivation

Electricity demand in India is expected to grow rapidly from 813 GWh in 2007-08 to 2,104 GWh in 2020 for a GDP growth rate scenario of 8% per year (Planning Commission, Government of India (GOI), 2011).[5] Current planning efforts call for the majority of this demand to be met by thermal power plants (i.e. coal and nuclear).

Historically, electricity demand has consistently outpaced electricity supply, leading to severe electricity shortages. Actual supply capacity additions have been consistently lower than the targets set by the government (Sathaye et al., 2010). As per the 11th five-year plan, approximately, 80 GW of new coal capacity was expected to come online by 2012; to date only 50 GW of that capacity has been constructed. Further, progress was slow in providing fuel for much of the coal capacity that was installed in 2010-11, suggesting that the capacity factors may be significantly lower than expected.

Clean energy options, such as renewable energy (RE) and energy efficiency (EE), meet not only the environmental and energy security objectives, but also can play a crucial role in reducing the chronic power shortages. Both RE and EE can be deployed far more rapidly than conventional large-scale thermal power plants.

Wind energy is one of the cheapest forms of RE available, which partially explains why it accounts for the largest portion of RE installed capacity in the world, with 16,078 MW installed in India and 238,000 MW installed worldwide by the end of 2011.[6] Wind energy costs in India are, typically, substantially lower than that of solar and are comparable to those of imported coal –based, nuclear, natural gas-based plants. Consequently, wind is a very promising additional option to meet electricity shortages, especially in the short to medium term.[7]

The official estimate of wind energy potential in India by the Center for Wind Energy Technologies (CWET) is 103 GW at a hub height of 80m (CWET, 2012) which is equivalent to only 8% of electricity needs (in energy terms) in 2022. Based on these potential estimates, most studies on India's energy future have predicted only a limited role for wind energy (See for example, Sargsyan, G. et al. (2010) (ESMAP report), McKinsey (2008), and Planning Commission (2011)).

In contrast, two recent studies have indicated a much higher wind energy potential in India. Xi Lu et al. (2010) and Jami Hossain et al. (2011) find that on-shore developable wind energy potential (>20% capacity factor) in India is about 1,300 GW and 2,076 GW, respectively, estimated at hub heights of greater than or equal to 80m, the typical height of new wind turbines. These results are intriguing, but the studies' parameters limit their usefulness to Indian policy makers.

In Table 1, the country-specific wind potential estimated by Xi Lu et al. is shown. Note that Xi Lu et al. (2010) focused on global wind energy potential, so their assessment does not take into account some details important to India, including the geographic distribution of the wind energy potential within India and variations in the quality of its wind resource.

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[5] These estimates reflect electricity demand at the bus bar, which is equivalent to electricity generation requirements.

[6] Source: Indian Wind Turbine Manufacturers Association -http://www.indianwindpower.com/. Global Wind Energy Council - http://www.gwec.net/index.php?id=30&no_cache=1&tx_ttnews[tt_news]=340&tx_ttnews[backPid]=97&cHash=cd58c26fe1

[7] Based on the cost and operating norms specified by the Central Electricity Regulatory Commission (CERC) and discussed in detail in section 3.

Table 1. Country-Specific Wind Potential

Country	On Shore (GW)	Off Shore (GW)	On Shore (TWh)	Off Shore (TWh)
Russia	54,794	10,502	120,000	23,000
Canada	35,616	9,589	78,000	21,000
U.S.	33,789	6,392	74,000	14,000
China	17,808	2,100	39,000	4,600
U.K.	2,009	2,831	4,400	6,200
Germany	1,461	429	3,200	940
India	1,324	502	2,900	1,100
Japan	260	1,232	570	2,700
S. Korea	59,	452	130	990
Italy	114	73	250	160

The assessment by Hossain et al. (2011) focuses on India and analyzes the distribution of the quality of the wind resource. Key areas which need further work, some of which have been identified by the authors include:

- They do not exclude certain key areas which are typically excluded from wind energy potential estimates because of practical difficulties, such as land on which the slope is greater than 20 degrees and elevation greater than 1,500m. As a result, their estimate of wind potential is likely to be far greater than what could be achievable.
- They estimate wind power potential at a hub height of 80m whereas wind turbines with hub heights of 100m are becoming increasingly common and wind turbines with hub heights of 120m are commercially available. An assessment of wind power potential at these heights will lead to a higher potential estimate than that at 80m.
- They do not estimate the cost of wind power for the estimated potential in order to compare it with other competing conventional and non-conventional options.

This wind potential study attempts to address the limitations of the previous studies discussed above.

Countries such as the U.S. and China have recently reassessed their wind energy potential and have found much higher potential. The estimate in China by China Meteorological Association (CMA) and in the U.S. by the National Renewable Energy Laboratory (NREL) increased about 800% and 400% respectively, as shown in Figure 1. A systematic reassessment of two main aspects of wind energy production, considered by Xi Lu et al. (2010) and Hossain et al. (2011), might suggest that India’s wind energy potential is higher than currently believed. Those aspects are 1) the rapidly improving wind turbine technology that allows better extraction of energy from wind and 2) the amount of available land suitable for wind farms.

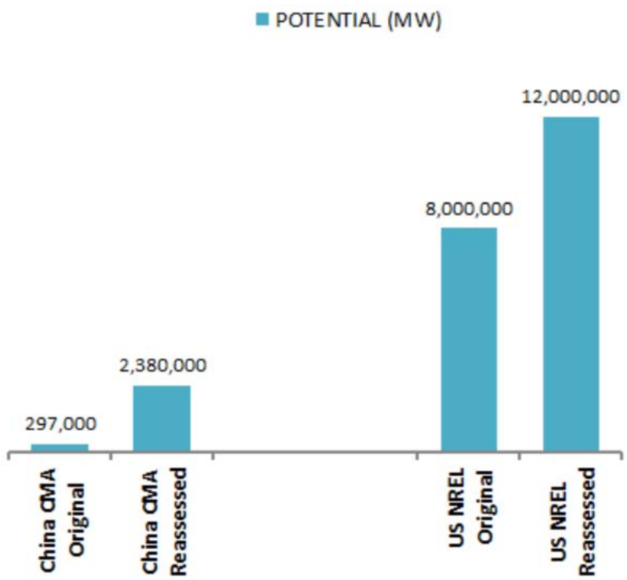

Figure 1. Results of Wind Potential Reassessments in US and China

US 0riginal: Described in Black & Veatch, "20 Percent Wind Energy Penetration in the United States: A Technical Analysis of the Energy Resource." Retrieved 7 August, 2011 from: http://www.20percentwind.org/Black_Veatch_20_Percent_Report.pdf. US reassessed -described in Elliott et al., 2010. *New Wind Maps and Resource Potential Estimates for the United States*. Retrieved from: http://www.nrel.gov/docs/fy11osti/50439.pdf.

