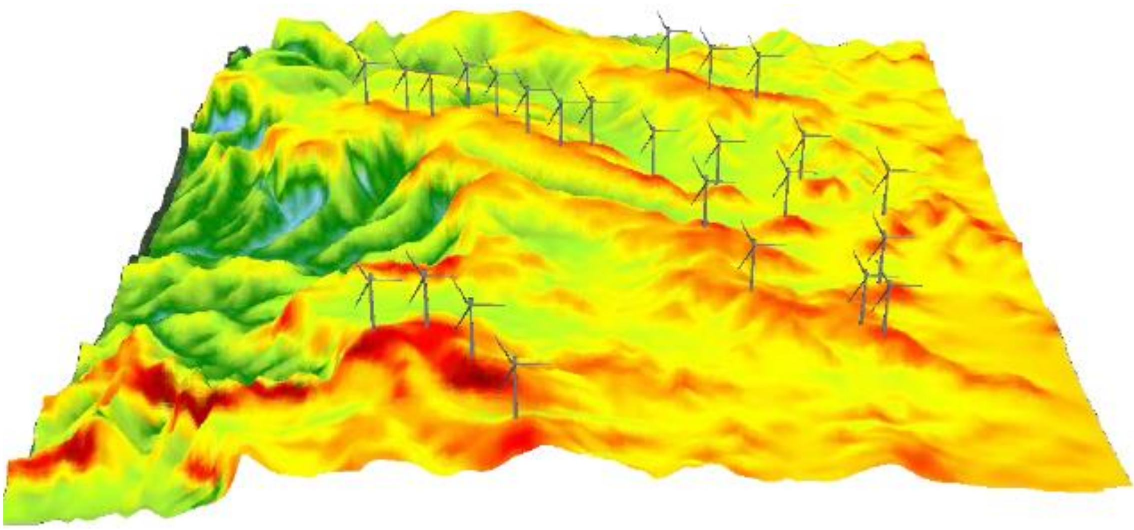
World Wind Energy Association

Welt-Windenergie Verband
Asociación Mundial de la Energía Eólica
世界⊠能⊠会
세계풍력에너지협회
Всемирной Ветроэнергетической Ассоциации

December 2014 ■ WWEA Technical Paper Series (TP-01-14)



World Wind Resource Assessment Report

by the WWEA Technical Committee

This is a technical report issued by the World Wind Energy Association

Main Author: Dr. Jami Hossain

Editing and Layout: Nopenyo Dabla

Assistance in Layout & Design: Danish Ahmad

Photo Back Cover: © WinDForce Management Services Private Limited

WWEA
World Wind Energy Association

Welt-Windenergie Verband
Asociación Mundial de la Energía Eólica
世界⊠能⊠会
세계풍력에너지협회
Всемирной Ветроэнергетической Ассоциации

Wind

Preface

The Wind Resource Report of WWEA Technical Committee presents a bird's eye-view of various wind resource assessment techniques, models, open data as well as a summary of wind resource assessment exercises carried out so far in the world at global, regional and country levels.

In order to come up with a realistic assessment of worldwide potential for utilization of wind energy, data and information has been accessed from varied but authentic sources such as national laboratories, research reports, peer-reviewed scientific publications and industry associations. Interestingly, we find that different methods and information sources have come up with assessment figures that are somewhat similar in order and magnitude for different parts of the world. Be it the wind energy potential for Germany, US, Russia, China or India or the entire world, the order of magnitude appears to be similar and one study corroborates the other. This sort of cross validates the studies and lends authenticity to the gross figures arrived at.

It is the stated opinion of WWEA that across the world, wind energy shall serve as one cornerstone and a driving force for the immediate application of a world energy system driven by renewable energies to completely substitute fossil and nuclear sources. This report, through summarization of a body of research and academic work on wind resource assessment, demonstrates that, indeed, wind energy is the front-runner in the process of clean energy transformation taking place in the world.

A word of thanks is due for the contributions made by members of the technical committee and even members of the WWEA Board and the WWEA Secretariat for the valuable inputs. I would perhaps be failing in my duty towards WWEA and to the readers if I do not mention that a very important contribution to this report comes from the work carried out by late Grigori Dmitriev, who did wind resource assessment work for Russia. Grigori was also one of the key functionaries and a Vice President of WWEA.

Dr. Jami Hossain

Technical Chair, WWEA

December 2014

World Wind Energy Association
Charles-de-Gaulle-Straße 5
53113 Bonn
Germany

WWEA Technical Committee

Main Author

Dr. Jami Hossain
Technical Chair

Members

Prof. Dr. Chuichi Arakawa
Tokyo University, Japan

Dr. Heinz L Dahl
Australia

Dechang Shen
Chinese Wind Energy Equipment Association, China

Dexin He
President WWEA, China

Stefan Gsänger
Secretary General WWEA, Bonn

Dr. Preben Maegaard
Director Emeritus Folkecenter, President Emeritus WWEA, Denmark

Prof. Dr. Conrado Moreno
CETER, CUJAE, Cuba

Nico Peterschmidt
Managing Director, Inensus, Germany

Jean-Daniel Pitteloud
PR Manager, WWEA, Bonn

Prof. Dr. Choong-Yul Son
Mokpo University, South Korea

Prof. Dr. Erico Spinadel
President, Argentinian Wind Energy Association, Argentina

Prof. Dr. Tanay Sidki Uyar
Marmara University, Turkey

Prof. Dr. Woldemariam Wolde-Ghiorgis
Addis Ababa University, Ethiopia

Editing and Layout: Nopenyo Dabla

Assistance in Layout and Design: Danish Ahmad

Executive Summary

1.1. Introduction

Winds blow in every nook and corner on the surface of this planet. Fundamentally, winds carry a part of the energy in solar radiations received on earth. Uneven heating of earth's surface and varying pressure differences cause movement of air in the atmosphere or the wind as we experience it.

As an energy source, it seems winds were harnessed even in the ancient times. Perhaps, the earliest use of wind energy was in the form of sails to steer ships. Egyptian civilization, even as far back as 3000 BC, was using boats and ships with sails. There is a mention of ambitious plans of Mesopotamian ruler Hammurabi to use windmills for irrigation around 1790 BC.

Today, modern wind turbines convert the kinetic energy in the wind to electrical energy and clusters of wind turbines in the form of wind farms generate electricity on a utility scale.

Over the last 50-60 years, electricity generation has grown in most parts of the world. The steepest growth has been in developing countries and, therefore, balancing energy access, economic development and environmental sustainability is going to be a major challenge not only for the nations concerned but also for the global community. The potential for utilization of wind generated electricity, which we have assessed in this report, can play the most significant role in mitigating global warming.

Three important challenges concerning sustainable development, i.e. energy security, climate change and energy access make a compelling case for large-scale utilization of wind energy across the world. As of June 2014, about 337 GW wind power generation capacity has been set up in the world. This capacity is more than the total installed electricity generation capacity from all sources in some of the largest countries in the world. With such a large wind power capacity having been installed and widespread geographical deployment in more than 100 countries, we can say that wind energy has arrived at the center-stage of the mainstream electricity sector.

1.2. Energy Security Perspective

Across the world, greater dependence on imported fossil fuels adds to national energy insecurity and uncertainty. Most countries do not have adequate indigenous fossil fuel reserves and hence have to import oil, coal and gas. Fluctuations in price and supply uncertainty results in serious long-term concerns for national economies. Those regions of the world that face energy resources constraints to meet their electricity demand are also the regions where wind energy has been utilized to the largest extent. Europe, where between 2000 and 2013 more than 100 GW of capacity was added, is one example. Europe's import dependency on fossil fuels is expected to rise and imported gas is likely to make up 80% of consumption by 2030. Similarly, in the United States, more than 80% of energy consumed comes from oil, natural gas or coal. By the end of 2013 more than 61.1 GW of wind power capacity had been installed in the US. In India heavy and growing dependence on imported fossil fuels, apart from adding to energy insecurity, creates serious monetary problems for the country. India has achieved nearly 21 GW of cumulative installed capacity of wind power by the end of March 2014. China is the largest global energy consumer and has overtaken US as the largest net importer petroleum and other liquid fuels in 2014. Energy security is of immense importance to this country because of massive industrialization. In just about eight years, China has emerged as the leading country with more than 91 GW of wind farmed capacity. Europe, India, China & US together account for 93% of the total wind power installed capacity.

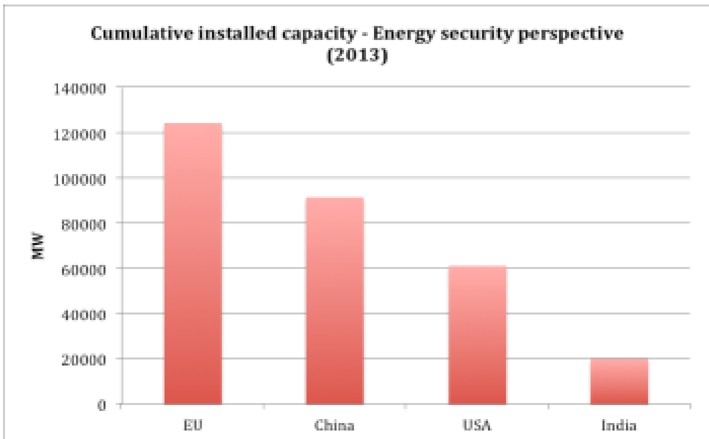


Fig (a): The energy security perspective

1.3. Climate Change Perspective

The Intergovernmental Panel on Climate Change (IPCC) has established that the climate is changing across our planet, largely as a result of human activities that have led to the accumulation of atmospheric greenhouse gases (GHG). Between 1971 and 2010, global CO2 emissions almost doubled and about 44% of these emissions in 2010 were from the electricity sector. According to the IPCC, Wind energy offers significant potential for near-term (2020) and long-term (2050) greenhouse gas (GHG) emissions reductions. The need to reduce GHG emissions is yet another major driver and a compelling reason for countries to set up wind power plants. The countries and regions that face energy security issues also face the challenge of environmental sustainability in planning their future energy mix.

1.4. Energy Access Perspective

Per capita energy consumption as well as total electricity consumption in vast areas of the developing world is a fraction of electricity consumption in some of the rich and developed countries. Most of Africa and large parts of Asia fall in this category. One can see that electricity access, too, is going to be one of the main drivers of wind power development in those countries that have an adequacy of wind resources. In countries with less than 50% electricity access, wind power generation in combination with solar energy, biomass and hydro can be a low carbon solution.

1.5. Wind Resource Assessment

The question of wind energy potential is important from different perspectives. At any given location or in a region, the question is how much electricity can be generated from wind, for how long and what may the total quantum of such energy in a given period of time be?

Anyone investing in wind energy would like to know how much electricity can be generated from a project so that the economic rationale of such an investment can be examined. This information could be of interest to various stakeholders - investors, financiers, utility managers or policy makers. It is the process of answering this question of '*how much capacity and how much energy from wind?*' that we term as 'Wind Resource Assessment' or 'Wind Potential Assessment' and it is this question that we have tried to address in this report at a world-wide level.

The Wind Resource Assessment (WRA) is the most important aspect of wind power development. At project level, it enables developers and investors to take a "go"/ "no go" decision and at a national or regional level, it enables the concerned agencies or the governments to figure out if there is enough potential to utilize wind energy and whether certain policy and regulatory frameworks are required in order to harness such potential on a large scale.

The techniques of undertaking WRA at project level differ from the techniques and approaches to assess the resource on a regional or a meso-scale. Project level WRA involves design of an optimized layout of wind turbines of a certain make or type in a given patch of land and assessment of the annual energy output.

The regional or meso-study differs significantly as here the area in question can be thousands of square kilometers. Some studies have covered the entire globe. Generally, Meso studies require global data sets such as NCEP/ NCAR and digitized terrain and satellite data.

A large number of such studies have been carried out across the world and we were able to compile these studies to arrive at an idea of the total global potential for wind farms in the world.

Table (a) below summarizes the worldwide potential for wind farms according to currently available official estimates, in most cases excluding offshore wind potential. It is easy to see that some of these figures, in particular "Rest of the World", are far too low, when considering the land masses in comparison with Europe, USA, Russia or India (where so far, the most comprehensive analysis has been done). In reality the wind potential in "rest of the world" must be significantly higher than that of Europe.

US	11
EU	37.5
Russia	36
Rest of the World	10.3953
Total	94.8953

Table (a): Total worldwide potential for wind (in TW)

According to the IEA, the world's total energy consumption for all sectors, including industries, heating and cooling as well as transport, in 2011 was 103'711TWh[1], which included 19'299 TWh[2] for power consumption. It is easy to see that the world's wind potential of at least 94.5 TW is sufficient to cover the whole world's energy demand - assuming on average 2000 full load hours, the identified wind potential could almost cover it twice. Of course, the actual deployment of a very large wind capacity will depend on smart integration into energy supply structures, combination with other renewable technologies, storage options, demand-side management etc. Wind integration will be dealt with in another report of the WWEA Technical Committee to be published soon.

Table of Contents

Preface ii

Executive Summary 1

Introduction 11

Wind Resource Assessment 19

2.1. Project level WRA 20

2.2. Modeling wind-farms 21

Meso-map studies 24

3.1. Secondary data 26

3.2. Weather Research and forecasting (WRF) 27

3.3. MM5 Modeling System 27

3.4. Boundary Layer Model 28

Worldwide studies 29

4.1. Global Studies 29

4.2. Regional and country level studies 31

Regional & Country wind maps 40

References 64

List of Figures

Figure 1.0: Cumulative Wind Power installed capacity (Energy Security Perspective) 15

Figure 2.0: Global Electricity Electricity Access (Data source: Worldbank) 17

Figure 3.0: Per Capita Energy Consumption 18

Figure 4.0: A Typical power curve 22

Figure 5.0: A Typical Thrust curve 22

Figure 6.0: A Typical wind speed distribution 23

Figure 7.0: Flow diagram of meso-map exercise 25

Figure 8.0: An offshore wind turbine 30

Figure 9.0: Technical potential for onshore wind energy up to 2030 based on estimated 80m average wind speed 35

List of Tables

Table 1.0: Studies on global wind energy potential……………………………………………31

Table 2.0: Estimates of wind potential in various countries around world……..32

Table 3.0: State-wise onshore and offshore wind potential of India……..………...36

Table 4.0: Projected technical potential ….. in EU-27……………………………..………37

Table 5.0: Wind energy potential for each state in U.S. ……………………….…….….....38

Table 6.0: World total assessed potential from Country-wise data (TW) ……….39

List of Abbreviations

AEO	Annual Energy Output
BLM	Boundary Layer Model
CDAS	Climate Data Assimilation System
COADS	Comprehensive Ocean-Atmospheric Data Set includes
CO2	Carbon Dioxide
DTM	Digital Terrain Model
EROS	Earth Resources Observation and Science
ESMAP	Energy Sector Management Assistance Program
EU	European Union
GW	Gigawatts
GHG	Green House Gas
GIS	Geographical Information System
HH	Hub Height
HVAC	Heating, ventilation and air conditioning
IPCC	Intergovernmental Panel on Climate Change
IEC	International Electrotechnical Commission
LBNL	Lawrence Berkley National Laboratory
MASS	Meso-scale Atmospheric Simulation System
MERRA	Modern-era retrospective analysis for research and applications
MM5	Fifth-Generation Penn State/NCAR Meso-scale Model
MW	Megawatt
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NMM	Non hydrostatic Meso-scale Model
NREL	National Renewable Energy Laboratory
NWP	Numerical Weather Prediction
PDF	Probability Density Function
PWh	Petawatt-hour
PBL	Planetary Boundary Layer
ROI	Region of Interest
SRTM	Shuttle Radar Topography Mission
SWERA	Solar and Wind Energy Resource Assessment
TW	Terawatt
TWh	Terawatt-hour

US	United States
UNFCCC	United Nations' Framework Convention on Climate Change
USGS	US Geological Survey
WRA	Wind Resource Assessment
WRF	Weather Research and Forecasting
WTG	Wind Turbine Generator
WAsP	Wind Atlas Analysis and Application Program
WWEA	World Wind Energy Association

Introduction

The movement of atmospheric air, felt as wind by us, touches every nook and corner on the surface of this planet. One can think of places that never experience any rain or sunshine, but one cannot imagine a place, where no wind is felt.

Fundamentally, winds carry a part of the energy in solar radiations received on earth. This is the part that is absorbed in the atmosphere through direct and indirect radiation. Evaporation and convection from water bodies transfers heat and vapors into atmosphere resulting in pressure differences. Atmospheric pressure differences are also caused by uneven heating of earth's surface due to varying surface conditions such as sea, forests, ice and deserts. The Earth's rotation on its axis and the tilt of its axis w.r.t. to the orbit results in a perceived force by us, known as the Coriolis force. The atmosphere is dynamic and there is always a flux. Either it is warming up or cooling down, resulting in air moving from high pressure to low pressure zones. These movements can be over different geographic and time scales such as monsoons that are seasonal and happen over a continental scale or the land-sea breeze felt locally in coastal areas that has a diurnal cycle. Similarly, localized wind systems get established over deserts, mountains, valleys and large water bodies.

However, unlike sunshine that is relatively uniform in a given region over a given period of time, winds are fickle, varying in space and time, changing from place to place, and blowing in fluctuating strengths over different timescales from a few seconds to years.

Winds carry the kinetic energy of the atmosphere and this energy can be converted into usable electrical form by modern wind turbines. This electricity, transmitted through wires can meet energy requirements in areas far away from the point of generation. Harnessed on a large scale, wind generated electricity can flow into regional and national electricity grids to contribute towards meeting load and energy requirements.

As of June 2014, about 337 GW of wind power generation capacity has been set up in the world. This capacity is more than the total installed electricity generation capacity in some of the largest countries of the world. With such large wind power capacities having been installed and deployment in more than 100 countries, we can say that wind energy has arrived at the center-stage of the mainstream electricity sector.

Nearly all countries are exploring ways of utilizing indigenous wind energy resource. This calls for systematic efforts, assessments and planning. However, before planning utility-scale wind energy projects – an important question needs to be answered, which is:

In any given region, "how much electricity can be generated from wind, for how long over different time scales such as a day, month or year and ultimately what is the total quantum of such energy?

Anyone investing in wind turbine, small or big or in a large wind farm would like to know how much electricity can be generated so that the economic rationale of such an investment can be examined. The entity looking at this question could be a farmer, an investor, a financier, a utility manager or a policy maker.

At national and regional levels, governments, policy makers, regulators and international bodies such as for example World Bank, would like to know the extent to which wind can be harnessed on a large scale to contribute to the electricity supply system. It is this question: '*how much capacity and how much energy from wind?*' that we have tried to address in this report at a worldwide level.

In recent times, renewable energy, in particular, wind energy has come to occupy center stage in the electricity sector due to energy security and climate change concerns around the world. It is now an established scientific fact that anthropogenic activities are at the root of global warming. In 2004 burning of fossil fuels in Industry and in general for electricity generation accounted for nearly 45 % of total emissions[3]. Moreover, according to an assessment, electricity requirements are expected to grow by 43% in the next 20 years. Over the last 50 to 60 years, electricity generation has grown in most parts of the world. The steepest growth has been in developing countries. According to the Intergovernmental Panel on Climate Change (IPCC)[4], developed countries (UNFCCC Annex I countries) hold a 20% share in the world population but account for 46.4% of global GHG emissions. In contrast, the 80% of the world population living in developing countries (non-Annex I countries) account for 53.6% of GHG emissions. The implication is that balancing energy access, economic development and environmental sustainability is going to be a major challenge not only for the nations concerned but also for the global community. The potential for utilization of wind generated electricity, which we have assessed in this report, can play the most significant role in mitigating global warming.

About fifteen years back, wind turbines were a fringe technology, not taken seriously and often seen as mere nuisance to the conventional power systems. Today, however, with more than 337 GW of wind power generation capacity installed in more than 100 countries meeting more than 4% of the electricity requirements of the world, the status of the technology has changed dramatically. It's a mainstream technology now.

Technical and scientific studies, and technological developments in wind turbines, smart grid concepts, power system reliability, grid integration and energy storage systems consistently point towards the fact that in spite of winds being variable in nature, wind farms on a large utility scale can meet a very significant part of electricity and load in the power system without any adverse impacts on its reliability. In combination with other renewable energy based generating systems, wind energy has the potential to meet all the energy requirements.

Today, many parts of the world are known to meet a significant part of electricity requirements from wind. Denmark, parts of Texas, Tamil Nadu in southern India, Spain and Northern Germany have wind penetration levels as high as 40%.

The story of modern wind technology that spearheads the clean technology movement is phenomenal as it leads this society in its transition from an exploitive and an extractive society running on fossil fuels to a much more sustainable one. An environmentally sustainable society, in which not only the direct electricity requirements of citizens are met, but also, that in transport, in the factories and in the processes deployed, energy needs are met by renewable energy. Once harnessed on a large scale, we foresee a time when wind-generated electricity will flow into the grid to a much larger extent. Perhaps, even the transport and mobility sector will also draw upon this electricity. The main drivers of wind energy development across the world are energy security, GHG reductions, and energy access.

1.1. Energy Security Perspective

Across the world, increasing dependence on imported fossil fuels adds to national energy insecurity and uncertainty. Most countries do not have adequate indigenous fossil fuel reserves and hence have to import oil, coal and gas. For countries like India, this creates a significant foreign exchange imbalance. The existence and competitiveness of the manufacturing industry also depends on the price and availability of electricity. Fluctuations in price and supply uncertainty result in serious long-term concerns for a national economy.

While undoubtedly, GHG reduction is one of the main drivers for investments in wind energy in Europe, energy security is equally and sometimes a more urgent need. For a highly developed and industrialized region of the world, also subject to very cold conditions in winters, the prospect of energy shortage can be a serious concern. In recent times, Europe has faced some of these uncertainties in gas supplies from Russia. Even traditionally, fuel supplies from middle-east, in some manner, are a source of price and supply uncertainty. Europe's import dependency on fossil fuels is expected to rise. Imported gas is likely to make up 80% of consumption by 2030[5]. Of the many policy and strategy options of a secure energy future, wind power development is a major option that has been pursued along with other renewable energies.

Likewise, in United States, more than 80% of energy consumed comes from oil, natural gas or coal[i]. Main energy consuming sectors are transportation, electricity generation, industrial processing and heating, ventilation and air conditioning (HVAC). By the end of 2013 more than 61.1 GW of wind power capacity had been installed in the US that generated nearly 171.02 TWh, accounting for 4.2% of electricity generated in US. Investments in wind energy are seen as diversification of energy supply sources that adds to energy security.

Similarly, India, the largest energy consumer in Asia after China has heavy dependence on fossil fuels amounting to nearly 72% of the total energy supplied in the country. In spite of large coal reserves, the country imports nearly 100,000 tons of coal. Oil imports are of the order of USD 100 billion. Heavy and growing dependence on imported fossil fuels, apart from adding to energy insecurity creates serious monetary problems for the country. India has achieved nearly 21 GW of cumulative installed capacity of wind power by the end of March 2014.

In the aforementioned case of China, energy security is of immense importance because of massive industrialization, urbanization and economic development that has taken place in recent years. The country came up with its renewable energy policy in 2005 and in about 8 years has emerged as the leading country with more than 91 GW of wind farm capacity.

A major driving force for wind power development in Europe, China, US and India is energy security. Sum total of cumulative installed capacities in these regions is about 297 GW (at the end of 2013), which is about 93% of the total installed capacity in the world (see Figure 1.0).

Energy security should be equally important to many other countries. Significant installations have also come up in Canada (7.7 GW), (Brazil 3.4 GW), Mexico (2 GW) and Japan (2.7 GW) and together these countries account for 5% of the total installed capacity.

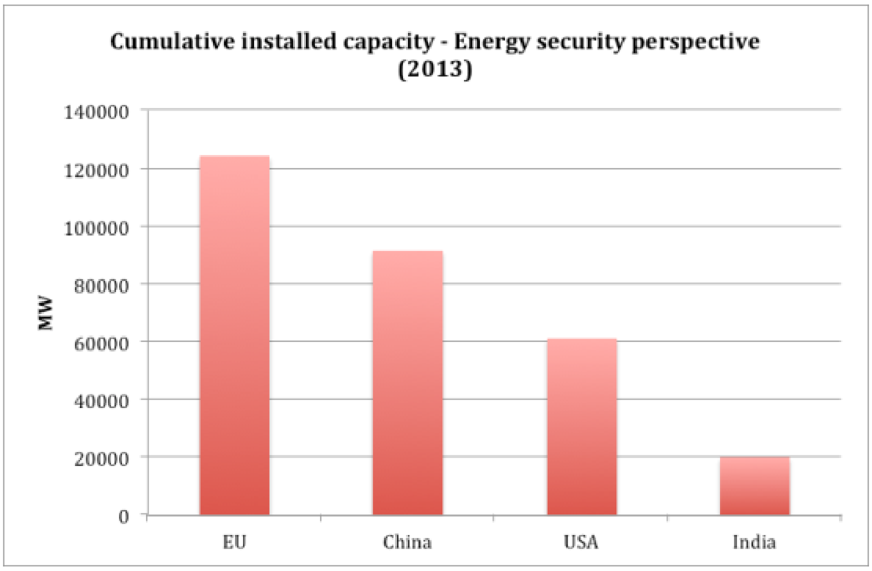


Figure 1.0: Cumulative Wind Power installed capacity (Energy Security Perspective)

1.2. Climate Change Perspective

The Intergovernmental Panel on Climate Change (IPCC) has established that the climate is changing across our planet, largely as a result of human activities that have led to accumulation of greenhouse gasses (GHG) in the atmosphere in the last two centuries. Between 1971 and 2010, global CO2 emissions almost doubled and about 44% of these emissions in 2010 were from electricity sector[4]. Wind energy utilization leads to avoidance of GHG emissions. The IPCC, in its recently published 5th Assessment Synthesis Report[5] has said:

> *Global warming mitigation pathways would require substantial emissions reductions over the next few decades and near zero emissions of CO2 and other long-lived GHGs by the end of the century….. Global mean surface temperature increases in 2100 in baseline scenarios – those without additional mitigation – range from 3.7 to 4.8°C above the average for 1850-1900 for a median climate response.*

According to the IPCC, wind energy offers significant potential for near-term (2020) and long-term (2050) greenhouse gas (GHG) emissions reductions. The EU has set itself targets for reducing its greenhouse gas emissions progressively up to 2050. Under the Kyoto Protocol, the 15 countries that were EU members before 2004 ('EU-15') are committed to reducing their collective emissions by 8% below 1990 levels by the years 2008-2012. For 2020, the EU has committed to cutting its emissions by 20% below 1990 levels, 40% by 2030 and 80-95% by 2050. More recently[6] European leaders have struck a broad climate change pact obliging the EU as a whole to cut greenhouse gases by at least 40% by 2030.

In 2012, the electricity sector was the largest source of United States' greenhouse gas emissions[7], accounting for about 32% of the US total. Greenhouse gas emissions from electricity have increased in the country by about 11% since 1990 as electricity demand has grown and fossil fuels have remained the dominant source for generation. The US were also the second largest emitter of CO2 in 2010.

China is the largest emitter of CO2 followed by US, EU-15 and India in that order.

Thus it can be seen that the countries that have together set up 93% of wind power capacity till date are also the largest emitters of CO2. Climate change concern has also contributed to their decisions and actions in setting up wind farms.

1.3. Energy Access Perspective

The per-capita energy consumption as well total electricity consumption in vast areas of the developing world is a fraction of electricity in some of the rich and developed countries. In as many as 77 countries more than 25% of the population has no electricity access. Most of Africa and large parts of Asia fall in this category. Figure 2.0 shows the number of countries with varying degrees of electricity access from less than 10% to 100%. Figure 3.0 presents the world map with per capita energy consumption in kg of oil equivalent.

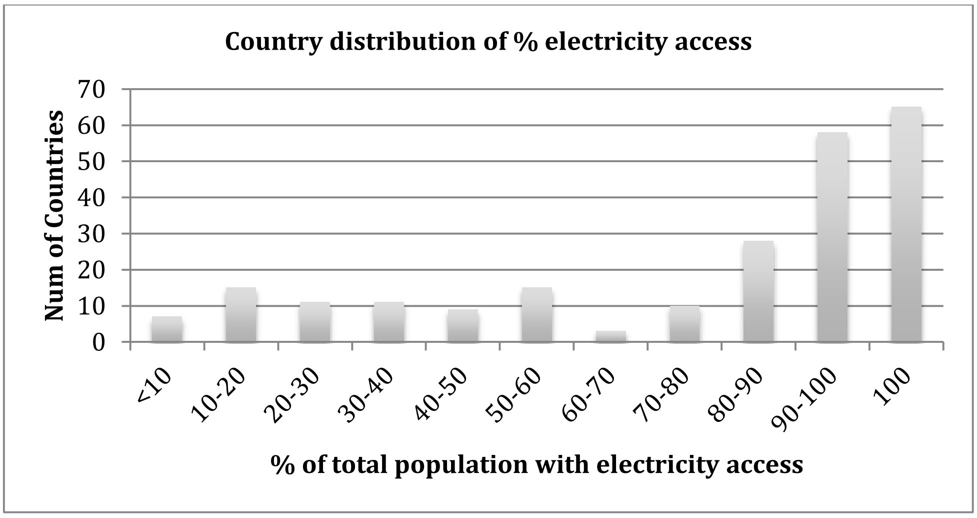


Figure 2.0: Global Electricity Access (Data source: World Bank)

Therefore, one can see that electricity access, too, is going to be one of the main drivers of wind power development in those countries that have adequacy of wind resources. In countries with less than 50% electricity access, wind power generation in combination with solar energy, biomass and hydro can be a low-carbon solution. Wind mapping programs being carried out under various projects including those of World Bank (ESMAP) or other agencies indicate that many African countries like Morocco, Egypt, Ethiopia, Kenya, etc…. have excellent wind resources and wind-solar hybrid projects in the form of micro grids or directly connected to the main grid can be major sources of energy for these countries.

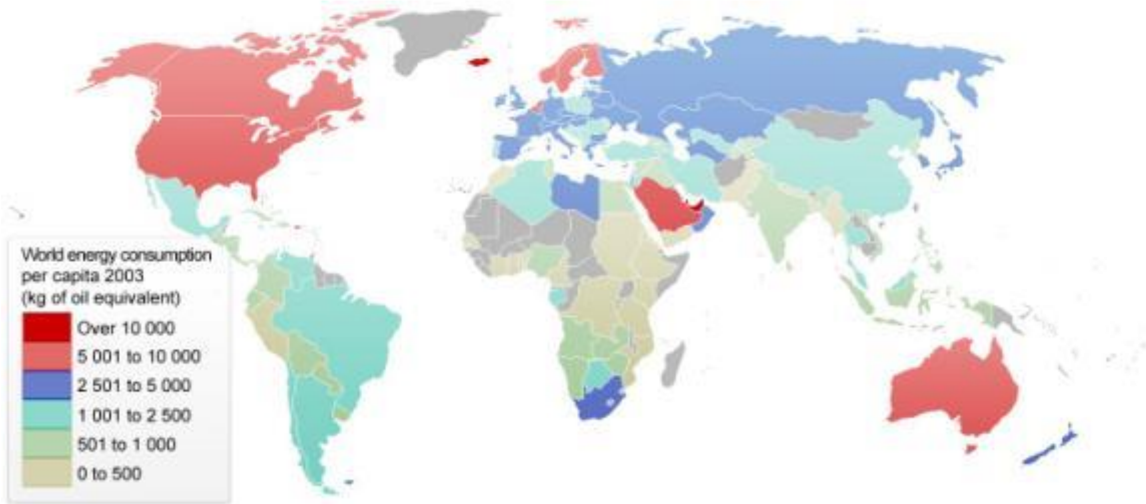


Figure 3.0: Per Capita Energy Consumption[i]

The contribution of wind energy in meeting the electricity requirements of the world is bound to grow significantly because of several drivers at work globally. Energy security, environmental sustainability, climate change, energy access and economic growth are some of the major drivers of clean energy across the world and within the clean energy sector, wind energy is the fastest growing technology and also the most predominant.