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From a technology perspective, the average nameplate capacity of wind turbines deployed in the world has been growing steadily over the last decade. For example, Wiser and Bollinger (2010) find that the average capacity of installed turbines in the U.S., which was about 0.8 MW in 2000, more than doubled to about 1.74 MW by 2009. Various state-of-the-art installations in the U.S., EU, and China consist of turbines with capacities greater than 3 MW and as high as 7 MW.[8] Ongoing research in EU suggests that greater than 10 MW capacity wind turbines are feasible.

In addition to the capacity of the wind turbine, the average hub-height and rotor diameter of wind turbines has been growing steadily.[9] Wiser and Bollinger (2010) report that the average hub-height and rotor diameter in the U.S. increased from about 60m in 2000 to about 80m in 2009. Better project planning and development have also led to steadily growing sizes of wind-farms and higher capacity factors. For example, Wiser and Bollinger (2010) find the average capacity factors in the U.S. have grown from about 25% to 30% over the last decade.

It is critical to systematically identify the ways high quality wind sites (e.g. with wind power density > 200 W/m^2) are being currently used and whether they are suitable for wind-farm development. The 2010 Indian Wind Atlas states : "On a conservative consideration, a fraction

[8] See, for example http://cordis.europa.eu/fetch?CALLER=FP7_PROJ_EN&ACTION=D&DOC=20&CAT=PROJ&QUERY=012309cd0ba0:677b:3e409c80&RCN=90994

[9] Higher hub-height allows wind turbines to exploit better quality wind resources at higher altitudes and larger rotor diameters allows wind turbines to sweep substantially larger areas thereby generating more energy.

of 2% land availability for all states except Himalayan states, Northeastern states and Andaman and Nicobar islands has been assumed for installable potential estimation. In Himalayan states, Northeastern states and Andaman and Nicobar islands, it is assumed to be 0.5%. However, the potential will change as per the real land availability in each state." In contrast, this study uses a GIS-based approach for excluding land that is not suitable for wind farm such as low quality wind areas (wind power density < 200 W/m^2), areas with slopes greater than 20 degrees, areas with elevation greater than 1,500m, forests, snow-covered areas, water bodies, urban areas, and protected areas.

In this study, we estimate the developable wind energy potential in India taking into account both new efficient wind technology and several constraints, including land availability, terrain, and the quality of wind power. We assess the geographic distribution of the wind power within India as well as the distribution of wind energy potential in terms of the quality of the resource. We estimate the cost of wind energy and compare it with other supply-side options.

It is important to note that this assessment of wind potential is a high-level assessment and does not identify investment-grade locations for siting actual wind farms. Nor are the energy generation estimates developed in this assessment actual forecasts of energy production for existing wind farms. For investment-grade decisions, it is necessary to make actual measurement of wind data for a sustained period, supplemented with on-the-ground verification of relevant land features.

In Section 2 we describe the data and methodologies used in this study for estimating wind energy potential and compare it to the ones used by previous studies. In Section 3 we present our findings of the wind energy potential. In Section 3 we also present results related to the geographic distribution of this potential and the cost of developing this potential. In Section 4 we summarize our findings and discuss their implications for clean energy development in India.

2 Methodology

In this section we describe the key data sources used in this analysis, the criteria and rationale for the selection of data sources, and the analytical steps used to estimate the technical potential for wind energy in India. In Figure 2, an overview of the methodology is presented. The methodology consists of four key steps – development of long-term temporal and spatial weather regimes over the Indian sub-continent, including meteorological parameters such as wind patterns, temperature, humidity, and others; development of wind power density and wind speed estimates at the required resolution level (e.g. 5 km by 5 km cell); application of land availability constraints to identify land suitable for wind power deployment; and mathematical calculation of wind energy that can be extracted from the land thus identified.

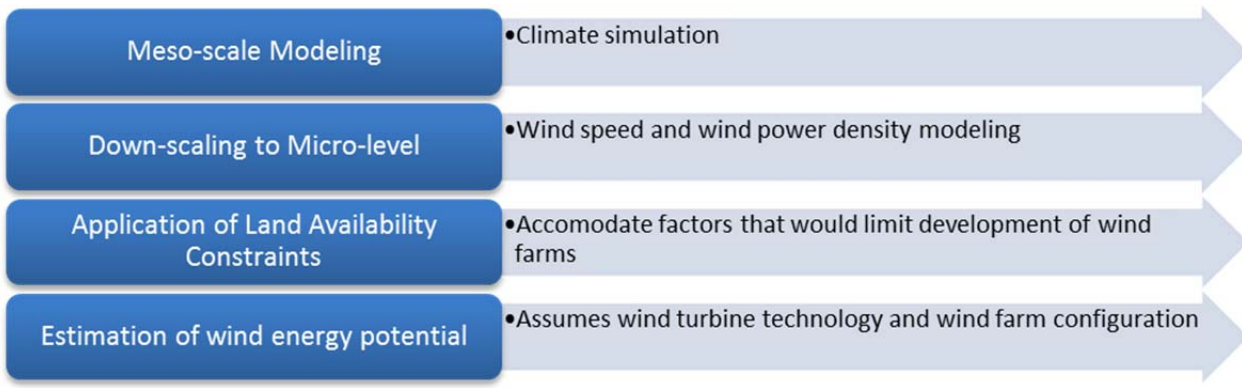

Figure 2 Overview of Methodology

2.1 Data Sources

The analysis presented here was largely conducted using Geographic Information System (GIS). Various types of datasets were evaluated using criteria such as format (i.e. compatibility with GIS systems and ease of use), quality of the data, and cost. The analysis presented here used off-the-shelf data, some of which was bought from a commercial vendor and the rest from publicly available databases.