[i] Source: http://en.wikipedia.org/wiki/List_of_countries_by_energy_consumption_per_capita
Re-used under the terms of the GFDL and CC-By-SA 2.5 licenses
By: Shahyar Ghobadpour, May 25th, 2007

Wind Resource Assessment

Winds are felt everywhere, yet their strength and the energy content in them varies from place to place. In order to carry out wind resource assessment at any given location, one needs to figure out the strengths (speed) of winds at that location over a sufficiently long period of time to make a long-term assessment about electricity that can be generated using modern wind turbines. In some places, wind speeds in general can be low and it may not be possible to extract energy meaningfully or in sufficient quantum to make economic sense. However, there can also be places where wind speeds are generally very high and can be harnessed in a profitable manner. Similarly, there can be locations that experience mediocre wind speeds and it may make sense to harness these winds under certain conditions – such as a location being far from the electricity network like an island or a remote place in a desert.

The Wind Resource Assessment (WRA) is the most important aspect of the entire business of harnessing wind energy or wind power development. Apart from providing information on strengths of wind speeds and the energy content in them, it also enables selection of the appropriate type of wind turbine design for deployment at a given location or in a region. For example, the International Electrotechnical Commission (IEC) classification of wind turbines in to Class I, Class II, Class III and Class IV turbines. These turbine classes are meant for different wind regimes varying from mean annual wind speed of 10 m/s to 6 m/s.

At project level, WRA enables project developers and investors to take a "go"/ "no go" decision with respect to that project and at a national or regional level it enables the concerned governments or agencies involved to figure out if there is enough potential to harness wind energy and if such potential to be harnessed on a large scale, requires some policy frameworks. To the major wind turbine suppliers, WRA at regional level can be used to decide on the WTG types that should be designed and marketed in that region and similar other regions of the world.

There are two different kinds of wind resource assessment exercises. One, relating to project level assessment which turns out to be a very detailed micro analysis with each wind turbine position and the other is a macro level assessment to find out wind resource areas and to assess the potential for wind energy utilization. Macro assessment happens at a regional or country level. A macro assessment can also be at global level, as we see later in this paper.

2.1. Project level WRA

Someone setting up a wind farm project or even a single wind turbine should have the knowledge of the characteristics, speeds and patterns in variations of winds at the location of interest. Such information can either be derived from secondary sources or in a primary manner through measurements at the site. In any case, one should be knowledgeable about wind turbine technology types and their performance characteristics so that analysis can be carried out with respect to specific models of wind turbines. Since winds vary from place to place, in case of any project involving even a few turbines, one would like to carry out measurements at one or more locations within the project site depending upon the extent of the site and its topography. It is recommended that these measurements are in accordance with IEC[8] standards.

To answer the question 'how much capacity and how much energy?' In short, WRA for the site, one needs to plan an optimized layout of a cluster of wind turbines and simulate its operation at least over a one year period to assess the annual energy output from wind turbines. The simplest way would be to run the short-term (10 min) averages of wind speeds through the wind turbine characteristics, which are the power and thrust curves of the wind turbine. Figures 4.0 and 5.0 present power and thrust curves of a typical wind turbine. For a single wind turbine, one can construct the wind speed histogram at site (Figure 6.0) or use one of the standard distributions such as Weibull, Rayleigh or Gaussian distributions in arriving at Annual Energy Output (AEO) from the wind turbine.

It is also possible to arrive at AEO using mathematical formulations. Lysen (1982)[9], in his book "Introduction to Wind Energy", has provided a comprehensive treatment on analysis of wind speeds, assessment of the frequency distribution parameters and modeling of the wind turbine power curve. A more recent book, Manwell et al. (2009)[10] and many other books also presents these formulations. An important fact presented in these books is that wind speed frequency distribution can be approximated by a Weibull distribution, which is described by shape parameter "k" and scale parameter "c". The Weibull distribution is one of the most widely used distributions in reliability engineering and it is a versatile distribution that can take on the characteristics of other types of distributions based on the value of shape parameter "k". It is used in survival analysis, reliability and failure analysis, manufacturing and delivery times, extreme value theory and weather forecasting[11]. Rayleigh distribution, a special case of Weibull distribution with k = 2, is also widely used to represent wind distributions.

Formulations presented by Lysen (1982) for calculation of wind speed frequency distribution Probability Density Function (PDF) and for energy calculations are well known and have been widely used in industry and academia. There has also been a debate on whether Weibull distribution is an adequate representation of wind speed distributions. Research carried out in recent times shows that a better fit to wind distributions can be obtained using multi-peak Gaussian distributions[12]

2.2. Modeling wind-farms

For wind farms or clusters of wind turbines, there are many models based on boundary layer theory or computational flow dynamics, which can simulate the performance of a wind farm over a defined period of time (1 year). These models account for ground elevation variations between the wind turbines and with respect to wind measurement mast as well as sensor heights and the wake effect of one wind turbine on the other. Some of the well-known models are Wind Atlas Analysis and Application Program (WAsP), Wind farmer and Meteodyne. These simulations require careful handling of wind speed and related data, its preparation for simulation and understanding of terrain and surface conditions.

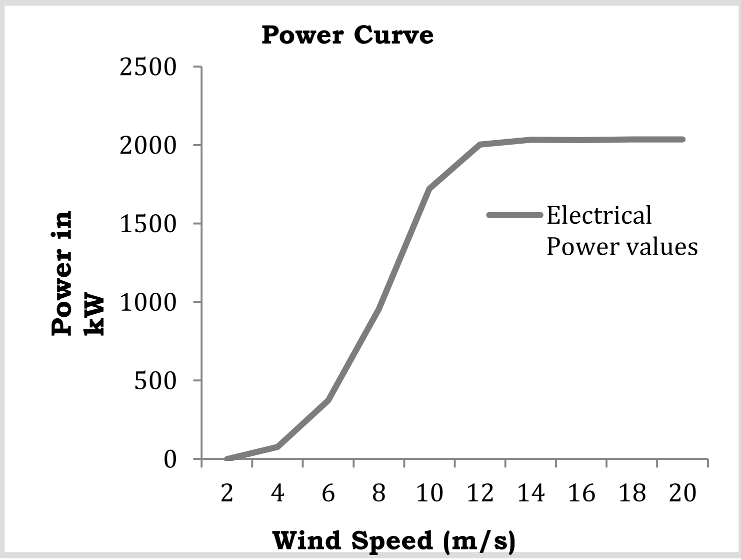


Figure 4.0: A Typical power curve

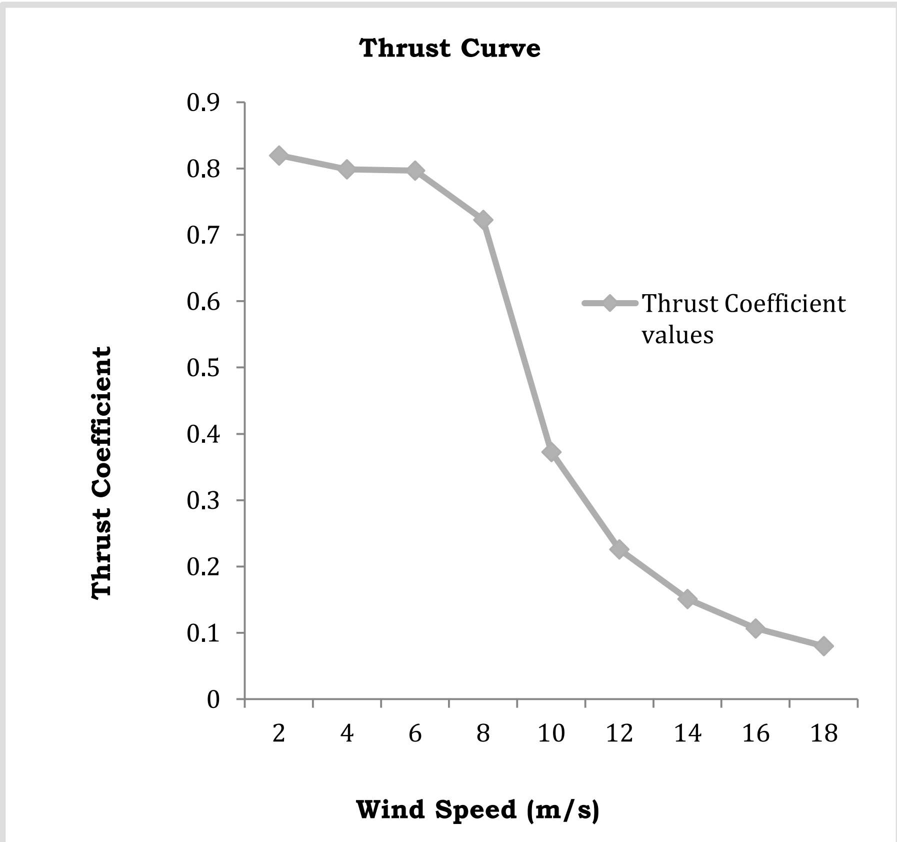


Figure 5.0: A Typical thrust curve

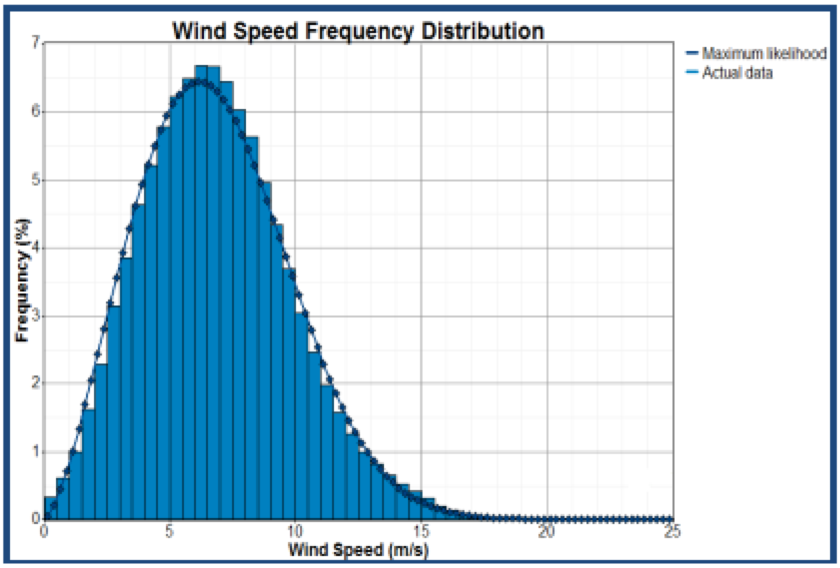


Figure 6.0: A Typical wind speed distribution

Meso-map studies

Wind resource assessment studies or wind potential assessment studies are also carried out at a macro level involving large regions over several thousand square kilometers. These studies are either meant for planning and policy purposes or to have an indicative idea about high potential areas. Such studies are also called meso-map studies. Typically, a meso-map system will have following elements:

1) Meso-scale Atmospheric Simulation System (MASS)
2) Datasets

   i) Reanalysis Dataset; ii) Measured Dataset; iii) Validation Dataset

MASS itself can have many sub models and can also be of two different types.

1) Models based on fluid dynamics that simulate fundamental physics of the atmosphere including conservation of mass, momentum, and energy. It contains a turbulent kinetic energy module that accounts for the effects of viscosity and thermal stability on wind shear. As a dynamical model, MASS simulates the evolution of atmospheric conditions in time steps. Depending on the time step, computational requirements can be rather huge.
2) Boundary Layer Model that can use both measured and Reanalysis data, applies concepts of Planetary Boundary Layer (PBL) physics on a Geographical Information System (GIS) platform. This is not a time step simulation and works on long-term parameters such as average annual wind speeds measured at different points in a region or long-term annual average, long-term Weibull parameters assessed, air density, etc. However, as in MM5 and WRF, open data such as NCEP/NCAR Reanalysis data along with measured data are effectively used.

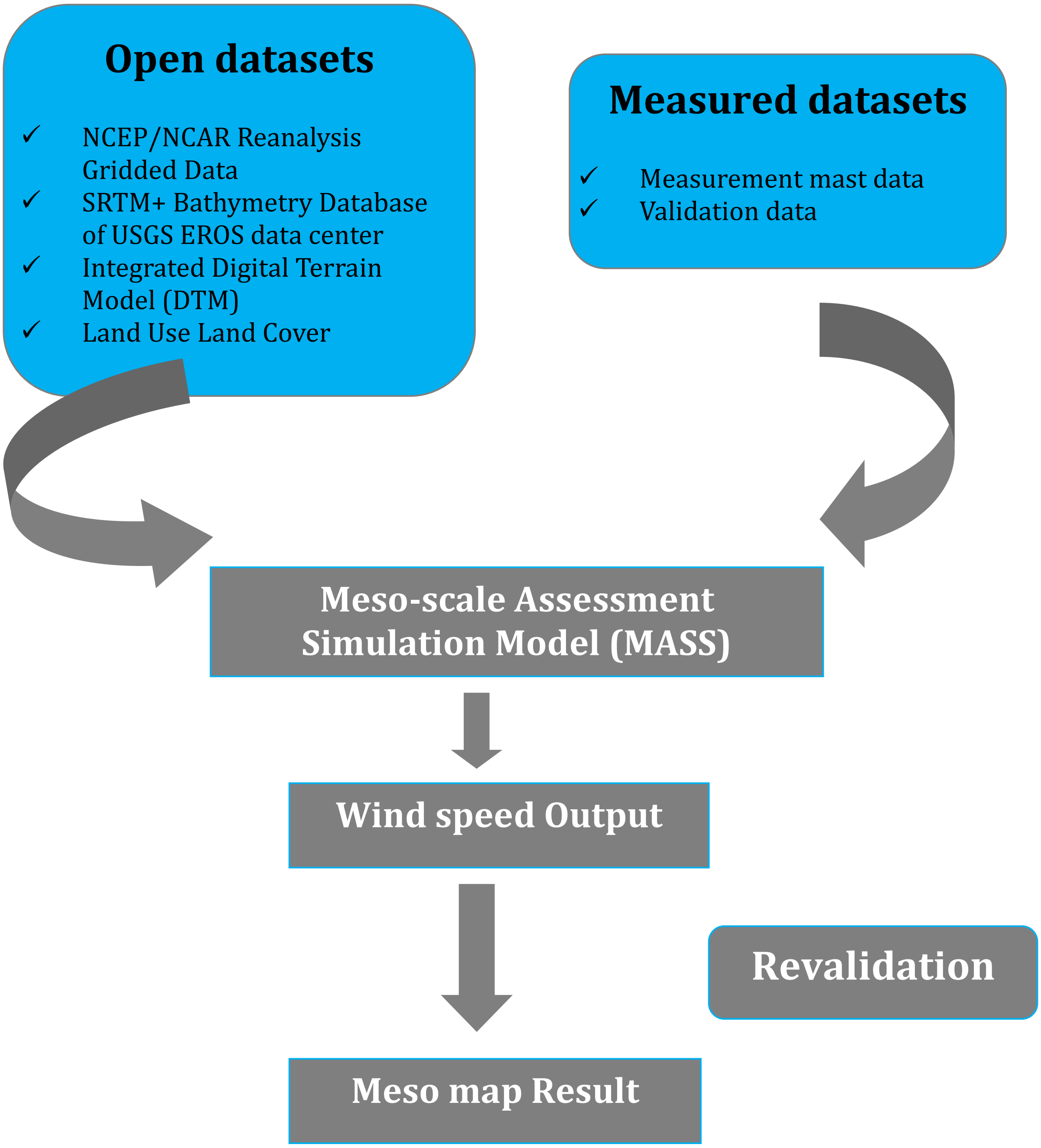


Figure 7.0: Flow diagram of meso-map exercise

3.1. Secondary data

An important secondary data source that has emerged over the last 15 years is gridded reanalysis data. There are different datasets such as NCEP/NCAR, MERRA etc.

The NCEP/NCAR Reanalysis[13] Project is a joint project between the National Centre for Environmental Prediction (NCEP, formerly "NMC") and the National Centre for Atmospheric Research (NCAR). The goal of this joint effort is to produce new atmospheric analyses using historical data as well as to produce analyses of the current atmospheric state (Climate Data Assimilation System, CDAS). It contains the information of climate variables with different time setups. A large subset of this data is available in its original 4 times daily format, daily averages and monthly averages and at various spatial resolutions. This dataset is available at various spatial resolutions of 0.5, 1, and 2.5 degree from 1948 till present. The original data has been collected from different data sources like, Comprehensive Ocean-Atmospheric Data Set includes (COADS), surface marine data, ships, fixed buoys, drifting buoys, pack-ice buoys, and near-surface data from ocean station reports. These data are quality controlled and assimilated with a data assimilation scheme that is kept unchanged over the reanalysis period to eliminate perceived climatic changes due to changes in the data assimilation scheme.

Meso-map models

3.2. Weather Research and forecasting (WRF)

The Weather Research and Forecasting (WRF) model[14] is a Numerical Weather Prediction (NWP) and atmospheric simulation system designed for both research and operational applications. NWP refers to the simulation and prediction of the atmosphere with a computer model, and WRF is a set of software for this. WRF features two dynamical parts, a data assimilation system, and a software architecture allowing for parallel computation and system extensibility. The model serves a wide range of meteorological applications across scales ranging from meters to thousands of kilometers. Some of the applications include:

- ✓ Meteorological investigations
- ✓ Real-time NWP
- ✓ Idealized atmospheric simulations
- ✓ Data assimilation studies and development
- ✓ Coupling with other earth system models

The two dynamical solvers and the variants of the model are known as WRF-ARW (Advanced Research WRF) and WRF-NMM (Non hydrostatic Meso-scale Model).

The Advanced Research WRF (ARW) is supported by NCAR meso-scale and microscale meteorology division. The WRF model can be run with either idealized or real-data initialization. In the recent release of WRF ARW, the tool supports programs that also generate input data for the WRF model.

The function of the WPS is to define WRF grid, generate map, elevation and land information for WRF, take real-data analyses/forecasts from other models, and interpolate the data to the WRF grid. The standard output from WPS, real, and WRF model is in netCDF format.

3.3. MM5 Modeling System

The PSU/NCAR meso-scale model (known as MM5) is a regional meso-scale model used for creating weather forecasts and climate projections. It is a community model maintained by Penn State University and the NCAR. The Weather Research and Forecasting model (WRF) was designed as the successor to MM5 and includes all capabilities available within the MM5. The model is a limited-area, non-hydrostatic model designed to simulate meso-scale atmospheric circulation. The model works with terrestrial and isobaric meteorological data, horizontally interpolated from a latitude-longitude grid to a variable high-resolution domain.

3.4. Boundary Layer Model

The boundary layer model (BLM) is a simulation model developed by "WinDForce", where a hypothetical field of boundary layer is created over a region of interest (RoI) with long term averaged data such as mean annual wind speeds, power law index, shape factor etc. The output derived from the BLM is used as an input in the meso-map model where it is mapped on every cell in the grid in the RoI to arrive at mean wind speed at specified height. This model also takes into account information on areas that are not suitable for wind power development such as areas marked out for urban expansion, densely populated regions, national parks, forest reserves, swamps and water bodies. Such areas can be masked out in the assessment.

Worldwide studies

It is widely accepted in scientific community that there is enough power in the Earth's winds to be a primary source of near-zero-emission electric power as the global economy continues to grow through the twenty-first century [15]. Wind Potential assessment studies carried out in the last 10 years or so have resulted in a phenomenal enhancement of knowledge with regard to global wind energy potential. Studies indicate that the near surface winds on earth that we measure and we harness today for power generation, seem to be indicative of a potential, which in a sense is just the tip of the iceberg. As we go up in the atmosphere wind speeds increase dramatically after 2,000 m above ground till 10,000 m. The global area-average of the median wind power densities at 1,000 and 10,000 m are 422 and 2,282 W/m2 respectively (Cristina L. Archer and Ken Caldeira, 2009)[16], which means that given a viable technology, winds in high altitudes can meet electricity requirements on Earth in a sustained and reliable manner. The present day wind turbine technologies barely get beyond 100 m above ground. Some of the latest large wind turbines have been set up at 120 m. Even at 80 m above ground, the potential assessments are of the order of 400 TW[13].

4.1. Global Studies

A number of studies carried out to assess the utilizable potential of wind energy at Global level have come up with large numbers, which are many times higher than the total electricity generation capacity in the world (Nearly 6250 GW)[17]. Assessment of global wind potential with 1.5 MW by Cristina Archer and Mark Jacobson (2005) is one of the best-known studies. With 1.5 MW wind turbines at 80 m hub height, this assessment projects a worldwide potential of 72000. GW. Xi et al. (2009) have concluded that a network of 2.5 MW land based wind turbines set up at 100 m hub height restricted to non-forested, ice-free, nonurban areas operating at as little as 20% of their rated capacity could supply >40 times current worldwide consumption of electricity (which is nearly 20 TWh) and >5 times total global use of energy in all forms. Similarly, Kate et al.[15] in a study published in 2013 have assessed a global wind energy potential of 400 TW. The results of these studies are summarized in Table 1.0.

Cristina and Xi Lu have undertaken their studies in 2005 - 2009, however, by now (in 2014), research and development in wind turbine technologies has resulted in designs that are optimized for lower wind regimes. The wind turbines now have more swept area per megawatt and are set up on higher towers up to 100 m. Some equipment suppliers are experimenting with 120 m towers. This means more energy generation per megawatt installed and, as a result many sites that may not have been feasible in the earlier studies mentioned above, become feasible with current technologies now. Therefore, the realizable offshore and onshore potential for wind energy utilization with the currently available technologies is sufficient to meet electricity requirements of the entire world many times over. We see in the review of scientific studies carried out that there is indeed enough energy in the winds that blow on the surface of this planet to meet all energy requirements.

It is, therefore, reasonable to conclude that looking at global electricity requirements and even growth in electricity over the next few decades, it is indeed possible to meet all electricity requirements with technologies and options that are a combination of wind, solar, hydro and biomass and storage technologies and devices. Technically, it is possible to phase out nuclear and fossil fuel based generating stations.

Figure 8.0: An offshore wind turbine

Table 1.0: Studies on global wind energy potential

Global Potential (GW)	Study	Remarks
3,500,000	King Hubbert (1971)[18]	Considering 2% of all Solar energy received on Earth is converted to Wind.
54,794	Monique Hoogwijk, 2004	Converted from 96 PWh/yr assuming CUF 20%
72,000	Cristina L. Archer and Mark Z. Jacobson 2005[19]	Considering 1.5 MW WTG at 80m hub ht
479,452	Xi Lu, Michael B. McElroy, and Juha Kiviluoma. 2009[20]	Considering 2.5 MW WTG at 100 m Hub height and assuming a 20% CUF
400,000	Kate Marvel, Ben Kravitz, & Ken Caldiera 2013[15]	80 m above ground level

4.2. Regional and country level studies

There have also been many regional and country level studies that indicate vast potential for utility scale wind power generation. In a pioneering initiative US based National Renewable Energy Laboratory (NREL) has carried out a number of studies and developed wind-maps for many countries across the world, particularly developing regions. Many other studies have been carried out by individual researchers and other institutes across the world. These studies listed in table 2.0, indicate immense potential in many countries, which was previously unknown. For example, 158 GW in Afghanistan or 2600 GW in China. Table 2.0 lists the estimates of wind energy potential for countries around the world, at different heights and with different wind turbine technologies.

At international level, there are now many other agencies also involved in developing wind maps for different parts of the World. For example Energy Sector Management and Assistance Program (ESMAP) of the World Bank is currently involved in developing these maps for different regions, a major focus being Africa. Similarly other international organizations and foundations are also involved in supporting such regional assessment.

Table 2.0: Estimates of wind potential in various countries around world

Region	Potential in country/ region (GW)	Data Source (Report, article, etc)	Remarks
India	1700	Hossain et. al, 2011[21]/ 2013[22]	With 2.1 MW S88 WTG of Suzlon at 80 m height
	3200		With 2.1 MW S88 WTG of Suzlon at 120 m height
	900	Offshore Hossain 2013[22] /Ansari et. al. 2014[23]	With 7 MW Vestas WTG at 120 m
Afghanistan	158	Wind Resource Assessment & Mapping for Afghanistan & Pakistan – Dennis Elliot et. al., NREL (2007)[24]	5 MW/km² assumed. Almost 5% of total land area above NREL Class 4 at 50m HH
Albania	11.7	Wind Energy Resources Assessment, Republic of Albania, Final Report (2007)[25]	@ 50 m height. AEP between 3000 to 25,800 GWh/year
Armenia	11.05	Wind Energy Resource Atlas of Armenia – D. Elliot et. al., NREL (2003)[26]	5 MW/km² assumed. Almost 7.8% of total land area above NREL Class 3 at 50m HH
Belize	3.68	Central America Wind Energy Resource Mapping Activity – NREL, SWERA Project (2006)[27]	5 MW/km² assumed. Almost 1.1% of total land area above NREL Class 3 at 50m HH
Central America (Belize, El Salvador, Guatemala, Honduras, Nicaragua)	131.20	Central America Wind Energy Resource Mapping Activity – NREL, SWERA Project (2006)[27]	5 MW/km² assumed. Almost 6.7% of total land area above NREL Class 3 at 50m HH
China	2600	High resolution mapping activity for China Wind Energy Resource – China Meteorological Administration, 2012[28].	1.5 - 5 MW/km² assumed with different geographic condition. Almost 7.3% of total land area above NREL Class 3 at 70m HH and available for wind farm building.
Cuba	21.40	Cuba Wind Energy Resource Mapping Activity – NREL, SWERA Project[29]	5 MW/km² assumed. Almost 3.9% of total land area above NREL Class 3 at 50m HH
Dominican Republic	30.50	Wind Energy Resource Atlas of Dominican Republic – D. Elliot et. al., NREL[30]	@ 30m height & above avg. wind sped 6.1m/s. Assumptions: 500 kW 40m HH 38m Rotor Dia. turbines at 10D x 5D spacing at 6.9 MW/km²

El Salvador	12.85	Central America Wind Energy Resource Mapping Activity – NREL, SWERA Project (2006)[27]	5 MW/km^2 assumed. Almost 6.6% of total land area above NREL Class 3 at 50m HH
Germany	1188	Umweltbundesamt, UBA[31]	3.4/ 3.2 MW wind turbines at 100 m hub height
Ghana	5.64	Ghana Wind Energy Resource Mapping Activity – NREL, SWERA Project[32]	5 MW/km^2 assumed. Almost 0.5% of total land area above NREL Class 3 at 50m HH
Guatemala	17.22	Central America Wind Energy Resource Mapping Activity – NREL, SWERA Project (2006)[27]	5 MW/km^2 assumed. Almost 1.4% of total land area above NREL Class 3 at 50m HH
Honduras	25.26	Central America Wind Energy Resource Mapping Activity – NREL, SWERA Project (2006)[27]	5 MW/km^2 assumed. Almost 1.9% of total land area above NREL Class 3 at 50m HH
Israel	3	Israeli Wind Energy Association – ISRAWEA	Based on the wind map released by the ISRAWEA and IMS
Kazakhstan	354	IRENA Case Study 2013 – Wind Atlas Kazakhstan[33]	A study commission by the UNDP-GEF project – Wind potential resource 929 TWh/year
Kenya	2.25	–WinDForce Wind Energy programme for Government of Kenya[34]	1 MW/km^2 assumed. 26% of the total area falls in wind speed area more than 6.0 m/s and 37% in less than 6.0 m/s at 80m height
Mongolia	1113	Wind Energy Resource Atlas of Mongolia – D. Elliot et. al., NREL (2001)[35]	@ 30m height & above NREL class 3. Assumptions: 500 kW 40m HH 38m Rotor Dia. turbines at 10D x 5D spacing at 6.9 MW/km^2
Nicaragua	72.17	Central America Wind Energy Resource Mapping Activity – NREL, SWERA Project (2006)[27]	5 MW/km^2 assumed. Almost 5.9% of total land area above NREL Class 3 at 50m HH
Other CIS	41.3	Ukrainian Wind Energy Association / CIS WWEA	Economically viable potential
Pakistan	132	Wind Resource Assessment & Mapping for Afghanistan & Pakistan – NREL (2007)[36]	5 MW/km^2 assumed. Almost 3% of total land area above NREL Class 4 at 50m HH
Philippines	173.6	Wind Energy Resource Atlas of the Philippines - D. Elliot et. al., NREL (2001)[37]	@30m height & above NREL class 3. Assumptions: 500 kW 40m HH 38m Rotor Dia. turbines at 10D x 5D spacing at 6.9 MW/km^2
Russia	36000	Wind Energy in Russia – G. Dmtriev, VetrEnergo for Gaia Apatity and INFORSE-Europe First Part – (2001)[38]	Gross wind energy potential of 8000 TWh/year for Russia, converted into TW assuming a Plant Load Factor of 25%
Sri Lanka	51.13	Wind Energy Resource Atlas of Sri Lanka and the Maldives - D. Elliot et. al., NREL (2003)[39]	5 MW/km^2 assumed. Almost 15.58% of total land area above NREL Class 3 at 50m HH. Lagoons included.

Turkey	10	US Department of Energy-Office of Fossil Energy, An Energy Overview of the Republic of Turkey (2005)[40]	Economically viable potential

In an assessment by European Environment Agency[41], the technical potential for onshore and offshore region for the years 2020 and 2030 is assessed to be 70,000 and 75,000 TWh. Assuming the wind power plant runs at a Capacity Utilization Factor (CUF) of 23%, the potential is assessed to be 35 TW and 37 TW for the year 2020 and 2030 respectively. The figure 9.0 highlights the technical potential for onshore wind energy up to 2030 based on estimated 80m average wind speed for all European countries in each Land Use category while, the total figures are given in the table 4.0.

Hossain (2011[42] and 2013[43]) conducted a pioneering assessment of wind potential in India. An assessment carried out in 2011, for the first time came up with figures that were significantly higher than the assumptions and understanding till that time. This assessment has subsequently been revalidated by a number of independent studies undertaken by different institutions including Lawrence Berkley National Laboratory (LBNL)[44], World Institute of Sustainable Energy (WISE)[45], The Energy & Resources Institute (TERI)[46] and Center for Study of Science, Technology and Policy (CSTEP)[47].