2.1.1 Wind Power Density and Wind Speed Data

The fundamental data needed to estimate wind energy potential for any geographic region consists of wind speed and wind power density – preferably at altitudes comparable to the hub-heights of the wind turbines that are likely to be installed and at a sufficiently high resolution level (both temporally and spatially) to ensure robustness of the estimates.

Four sources of wind data were reviewed: the U.S. National Aeronautics and Space Administration (NASA); 3Tier; AWS True Power; and the Centre for Wind Energy Technology (CWET). A summary of the key characteristics of data from each source is summarized in Table 2.

The spatial resolution of the NASA dataset was considered to be too large for the type of assessment conducted in this analysis and hence, was not selected. The resolution and quality of 3Tier, AWS True Power, and CWET data appears to be similarly appropriate for this high-level analysis. However, CWET data is not currently available in the needed GIS-compatible format. Data from AWS True Power is of the highest resolution but is substantially more expensive than that from 3Tier. Given the budget constraints and the comparable quality of data from 3Tier and AWS True Power, data from 3Tier was selected and procured for this analysis.

Table 2: Key Characteristics of Wind Datasets

Source	Location	Resolution (cell size)	Typical Uses of Data		
			Strategic Planning	Preliminary Feasibility Study	Bankable Resource Assessment[10]
NASA	International	100 km by 100 km	No	No	No
3Tier	USA	3.6 km by 3.6 km	Yes	Yes	No
AWS True Power	USA	200 m by 200m to 1 km by 1 km	Yes	Yes	No
CWET[11]	India	5 km by 5 km	Yes	Yes	No

3Tier's data used in this analysis is developed using a mesoscale model called Weather Research and Forecasting (WRF). WRF is a numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs and is suitable for a broad spectrum of applications across scales ranging from a few meters to thousands of kilometers.[12]

3Tier data were validated against surface observations from the National Centers for Environmental Prediction (NCEP) network, which includes data from 1975 to the near present collected from moving ships, fixed ships, and both moored and drifting buoys. The collected data includes observations of cloud and wave behavior, surface and sea level pressure, air and surface temperature, dew point temperature, precipitation, and wind direction and speed.[13] The validation report focusing on South Asia (including India) shows an overall bias of 0.19 m/s and a root mean square error of 0.69 m/s when compared to 24 meteorological stations in the area. For the high-level analysis presented here, these levels of bias and error are reasonable.

2.1.2 Land Suitability Data

Land use and terrain data was used to eliminate geographical areas not suitable for wind developments. Multiple databases with land use and elevation data were evaluated for resolution, format, quality, and ease of use. However, only one database was identified for protected areas.

Three sources of land use data were evaluated: GlobCover, Digital Chart of the World (DCW), and Center for International Earth Science Information Network (CIESIN). The sources vary in terms of both quality of the data and resolution - See Table 3. DCW data is relatively old, of low quality, and incomplete. No details were available about the vintage of the CIESIN dataset. Both datasets were rejected for this analysis.

GlobCover data, which was selected for this analysis, is of a relatively recent vintage, has a high spatial resolution, and classifies land into categories relevant to the analysis.[14] The GlobCover project was launched in 2004 as an initiative of the European Space Agency (ESA), and has since evolved into an international collaboration among several global agencies. GlobCover

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[10] Minimum requirement is an independent 3rd party wind resource assessment of at least a year of onsite data measurement, long term reference, wind flow model, loss estimates and uncertainty analysis.

[11] Wind data is not yet in GIS format.

[12] WRF has been a collaborative partnership of various US institutions, principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration's National Centers for Environmental Prediction (NCEP and its Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). For more details on WRF, see - http://www.wrf-model.org/index.php.

[13] http://www.3tier.com/en/support/wind-prospecting-tools/what-were-3tiers-data-validation-procedures-prospecting/

[14] http://www.gofc-gold.uni-jena.de/sites/globcover.php

produced a global land-cover map, using as the main source of data the fine-resolution (0.3 km by 0.3 km) mode data acquired over the full year of 2005 from the MERIS sensor on-board ENVISAT satellite.

The validation approach for GlobCover data consisted of the creation of a dataset of validation sites that could be used to validate any new land cover map. The sites selected are not associated with any specific land cover map and retain statistical rigor when used on a variety of maps. The actual validation uses high spatial resolution satellite image data. International remote sensing experts interpret the local land cover characteristics and provide data for the statistical assessment of map accuracies. Each 0.3 km by 0.3 km cell in the GlobCover dataset is classified into one of 21 categories based on the United Nations Land Cover Classification System – see Table 6.[15]

Table 3: Key Characteristics of Land Use Datasets

Source	Spatial Resolution	Types of Data Available	Root Data	Date
GlobCover	0.3 km by 0.3 km	Land Cover (including water, urban areas)	ENVISAT MERIS Satellite	12/2004 to 6/2006
Digital Chart of the World (DCW)	N/A[16]	Water, Urban Areas, Transportation, Utility lines, Land Cover	Digital Aeronautical Flight Information File, USGS, Joint Operation Graphics and Tactical Pilotage Charts[17]	1991/ 1992
Center for International Earth Science Information Network (CEISIN)	30 arc-second (~1 km by 1 km)	Urban Areas, Population Density	Various sources including satellite data from Moderate Resolution Imaging Spectro-radiometer (MODIS) and Satellite Pour l'Observation de la Terre (SPOT) Image Vegetation sensor, and NASA	Unknown

2.1.3 Terrain Data

Four datasets that provided information on the altitude and slope of terrain were evaluated. These include Aster, Shuttle Radar Topography Mission (SRTM), GTopo30, and NOAA Globe. All four of the datasets have high resolution - see Table 4. However, only three – Aster, SRTM, and GTopo30 – had the appropriate GIS-compatible format.

GTopo30 was completed in 1996 after a three-year long collaboration among international agencies.[18] It is a global digital elevation model (DEM) with a horizontal grid spacing of 30 arc

[15] http://www.fao.org/docrep/003/x0596e/x0596e00.htm
[16] Vector data, resolution not applicable.
[17] http://earth-info.nga.mil/publications/specs/printed/89009/89009_DCW.pdf
[18] The effort was led by staff of the U.S. Geological Survey's EROS Data Center (EDC) and several organizations including the National Aeronautics and Space Administration (NASA), the United Nations Environment Programme/Global Resource Information Database (UNEP/GRID), the U.S. Agency for International Development (USAID), the Instituto Nacional de Estadistica Geografica e Informatica (INEGI) of Mexico, the Geospatial Information Authority of Japan (GSI) Manaaki Whenua Landcare Research of New Zealand, and the Scientific Committee on Antarctic Research (SCAR).

seconds (or approximately, 1 km by 1 km cell) and is derived from several raster and vector sources of topographic information. It is of a relatively older vintage and less accurate than the Aster and SRTM datasets. However, the authors of this analysis had previously attempted to use the Aster and SRTM datasets for high level analysis and had encountered significant problems in manipulating them. Consequently, it was decided to use GTopo30 for this analysis.[19]

Table 4: Key Characteristics of Terrain Datasets

Source	Spatial Resolution	Coverage Area	Root Data	Notes
Aster	30 m by 30 m	Global	NASA Satellite	Highest quality, GIS compatible, potentially difficult to obtain and use
Shuttle Radar Topography Mission (SRTM)	3 arc-seconds (~90 m by 90 m)	Global	NASA Satellite	Most popular, GIS compatible, difficult to use
GTopo30	30 arc-seconds (~1 km by 1 km)	Global	Eight sources including National Imagery and Mapping Agency, Digital Chart of the World and International Map of the World[20]	Used in past analysis, GIS compatible, easy to use, older and less accurate
NOAA Globe	30 arc seconds (~1 km by 1 km)	Global	U.S. Department of Defense/NASA Satellite	Higher quality than GTop30, format not clearly GIS compatible

2.1.4 Protected Areas Data

The World Database of Protected Areas (WDPA) is a database created by the United Nations Environment Programme, World Conservation Monitoring Centre, and the International Union of Conservation of Nature's World Commission of Protected Areas. It is a worldwide database of protected areas, which are defined as clearly delimited geographical space, recognized, dedicated and managed through legal or other effective means to achieve the long-term conservation of nature with associated ecosystem services and cultural values.[21] The database is updated and released annually in polygon format. The 2010 release was used for this analysis.

2.2 Estimation of Technical Potential from Wind Power Density and Wind Speed

The analysis presented here assumes a minimum threshold of 200 W/m^2 for the wind power density for all three hub-heights (i.e. 80m, 100m, and 120m). Each 5 km by 5 km cell was classified into a bin based on wind power density increments of 10 W/m^2 (e.g. 200-210, 210-220, and so on).

Each bin was assigned a net capacity factor. The capacity factor was based on the norms established by CERC in their most recent renewable energy tariff regulations.[22] More advanced commercially available wind turbines such as GE's 1.6 XLE can operate at higher capacity factors in the lower wind class areas and will result into a higher wind generation potential estimate. Turbines considered advanced today are likely to become more common in the future

[19] For more details, see - http://www1.gsi.go.jp/geowww/globalmap-gsi/gtopo30/gtopo30.html
[20] http://www1.gsi.go.jp/geowww/globalmap-gsi/gtopo30/README.html#h17
[21] http://www.wdpa.org/
[22] http://cercind.gov.in/2012/regulation/CERC_RE-Tariff-Regualtions_6_2_2012.pdf

and hence the wind potential in the future is likely to be higher than estimated by this analysis. Further, turbines with higher rotor diameter have shown to be more suitable for lower wind speeds and will lead to higher capacity factors than estimates in this analysis.

Table 5: Wind Power Density and Capacity Factors as per CERC norms

Annual Mean Wind Power Density (W/m^2) at 80m hub-height	Capacity Factor (%)
< 200	20
201 – 250	22
251 – 300	25
301 – 400	30
> 400	32

2.3 GIS Analysis

Once each 5 km by 5 km cell in India was assigned to a wind power density bin at each of the three hub-heights, they were separated according to their suitability for wind power development as identified using GIS data. The thresholds for exclusion and the sources of data used to establish them are summarized in Table 6. Specifically, we exclude land having the following characteristics – WPD less than 200 W/m^2, slope greater than 20 degrees, elevation greater than 1,500m, snow/ice, and water-bodies because of the relatively higher level of technical difficulties associated with project development activities. We exclude rural and urban built-up areas, “protected” areas, and forests because they are relatively less likely to be made available by policymakers for any new infrastructure development such as wind turbines. In India and elsewhere, using “protected” areas and forests for any sort of infrastructure development faces high levels of opposition from the civic society. Although, it is technically feasible to build wind projects in these areas, we simply remove them from further consideration.

Hossain et al (2011) listed the following LULC types as unsuitable for wind power development – mangroves, coral reefs, water bodies, snow, sea, swamp, and mud flats. Lu et al (2010) excluded areas classified as forested, areas occupied by permanent snow or ice, areas covered by water, and areas identified as either developed or urban. Consequently, our approach is consistent with that used by other researchers both in India and internationally.