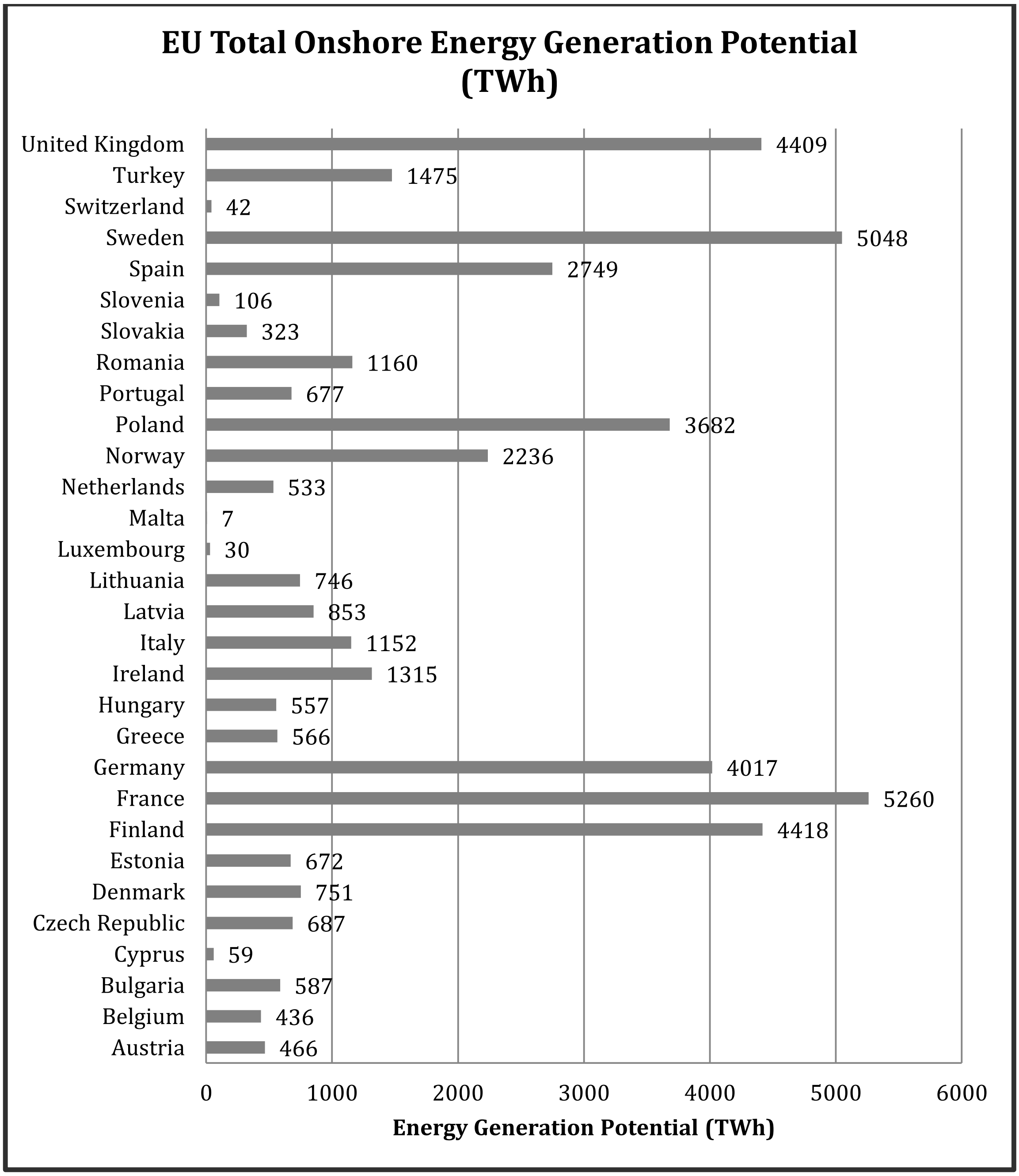


Figure 9.0: Technical potential for onshore wind energy up to 2030 based on estimated 80m average wind speed[33]

In another assessment on Offshore wind potential, Hossain (2013[22]) and Ansari et. al (2014[48]), the theoretical offshore wind potential of India is assessed to be 966 GW. The potential is assessed at 120m height considering high capacity wind turbines. The state wise potential of the country both offshore and onshore is given in table 3.0. The Ministry of New and Renewable Energy (MNRE), Government of India (GoI) has now constituted a committee comprising of experts representing different stakeholder groups to come up with a national assessment figure for the country. The need for such an assessment, acceptable to all stake holders stems from the need to have a realistic understanding of such potential from a policy perspective.

Table 3.0: State-wise onshore and offshore wind potential of India

State wise	Potential (GW)	Data Source (Report, article, etc)	Remarks
Onshore wind potential			
Punjab	2	Hossain et. al, 2011[21]/ 2013[22]	With 2.1 MW S88 WTG of Suzlon at 80 m height
Goa	4		
Madhya Pradesh	13		
Orissa	14		
Rajasthan	148		
Kerala	149		
Maharashtra	172		
Tamil Nadu	199		
Gujarat	295		
Karnataka	331		
Andhra Pradesh	384		
Offshore wind potential			
Gujarat	262	Hossain et. al 2013[22] Ansari et. al. 2014[23]	With 7 MW Vestas WTG at 120 m
Maharashtra	105		
Karnataka	76		
Kerala	82		
Tamil Nadu	187		
Andhra Pradesh	108		
Orissa	98		

In a study by African development bank, countries namely Somalia, Sudan, Libya, Mauritania, Egypt, Madagascar, Chad, Kenya etc. have been found to have large onshore wind energy potential[49]. While, countries such as Mozambique, Tanzania, Angola, South Africa and Namibia have potentially large offshore wind energy resources. Despite high wind potential, the installed capacity in Africa is only 1.1 GW in 2011.

NREL also estimated the wind energy potential for each state in US using third party data. The wind potential estimates are based on meso-map studies, where LULC category not suitable for wind farm development is excluded. A capacity factor of 5 MW/km^2 has been assumed for estimation. Table 5.0 presents potential assessed and the total potential assessed by NREL for US is of the order of 11 TW.

Worldwide potential assessed in this manner from country and region-wise data and based on our literature search, which is not as exhaustive as one would desire, turns out to be nearly 94.5 TW. It can be seen in table 6.0 that the potential assessed for US, EU and Russia is higher than that for the rest of the world. This, we feel is due to two main reasons – first, the north latitudes are subject to high wind speeds and therefore North America, Ireland and Northern parts of Europe, Siberian and north Russian regions should experience high wind speeds and second, the fact that these US and EU have far better concentration of wind measurement points and much more stronger database than that in other parts of the world. In reality, the potential for rest of the world should be significantly higher than 10 TW. It may also be noted that the order of magnitude arrived at through the summation of regional and country studies is similar to some of the global studies cited in table 1.0. According to the IEA, the world's total energy consumption for all sectors, including industries, heating and cooling as well as transport, in 2011 was 103'711TWh[1], which included 19'299 TWh[2] for power consumption. We therefore, conclude there is enough energy in the winds blowing on the surface of Earth to meet all its energy requirements

Table 4.0: Projected technical potential for wind energy development in EU-27[33]

		Year	TWh	Potential (TW)
	Onshore	2020	45000	22.5
		2030	45000	22.5
Technical Potential	Offshore	2020	25000	12.5
		2030	30000	15
	Total	2020	70000	35
		2030	75000	37.5

Table 5.0: Wind energy potential for each state in U.S (in MW) [25]

State	Wind Energy Potential at 80m
Alabama	118
Alaska	494703
Arizona	10904
Arkansas	9200
California	34110
Colorado	387220
Connecticut	27
Delaware	10
Georgia	130
Hawaii	3265
Idaho	18076
Illinois	249882
Indiana	148228
Iowa	570714
Kansas	952371
Kentucky	61
Louisiana	410
Maine	11251
Maryland	1483
Massachusetts	1028
Michigan	59042
Minnesota	489271
Mississippi	0
Missouri	274355
Montana	944004
Nebraska	917999
Nevada	7247
New Hampshire	2135
New Jersey	132
New Mexico	492083
New York	25781
North Carolina	808
North Dakota	770196
Ohio	54920
Oklahoma	516822
Oregon	27100
Pennsylvania	3307
Rhode Island	47

South Carolina	185
South Dakota	882412
Tennessee	309
Texas	1901530
Utah	13104
Vermont	2949
Virginia	1793
Washington	18479
West Virginia	1883
Wisconsin	103757
Wyoming	552073

Table 6.0: World total assessed potential from Country-wise data (in TW)

US	11
EU	37.5
Russia	36
Rest of the World	10.3953
Total	94.8953

Regional & Country wind maps

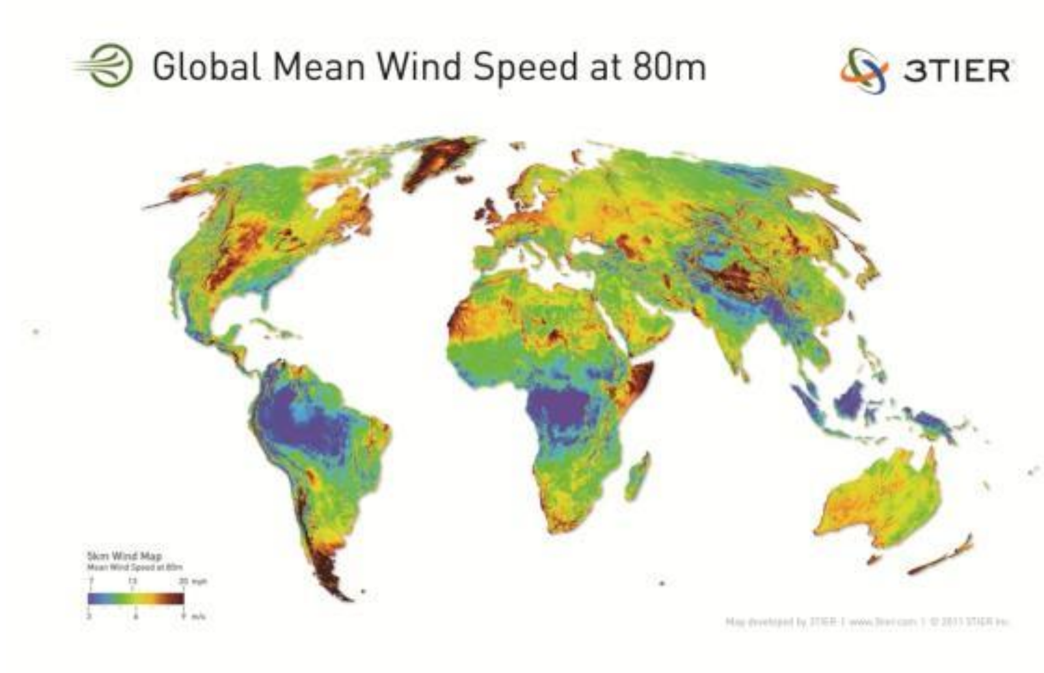
Global, regional and many of the country maps from different sources are presented in this section. It is worth noticing that many areas of the world with vast wind energy potential are not really very close to load centres. While wind turbines are known to generate electricity in distributed manner often for consumption at local load centres, in the long term for wind to emerge as a mainstream source of energy, more than what it is today, one may have to explore large scale generation in high potential areas and transmission of electricity over hundreds of kilometers on high voltage AC or high voltage DC. Such high potential areas present a great opportunity for large scale wind farm development in near future and could supply electricity to distant load centres through transregional or even transnational transmission links. In many parts of the world, getting over the national political and geographical barriers to set up these transmission links is not easy. Some of these regions with vast potential are:

- North and North West Africa: Wind farms set up in this region can either supply electricity to African countries through a yet to be constructed African grid or to Europe through a sub-marine link also possibly to mid-East.
- Mongolia: There is vast potential in this country which can possibly supply electricity to China
- North Europe / Scandinavian region : Can supply electricity to Europe
- Canada East/ Alaska region West: Can supply electricity to US
- Sri Lanka (Jaffna and North Sri Lanka) can supply electricity to India.

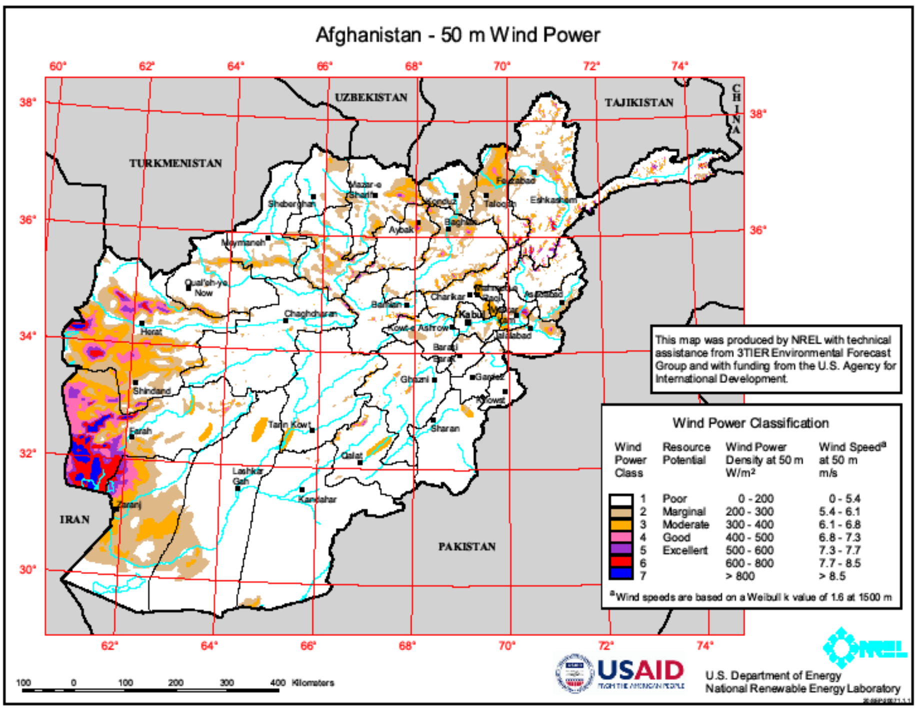
Countries for which maps have been presented in this report are listed below.

Afghanistan	Guatemala
Africa	Honduras
Albania	Iran
Angola	Israel
Australia	Kazakhstan
Azerbaijan	Mongolia
Bangladesh	Nicaragua
Belarus	Pakistan
Bhutan	Philippines
Central America	South Africa
China	Sri Lanka, Maldives
Cuba	Sweden
Dominican Republic	Thailand, Cambodia, Laos
El Salvador	Turkey
Europe	UAE
France	UK
Georgia	Ukraine
Germany	USA
Ghana	Global

Global Wind Speed Maps[ii]

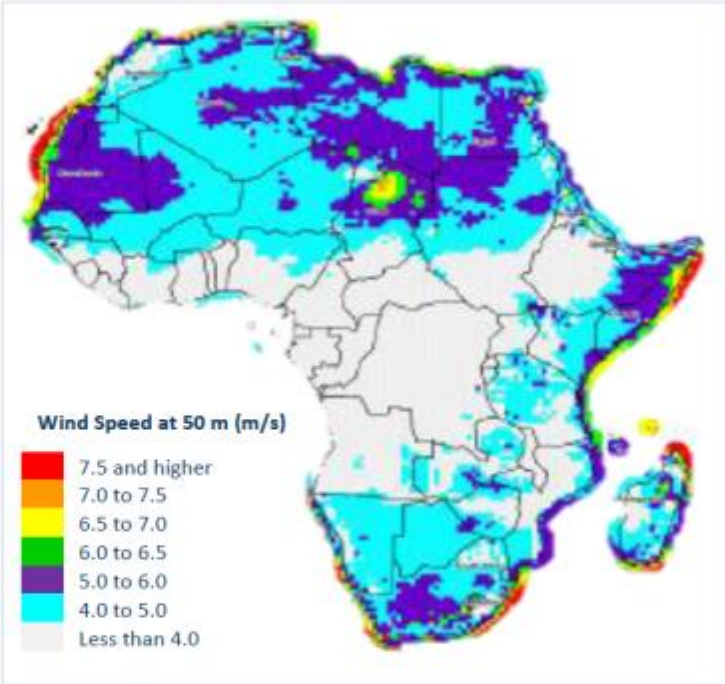


Afghanistan[iii]



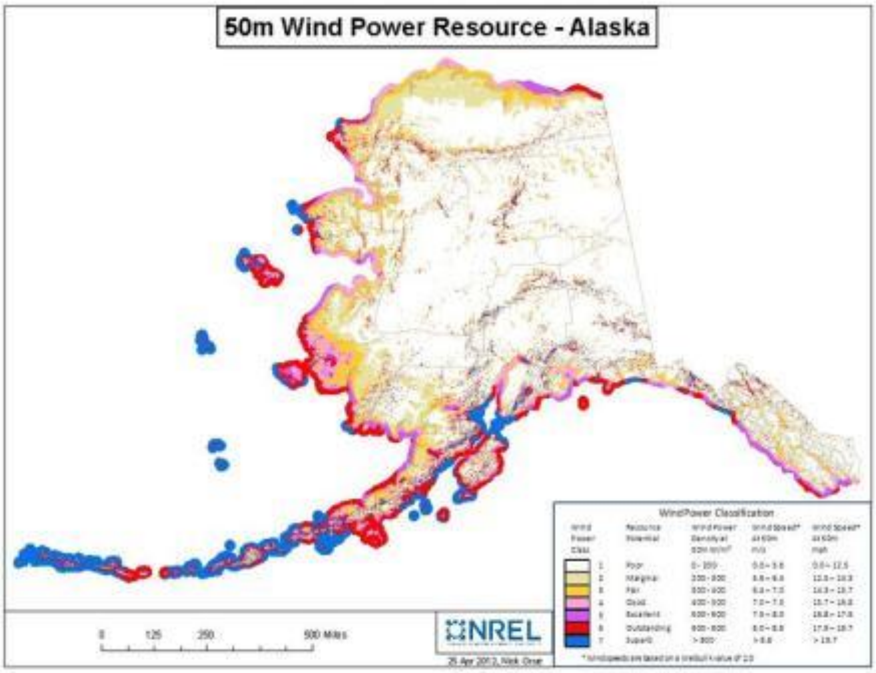
ii http://deepresource.files.wordpress.com/2012/12/3tier_5km_global_wind_speed.jpg
iii www.nrel.gov/wind/images/

Africa[iv]



Source: African Development Bank, 2004

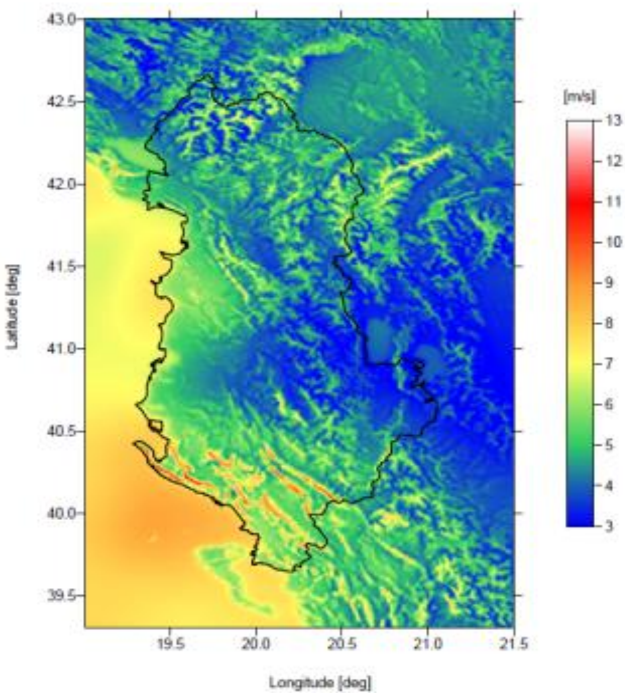
Alaska[v]



[iv] Mukasa, Alli D.; Mutambatsere, Emelly; Arvanitis, Yannis; and Triki, Thouraya (2013), Development of Wind Energy in Africa, Working Paper Series N° 170 African Development

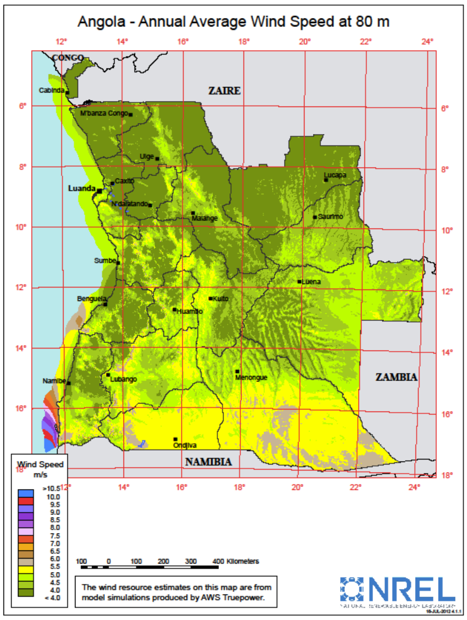
[v] http://en.openei.org/wiki/List_of_NREL_Map_Files

Albania[vi]



Actual Average Wind Speed (m/s) at 50 m a.g.l

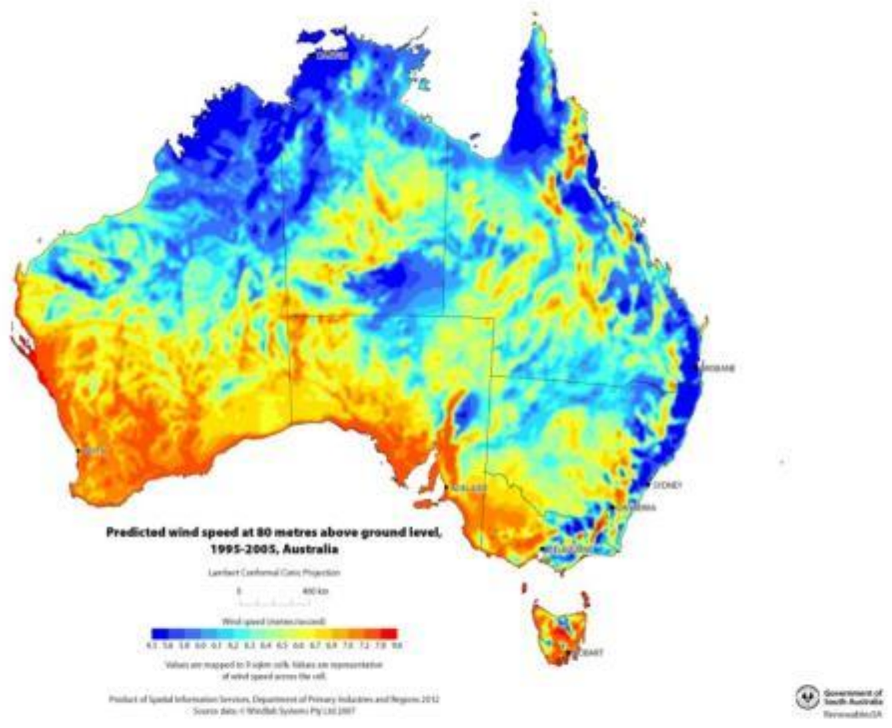
Angola[vii]



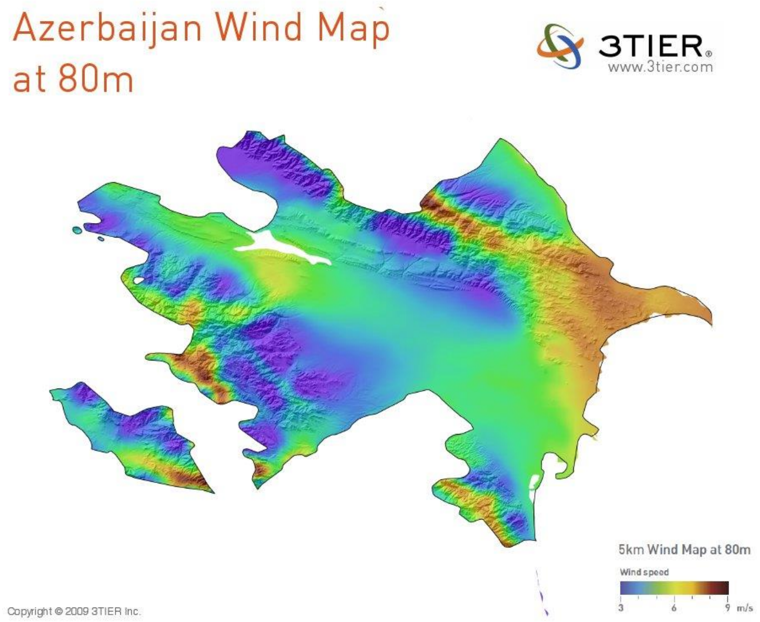
[vi] Wind energy resources assesment, Republic of Albania, Italian Ministry for the Environment, Land and Sea

[vii] www.nrel.gov/wind/images/

Australia[viii]

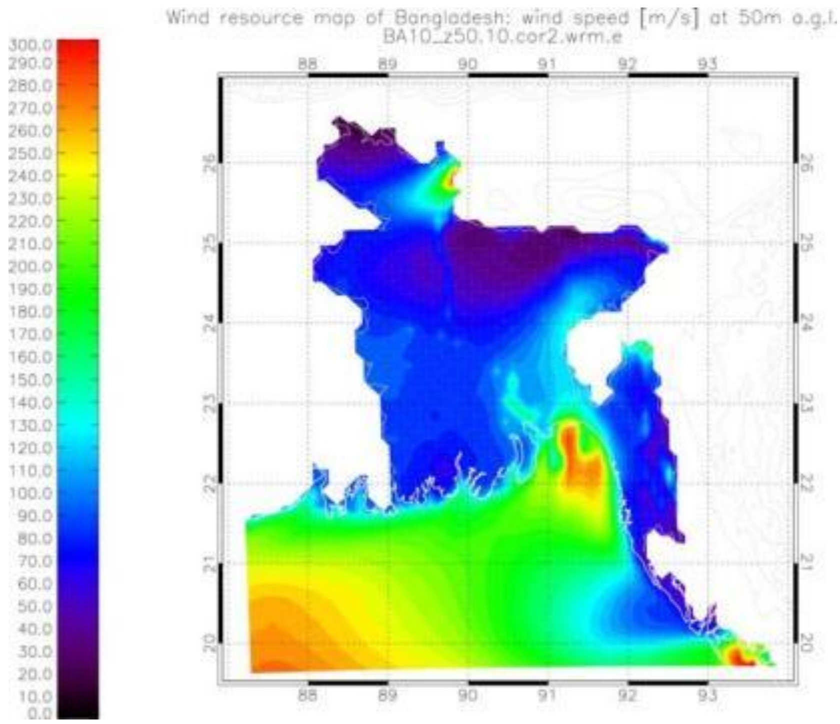


Azerbaijan[ix]

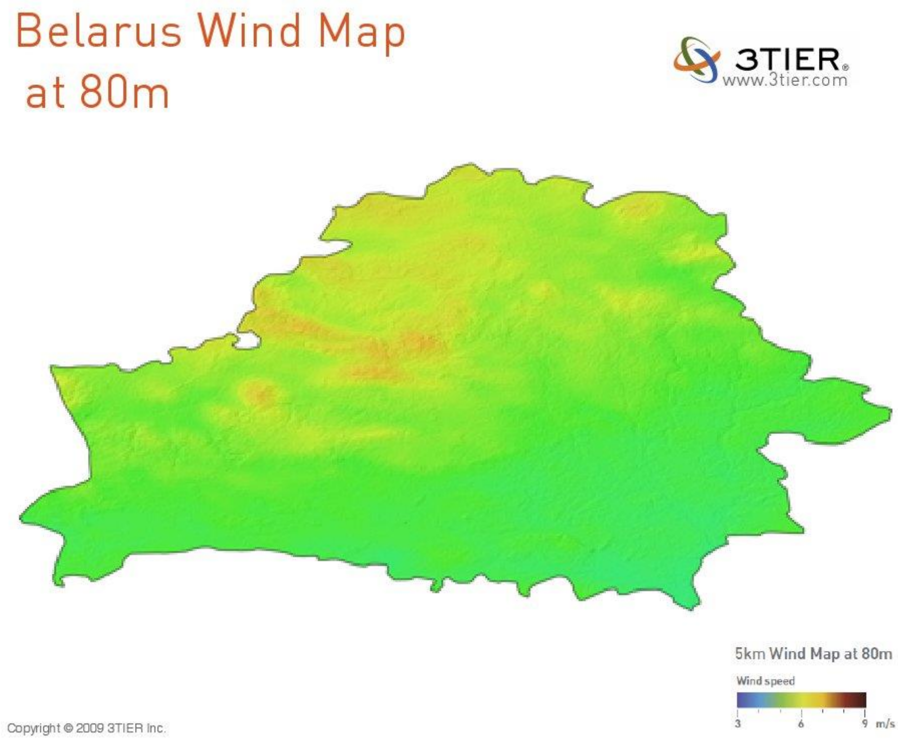


[viii] www.renewablessa.sa.gov.au/files/121221windresourcemappingaustralia.jpg
[ix] http://www.3tier.com/

Bangladesh[x]

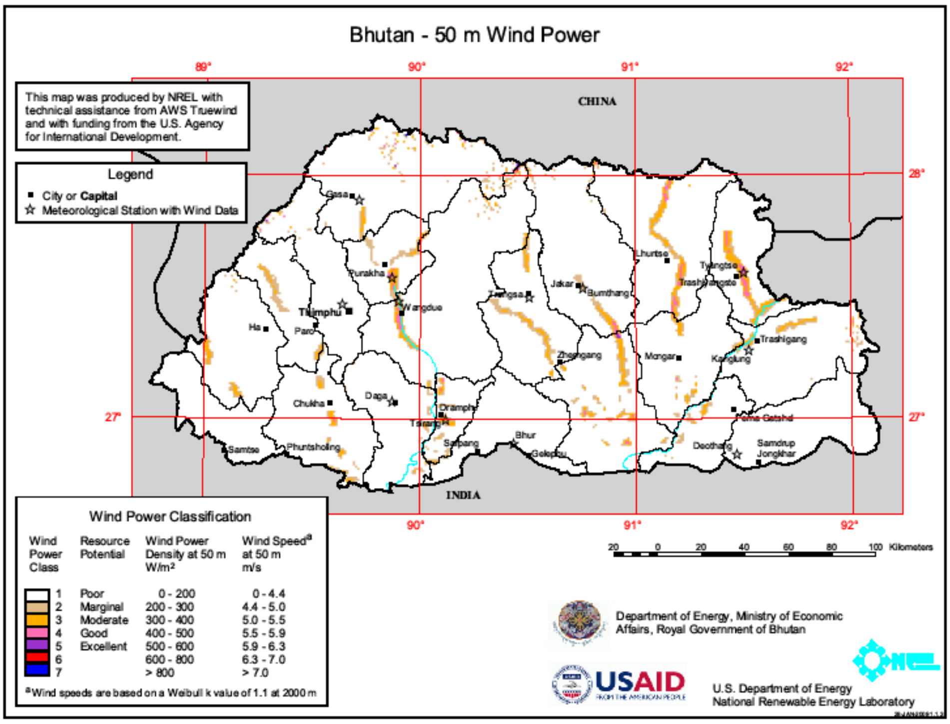


Belarus[xi]