Table 6: Land Use/Cover Classification for Wind Power Development

Parameter		% Excluded	Data Source
Terrain slope (or gradient) > 20 degrees		100%	GTopo30
Elevation > 1,500 m		100%	GTopo30
Protected areas		100 %	WDPA
Water Bodies	Water bodies	100 %	GlobCover
	Closed (>40%) broadleaved forest or shrub-land permanently flooded - Saline or brackish water	100 %	GlobCover
	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water	100 %	GlobCover
	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water	100 %	GlobCover
Snow/ Ice	Permanent snow and ice	100 %	GlobCover
Rural/ Urban	Artificial surfaces and associated areas (Urban areas >50%)	100 %	GlobCover
Forests	Closed (>40%) broadleaved deciduous forest (>5m)	100 %	GlobCover
	Closed (>40%) needle-leaved evergreen forest (>5m)	100 %	GlobCover
	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	100 %	GlobCover
	Closed to open (>15%) mixed broadleaved and needle-leaved forest (>5m)	100 %	GlobCover
	Mosaic forest or shrub-land (50-70%) / grassland (20-50%)	100 %	GlobCover
	Mosaic grassland (50-70%) / forest or shrub-land (20-50%)	100 %	GlobCover
	Mosaic vegetation (grassland/shrub-land/forest) (50-70%) / cropland (20-50%)	100 %	GlobCover
	Open (15-40%) broadleaved deciduous forest/woodland (>5m)	100 %	GlobCover
Miscellaneous	Bare areas	0 %	GlobCover
	Closed to open (>15%) (broadleaved or needle-leaved, evergreen or deciduous) shrub-land (<5m)	0 %	GlobCover
	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	0 %	GlobCover
	Mosaic cropland (50-70%) / vegetation (grassland/shrub-land/forest) (20-50%)	0 %	GlobCover
	Post-flooding or irrigated croplands (or aquatic)	0 %	GlobCover
	Rain-fed croplands	0 %	GlobCover
	Sparse (<15%) vegetation	0 %	GlobCover

As shown in Figure 3 and Figure 4, the GIS analysis for assessing the land area suitability was done in the following steps

1) Each 3.6 km by 3.6 km cell was assigned to a unique wind power density bin (refer to Table 5 for definition of the bins)
2) 3.6 km by 3.6 km cells that were identified as protected areas, had slope greater than 20%, had elevation greater than 1,500 m, or had WPD less than 200 W/m^2 were removed
3) Land cover layer was applied to the 3.6 km by 3.6 km cells remaining after step 2
   a) Each 3.6 km by 3.6 km cell remaining after step 2 contains 144 cells of 0.3 km by 0.3 km land use/land cover cells
   b) Each 0.3 km by 0.3 km cell has two characteristics:
      i) WPD bin classification; and
      ii) Land use/land cover
   c) 0.3 km by 0.3 km cells of land cover that are not suitable for wind power development were removed
4) Wind potential in all remaining 0.3 km by 0.3 km cells was added to produce the aggregate estimate at state and national levels
5) Data output from GIS was total area for each land cover layer grid with wind density bins

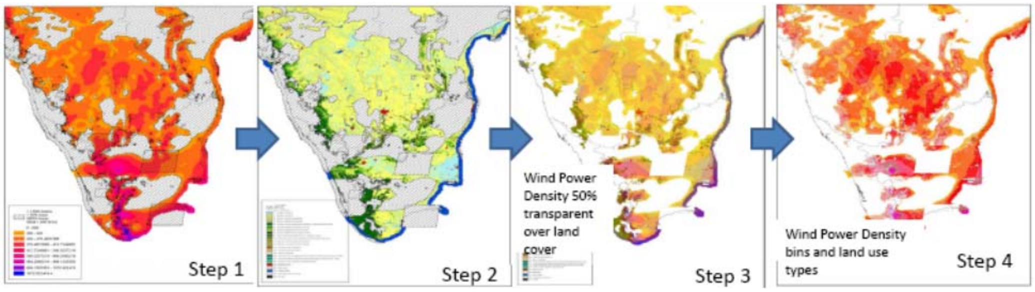

Figure 3: Results of the GIS Analysis

CWET's wind potential estimate is based on the assumption of a capacity density of 9 MW/km^2 (or ~11 hectare/MW). Lu et al (2010), has also assumed a capacity density of ~9 MW/km^2 based on a 2.5 MW turbine (rotor diameter: 100m; and configuration of 4D by 7 D array). For the sake of consistent comparison, we use the CWET capacity density estimate of 9 MW/km^2 in this analysis. The National Renewable Energy Laboratory (NREL) uses 5 MW/km^2 in its high-level potential estimates.[23]

NREL also has conducted empirical research on the land use requirements of wind power plants in the U.S.[24] Data analyzed by NREL for 161 wind projects 20 MW and larger show that average capacity density is 3.0 ± 1.7 MW/km^2 with the actual range being 1-11 MW/km^2. They further note that a typical configuration for modern turbines – 5D by 10D array – yields a capacity density of 5-8 MW/km^2.

[23] http://www.windpoweringamerica.gov/wind_maps.asp for Wind Resource Potential in United States; http://www.nrel.gov/international/pdfs/afg_pak_wind_june07.pdf for Wind Resource Assessment and mapping for Afghanistan and Pakistan

[24] http://www.nrel.gov/docs/fy09osti/45834.pdf

3 Results

The total techno-economic wind potential in India ranges from 2,006 GW at 80m hub-height to 3,121 GW at 120m hub-height. More than two-thirds of the techno-economic wind energy potential is in the lower quality (i.e. WPD > 200 W/m^2 but < 250 W/m^2 and corresponding to an average CF of 22%) wind energy sites. High quality wind energy (i.e. WPD > 250 W/m^2 and CF > 25%) sites alone, at 80m hub-height with a minimum capacity factor of 25 percent, have a techno-economic potential of 543 GW, more than five times the current official estimate.