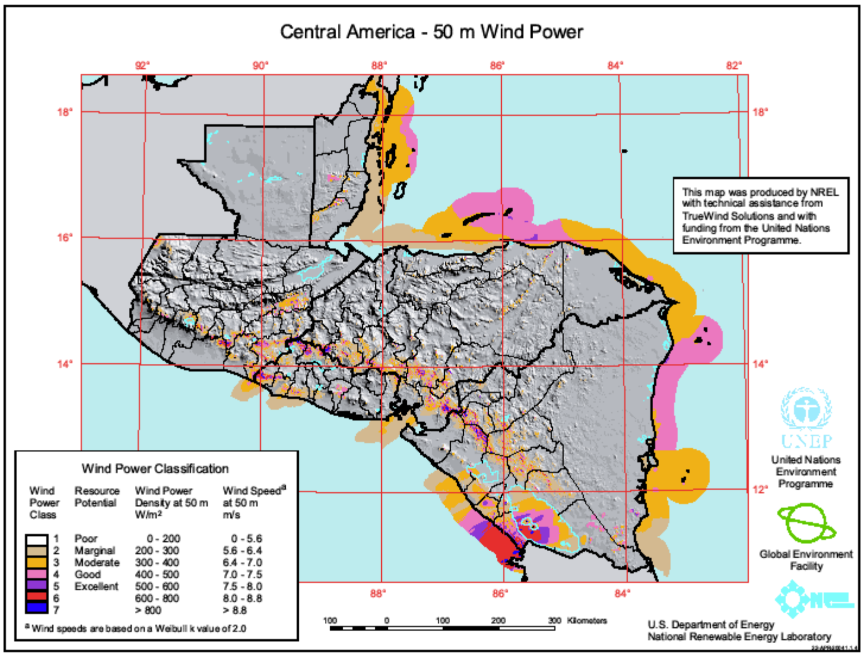


[x] Report of Solar and Wind Energy Resource Assessment. 2007. SWERA
[xi] http://www.3tier.com/

Bhutan[xii]

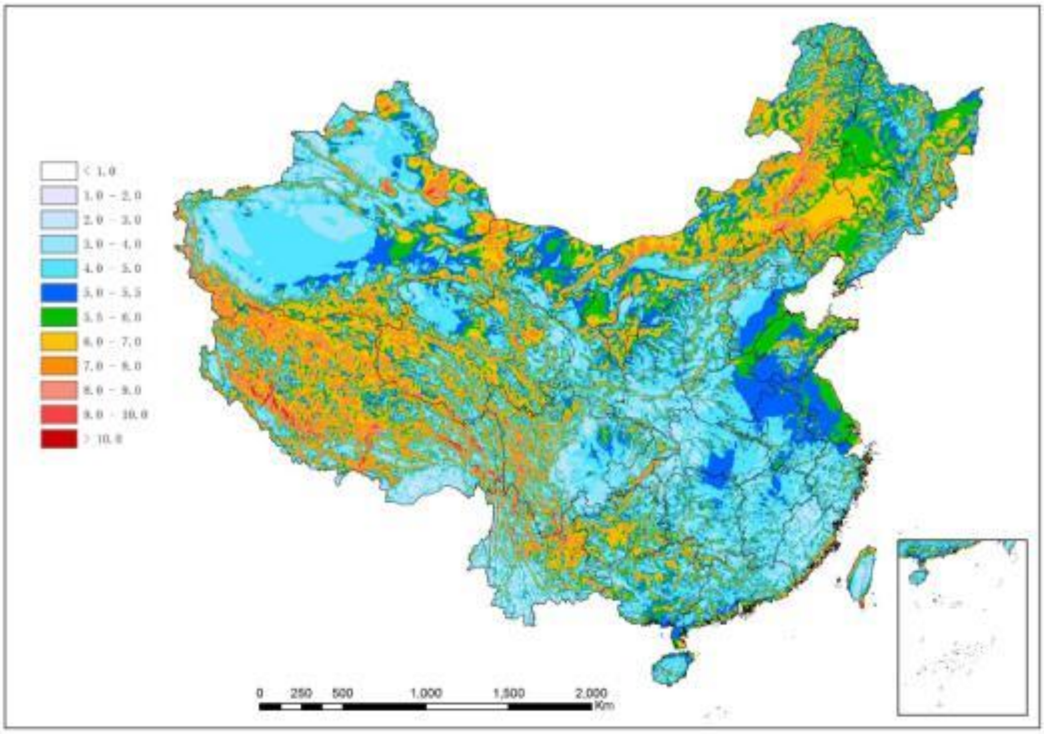


Central America[xiii]



xii www.nrel.gov/wind/images/
xiii www.nrel.gov/wind/images/

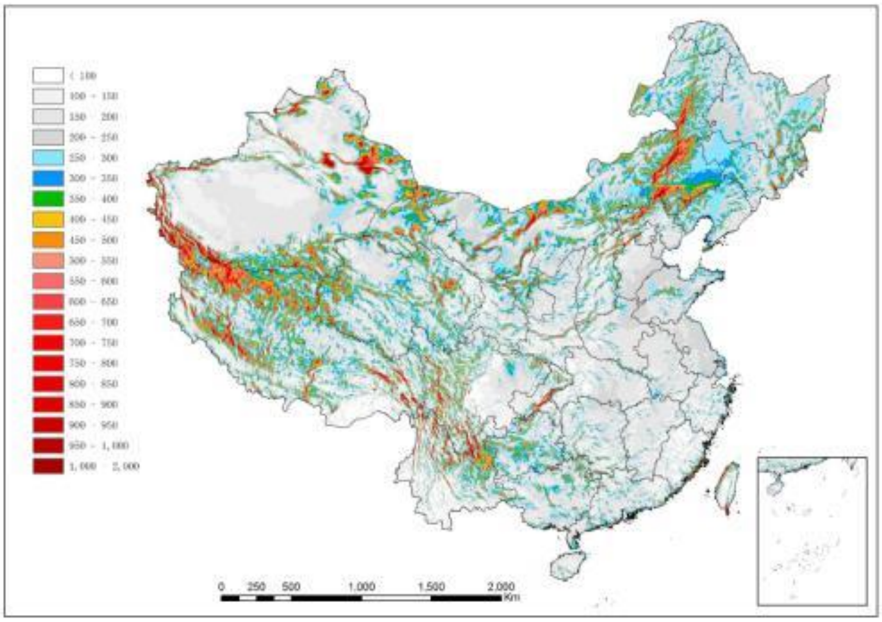
China[xiv]



Mean Annual Wind Speed Map at 70m height above ground

Source : Chinese Wind Energy Association (CWEA)

China[xv]

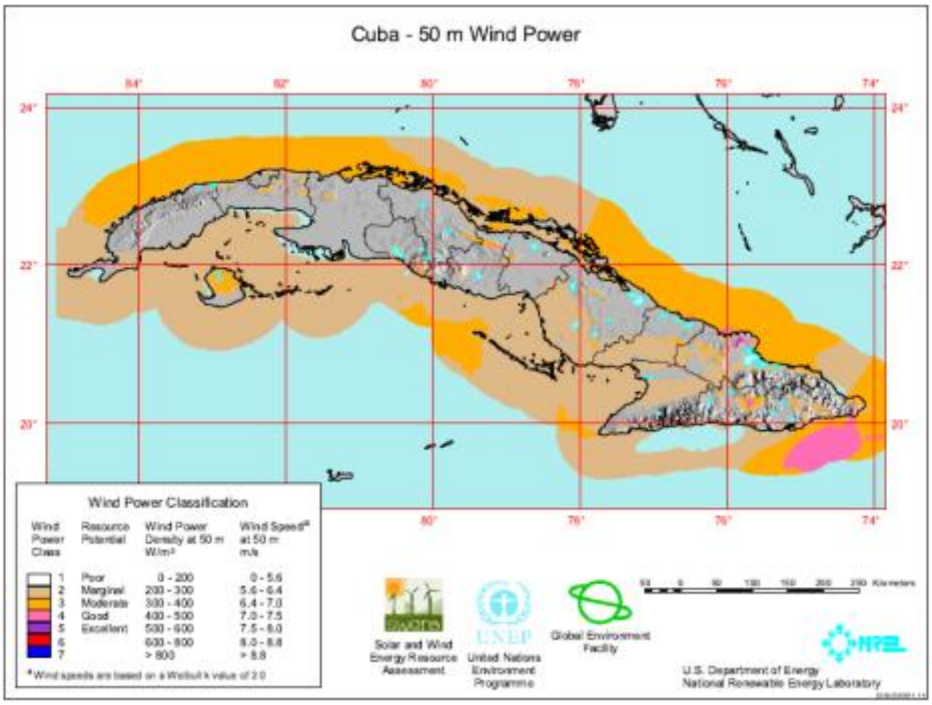


Chinese Wind Power Density Map at 70m height above ground

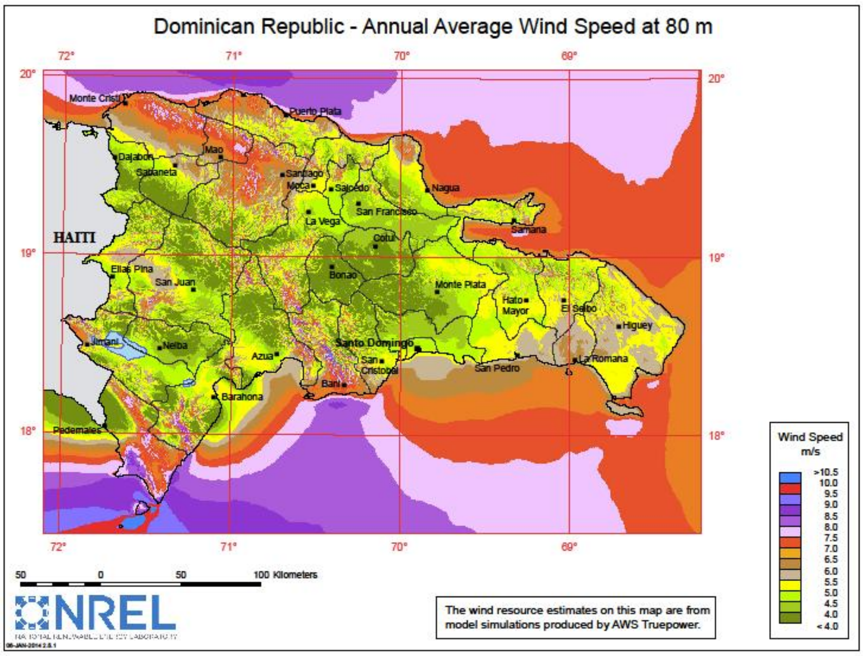
Source : Chinese Wind Energy Association

[xiv] Chinese Wind Energy Association (CWEA)
[xv] Chinese Wind Energy Association (CWEA)

Cuba[xvi]

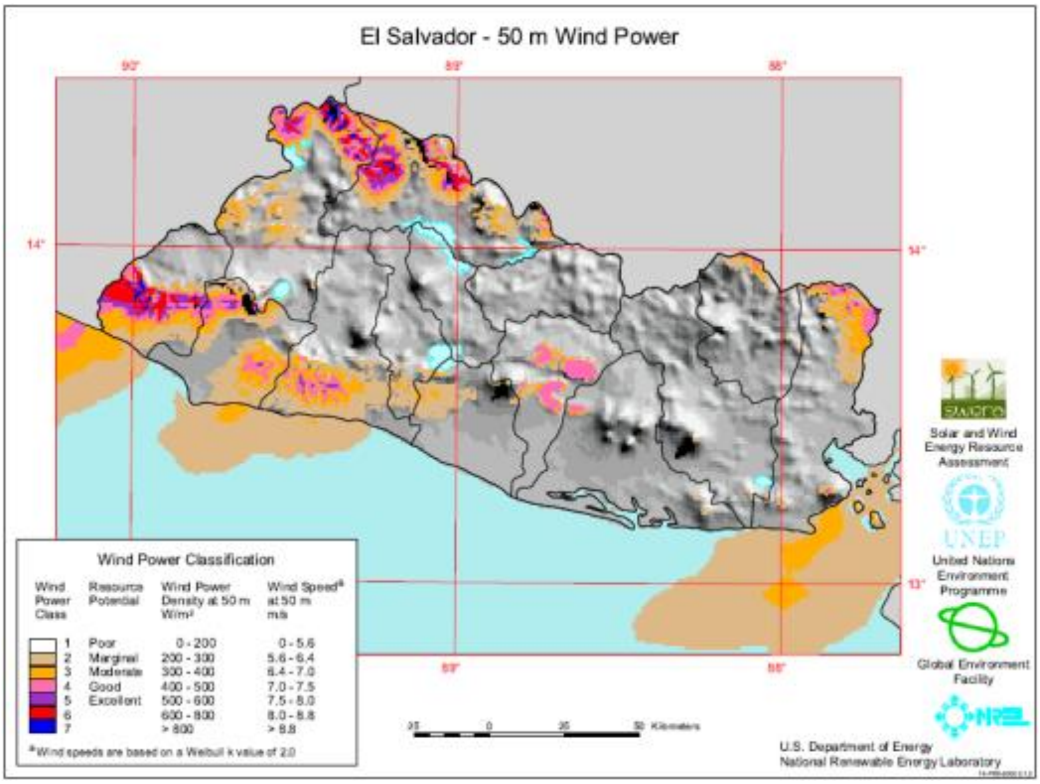


Dominican Republic[xvii]

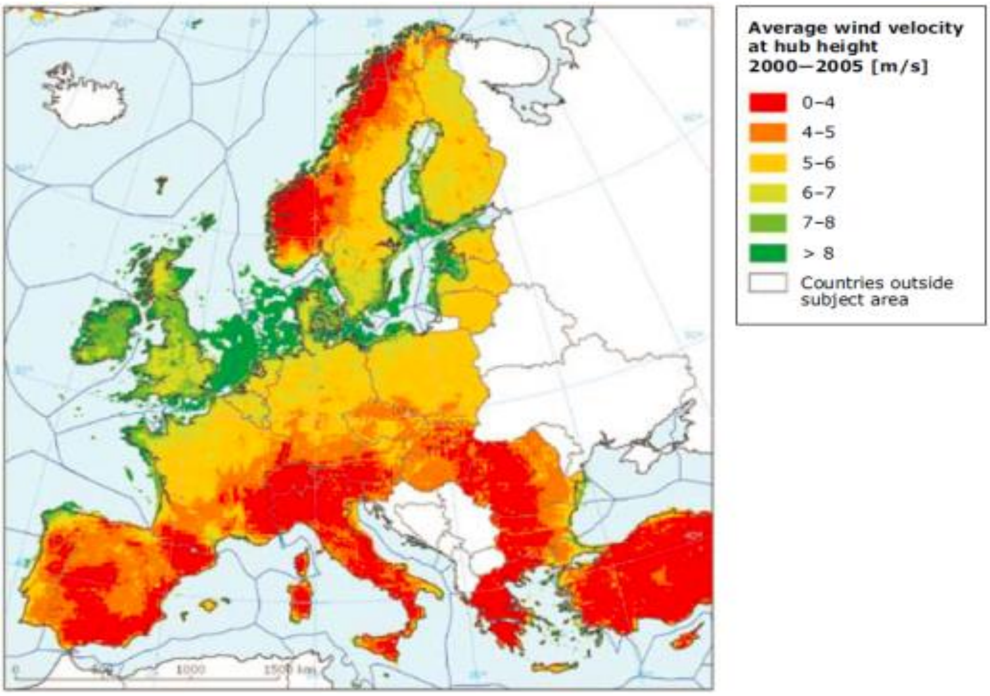


xvi www.nrel.gov/wind/images/
xvii www.nrel.gov/wind/images/

El Salvador[xviii]