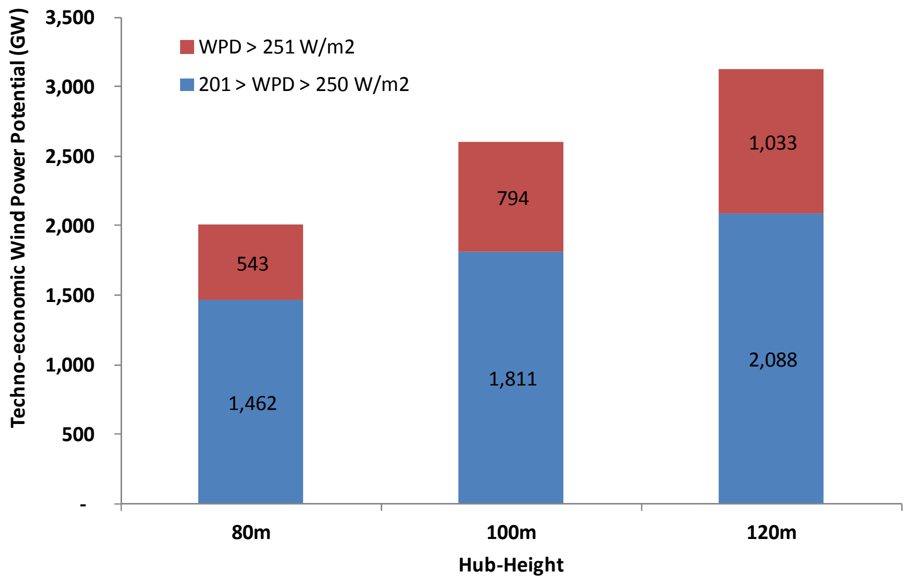

Figure 4: On-Shore Techno-Economic Wind Potential in India

The techno-economic potential estimated in this analysis is at least about twenty times that of the official Indian estimate published CWET in February 2012 at 80m hub-height, and is similar to the estimate by Xi Lu et al. (2009) and Hossain et al. (2011). The most likely reason for the large difference between the estimate in this analysis and the official Indian estimate is the difference in assumed land availability. Without stating any rationale, CWET assumes that only two percent of the total windy land will be available for wind power development (CWET, 2010). CWET does note that the potential will be higher if more land is considered available for wind power development.

The total land area of India is 3,287,263 km^2.[25] Applying the topographical exclusion criteria (i.e. WPD > 200 W/m^2, slope > 20%, and elevation > 1,500m) described in the previous section, we find that the land area available for potential wind power development ranges from 281,432 km^2 (or 9%) to 425,795 km^2 (or 13%) at 80m and 120m, respectively. Applying the land use/cover exclusion criteria described in the previous section reduces the range of land area available for potential wind power development to 222,844 km^2 (or 7%) and 346,787 km^2 (or 11%) at 80m and 120m, respectively. In Table 7, we present a transparent picture of how much techno-economic wind potential is available at 80m hub-height by the LULC classification provided by GlobCover. The techno-economic wind potential that we use in this study considers

[25] http://india.gov.in/knowindia/profile.php

only the "Miscellaneous" category from Table 7. Approximately, 500 GW (or 20% of total) of techno-economic wind potential is not considered in this study as it is available in forests.

Table 7. Land and techno-economic wind potential (Hub-height: 80m; WPD > 200 W/m^2; Slope < 20%; Elevation < 1,500m) by GlobCover LULC categories.

Category	Land Use/Cover Classification Provided by GlobCover	Land (km^2)	Techno-Economic Wind Potential (GW)
	Excluded Areas		
Water Bodies	Water bodies	3930	35
	Closed (>40%) broadleaved forest or shrub-land permanently flooded - Saline or brackish water	105	1
	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water	1	0
	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water	62	1
Snow/Ice	Permanent snow and ice	51	0
Rural/Urban	Artificial surfaces and associated areas (Urban areas >50%)	1,698	15
Forests	Closed (>40%) broadleaved deciduous forest (>5m)	12,806	115
	Closed (>40%) needle-leaved evergreen forest (>5m)	391	4
	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	17,678	159
	Closed to open (>15%) mixed broadleaved and needle-leaved forest (>5m)	0	0
	Mosaic forest or shrub-land (50-70%) / grassland (20-50%)	16	0
	Mosaic grassland (50-70%) / forest or shrub-land (20-50%)	21	0
	Mosaic vegetation (grassland/shrub-land/forest) (50-70%) / cropland (20-50%)	22,625	204
	Open (15-40%) broadleaved deciduous forest/woodland (>5m)	2	0
	Included Areas		
Miscellaneous	Bare areas	1,073	10
	Closed to open (>15%) (broadleaved or needle-leaved, evergreen or deciduous) shrub-land (<5m)	5,159	46
	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	8,280	75
	Mosaic cropland (50-70%) / vegetation (grassland/shrub-land/forest) (20-50%)	47,326	426
	Post-flooding or irrigated croplands (or aquatic)	48,551	437
	Rain-fed croplands	112,436	1,012
	Sparse (<15%) vegetation	18	0
TOTAL		**278,301**	**2,505**

It is necessary to acknowledge a unique aspect of wind energy. Unlike various other conventional power generation sources (e.g. coal, natural gas, solar PV/thermal), only a small portion of the land area within a designated "wind power plant" is disturbed either permanently or temporarily with the rest of the land area being available for alternative uses including but not limited to farming, cattle-raising, and others. NREL (2009) has developed empirical estimates of the portion of land area disturbed under various configurations of wind turbines and various land use types in the US.[26] Out of an average “wind power plant” area of 34.5±22.4 hectare/MW, 0.3±0.3 hectare/MW is disturbed permanently and 0.7±0.6 hectare/MW is disturbed temporarily. Hence less than 3% of the wind power plant area is permanently disturbed and remaining area can be used for other purposes.

The total land area necessary for the high quality (i.e. WPD > 250 W/m^2 and CF > 25%) techno-economic wind potential of 543 GW (at 80m hub-height) is 60,362 km^2. Out of these 60,362 km^2, the average temporarily disturbed area (i.e. during construction phase) is likely to be approximately 3,801 km^2 while the average permanently disturbed area is likely to be approximately l,629 km^2 accounting for 0.12% and 0.05% of total land area of India, respectively. In other words, the permanently disturbed area by wind power plants would be similar to a 40 km by 40 km cell, and can potentially provide at least as much energy as 180 GW coal plant operating at 76% plant load factor.

As seen from the map shown in Figure 5, more than 95 percent of the techno-economic wind energy potential is concentrated in just five states in southern and western India – Tamil Nadu, Andhra Pradesh, Karnataka, Maharashtra, and Gujarat.

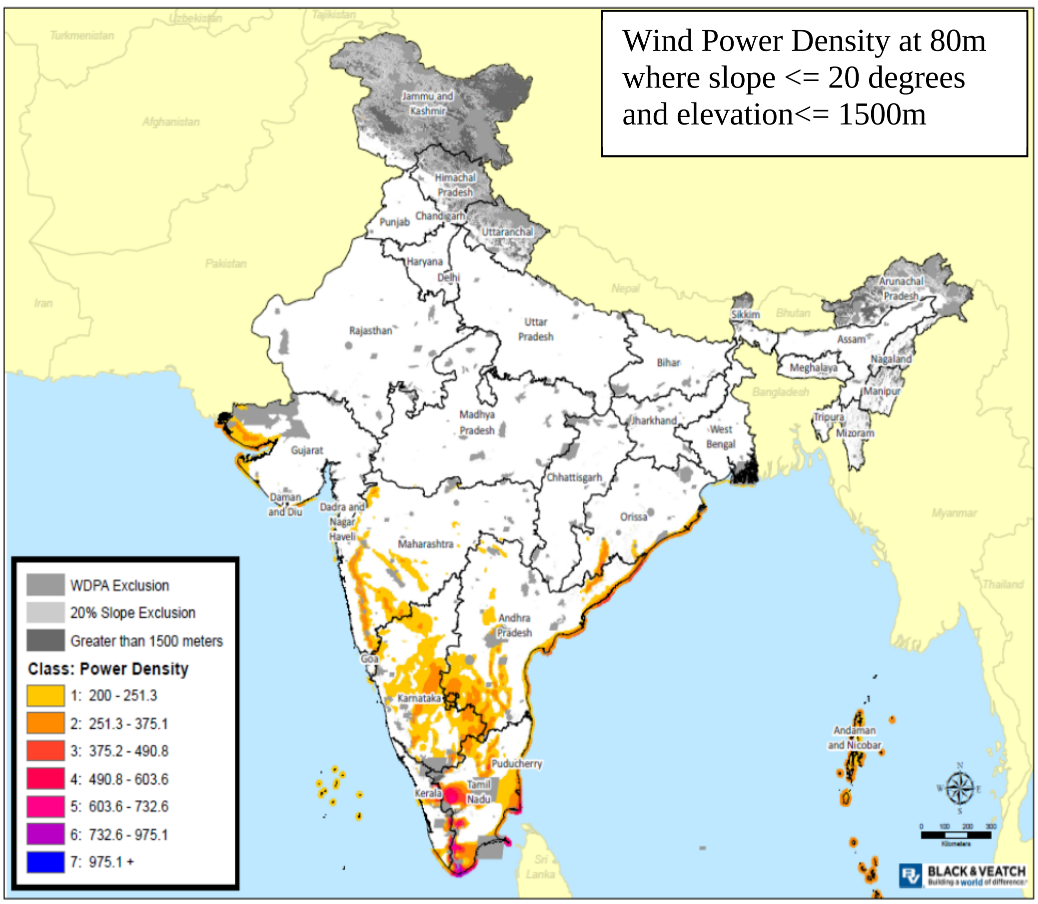

Figure 5. Wind Power Density at 80m

[26] http://www.nrel.gov/docs/fy09osti/45834.pdf

Interestingly, the state with the overall largest resource is Karnataka (~655 GW at 80m) while the state with largest best-quality resource (i.e. WPD > 400 W/m2; CF > 32%) is Tamil Nadu (~65 GW at 80m). From a cost-effective perspective, the full development of best-quality wind resources in Tamil Nadu – which already leads all states in installed wind capacity – would yield a capacity of 65 GW at a 80m hub-height and a minimum capacity factor of 32% (See Figure 7).[27] This is more than four times the total installed wind capacity in India.

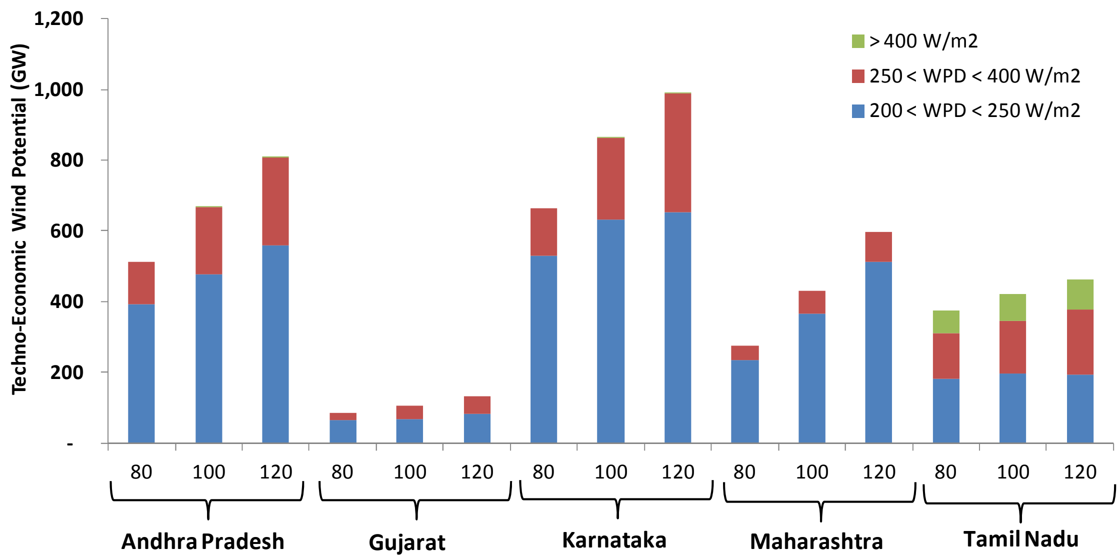

Figure 6: Techno-Economic Wind Energy Potential for five states

It is necessary to note that the estimates presented here regarding yields and the extent of land most suitable for wind power development in India are not detailed enough to determine a site for an actual wind generation facility or predict its exact output. These estimates are however appropriate for use in high-level policy-making; estimates based on methodologies similar to the one used here serve as the basis for policy development and long-term power sector planning purposes in the U.S., China, and the European Union.

Using the norms specified by the CERC (see Table 8) for estimating the levelized tariff of wind power projects in India (CERC, 2012), the wind potential at various levels of levelized cost were estimated.

[27] Note: this would likely involve re-powering existing installations with more efficient technology.

Table 8. Wind Power Levelized Tariff Assumptions Based on CERC norms

Debt: Equity Ratio	70:30	Loan tenure years	12
Capital Cost (Rs Cr/MW) at 80m	5.75	Depreciation rate (up first 12 years)	5.83%
O&M Expenses (Rs Cr/MW/yr)	0.09	Normative interest rate	Average State Bank of India base rate prevalent during the first six months of the previous year plus 300 basis points
O&M cost escalation	5.72%	Return on Equity (pre-tax) - first 10 years	20%
Useful life years	25	Return on Equity (pre-tax) - after 10 years	24%

Using the CERC norms, in Figure 7, the cumulative wind capacities available at various capacity factors and their corresponding levelized tariffs (without accelerated depreciation) are presented.

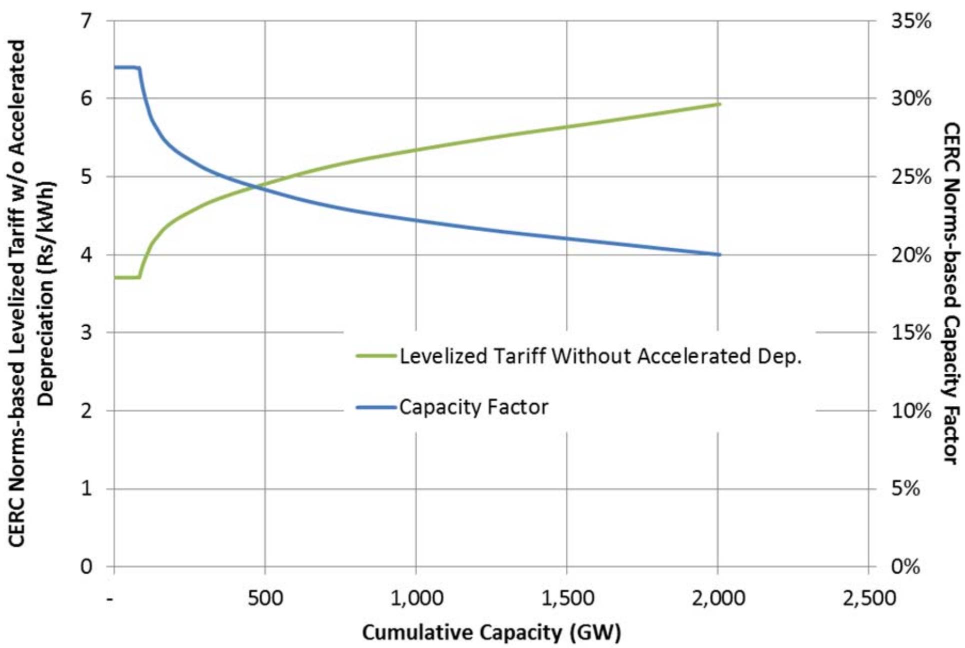

Figure 7: Levelized Cost of Techno-Economic Wind Potential

Note:

- As per CERC norms, we assume that techno-economic wind-potential on sites with WPD > 400 W/m^2 would yield a capacity factor of 32% when it could be substantially higher. The levelized tariff associated with this capacity factor is Rs.3.71/kWh.

All the techno-economic wind potential estimated in this study – 2,006 GW at 80m hub-height – is available at Rs.5.93/kWh or less. In contrast, as of February 2012, the lowest price for a solar PV project selected via competitive bidding in India is Rs 7/kWh.[28]

[28] http://www.thehindubusinessline.com/companies/article2939306.ece

More than 500 GW of the potential at 80m hub-height is available at Rs.5/kWh or less, more than 200 GW of wind potential is available at levelized tariff of Rs.4.5/kWh or less, and more than 100 GW of wind is even available at a levelized tariff of Rs. 4/kWh or less in some part of India – especially, Tamil Nadu.

The cost of wind power from high quality wind resource areas is likely to be comparable to the cost of power from imported coal which is likely to be around Rs 3.5/kWh or more especially given the recent rise in the prices of imported coal (see Gadag et al., 2011, for details of the costof coal power in India).

4 Conclusions and Future Directions

The official wind energy potential estimate as described in the latest (i.e. 2012) Wind Energy Atlas of India is about 103 GW. However, two recent studies – Xi Lu (2009 and Hossain et al. (2011) – indicate that the wind energy potential for India is at least one order of magnitude greater than the official estimate. Recent re-assessments of wind energy potential in the U.S. and China that have accounted for the improved capability of the latest wind technology have led to substantial upward revision of the wind potential in each country. Lastly, the Wind Energy Atlas of India made ad-hoc assumptions about the land available for wind power development instead of systematically identifying various land uses and their suitability for wind power development. In order to address the concerns and discrepancies described above, this study – using best practice methods and vetted data – developed the potential wind energy available in India. Results include the following:

- The techno-economic on-shore wind potential ranges from 2,006 GW at 80m hub-height to 3,121 GW at 120m hub-height with a minimum capacity factor of 20 percent.
- The potential at high-quality wind energy sites alone (80m hub-height with a minimum capacity factor of 25 percent) is 543 GW, more than five times larger than the current official estimate

More than 95 percent of the nation's wind energy potential is concentrated in five states in southern and western India – Tamil Nadu, Andhra Pradesh, Karnataka, Maharashtra, and Gujarat. The state with the overall largest resource is Karnataka while the state with largest best quality resource is Tamil Nadu.

Under the CERC norms, approximately 500 GW of wind potential is available at a levelized cost of Rs. 5/kWh or less – at 80m hub-height. At least 100 GW of wind energy potential can be developed today at less than Rs. 4/kWh at 80m hub-height.

Considering the findings of the large wind potential, it is possible to imagine scenarios where wind energy can play a substantial role in India’s energy mix and contribute significantly to reduction in power shortages in the short term and energy security and environmental sustainability in the long term. These promising results provide sufficient support for conducting further analysis (on topics such as wind integration, transmission planning, regional co-ordination, cost effective development, and land policies) and dialogue that would ensure that this large, cheap, and clean resource available in India is developed as quickly and as cost-effectively as possible.

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