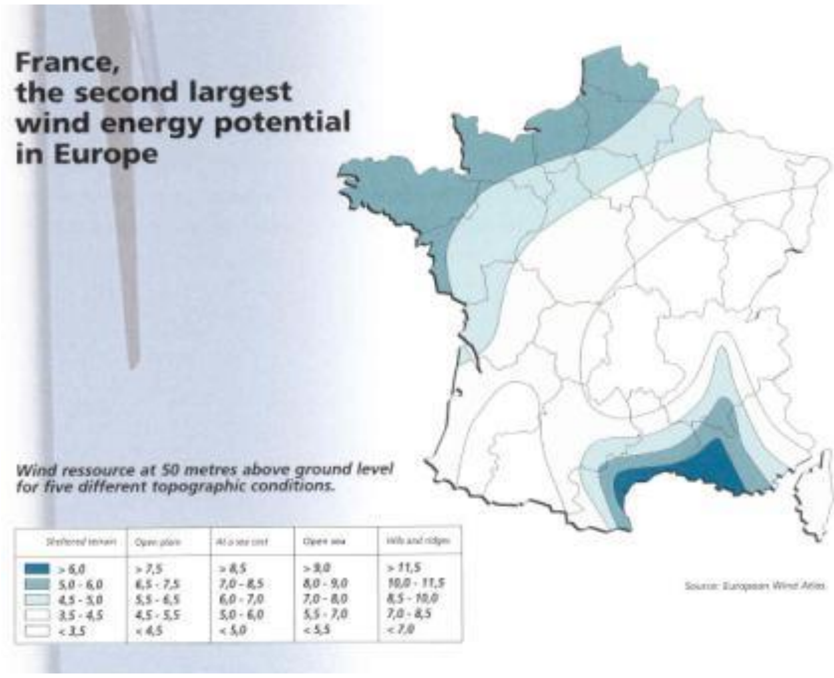
Europe[xix]



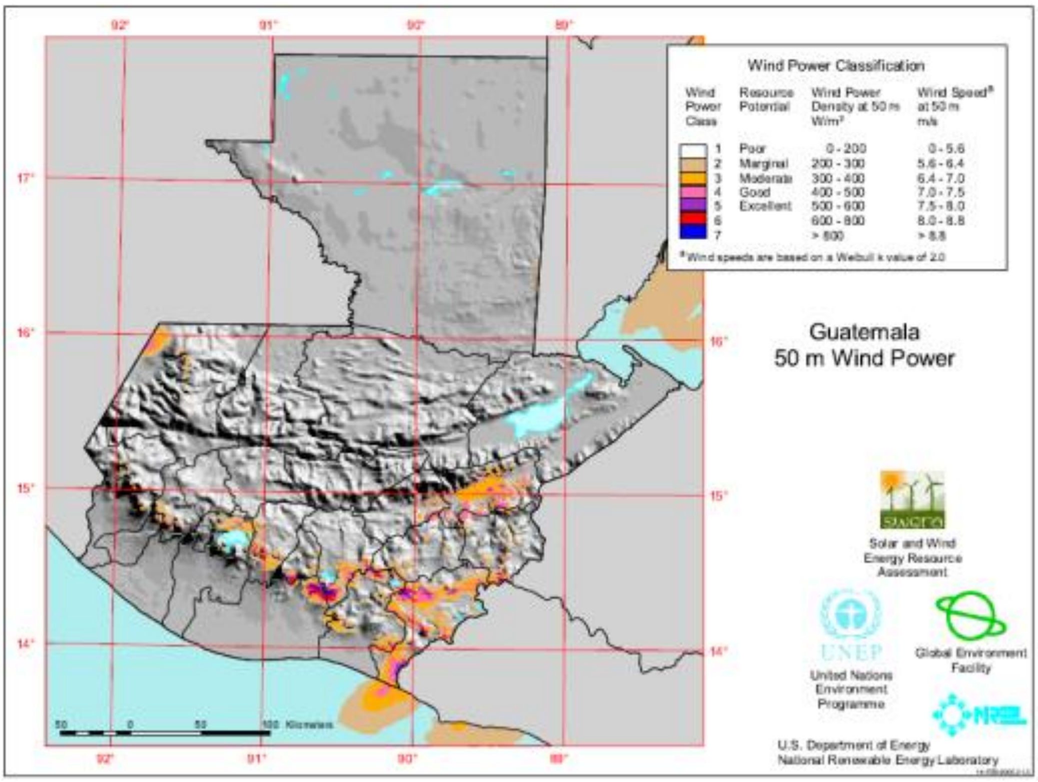
ECMWF wind field data after correction for orography and local roughness (80 m onshore, 120 m offshore)

xviii www.nrel.gov/wind/images/
xix EEA, 2008

France[xx]

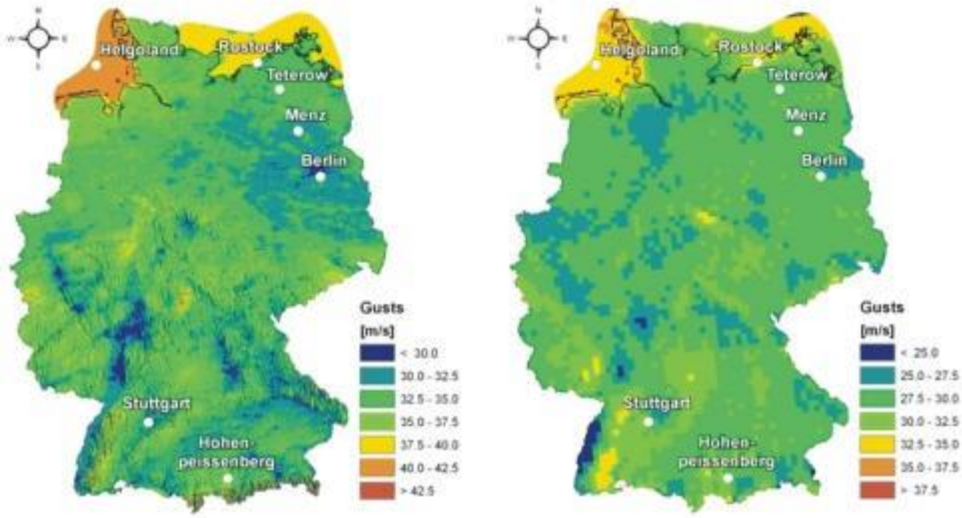


Guatemala[xxi]

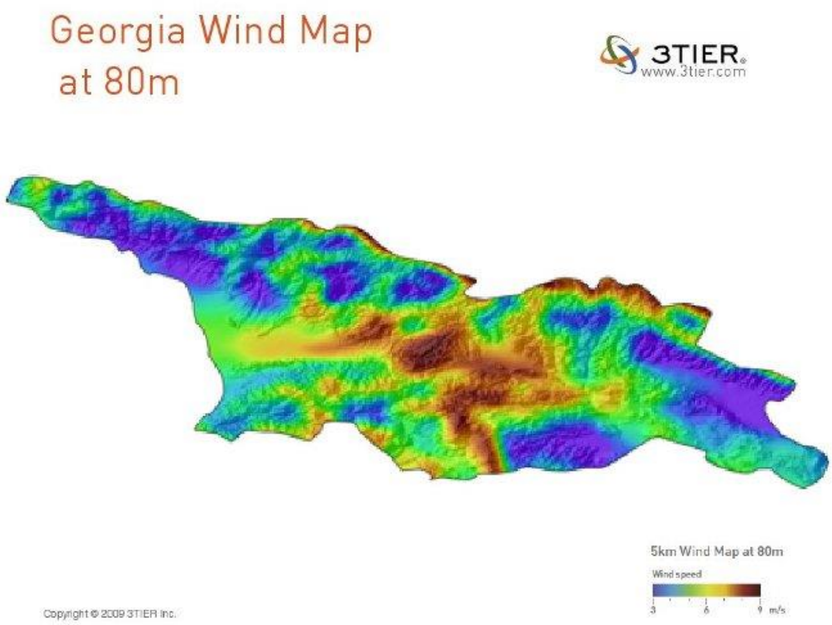


xx http://130.226.56.150/extra/web_docs/windmaps/france.jpg
xxi www.nrel.gov/wind/images/

Germany[xxii]

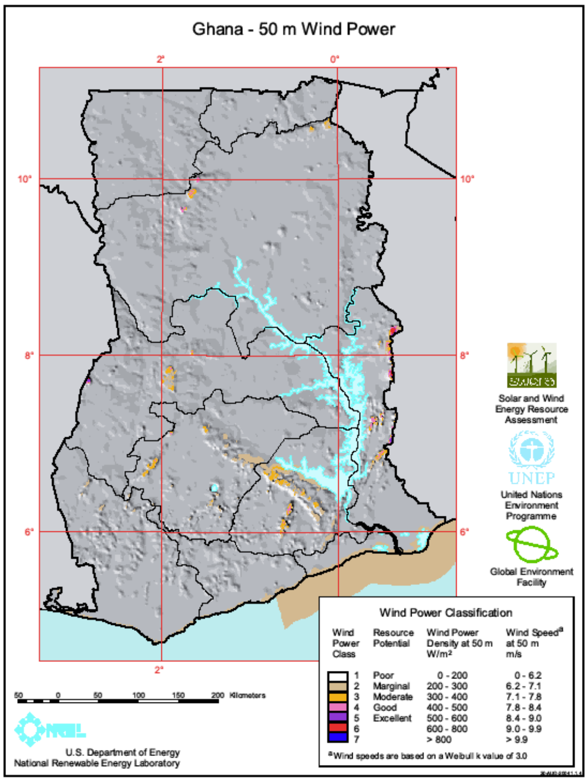


Georgia[xxiii]

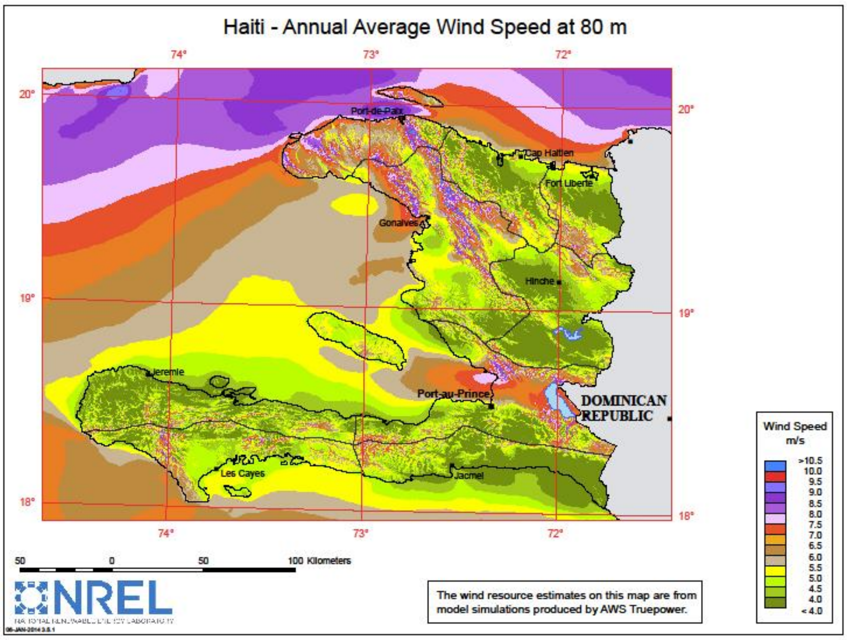


[xxii] www.imk-tro.kit.edu/img/content/sturm_1_758px.jpg
[xxiii] http://www.3tier.com/

Ghana[xxiv]

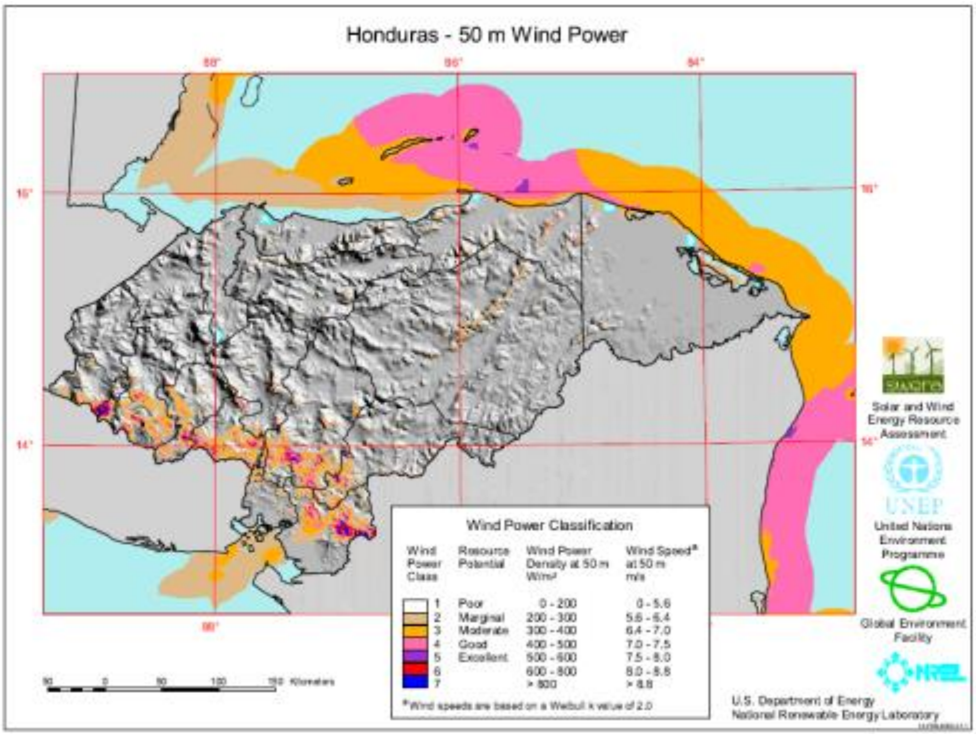


Haiti[xxv]

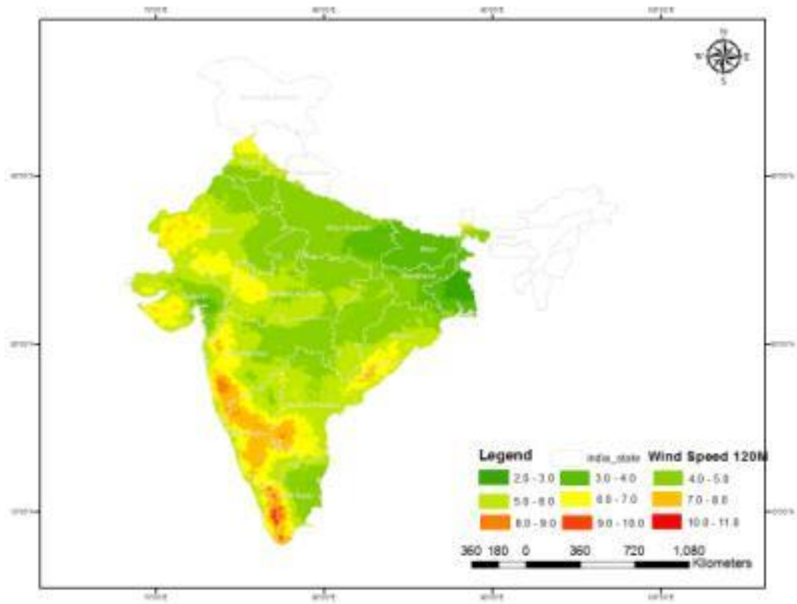


xxiv www.nrel.gov/wind/images/
xxv www.nrel.gov/wind/images/

Honduras[xxvi]



India[xxvii]



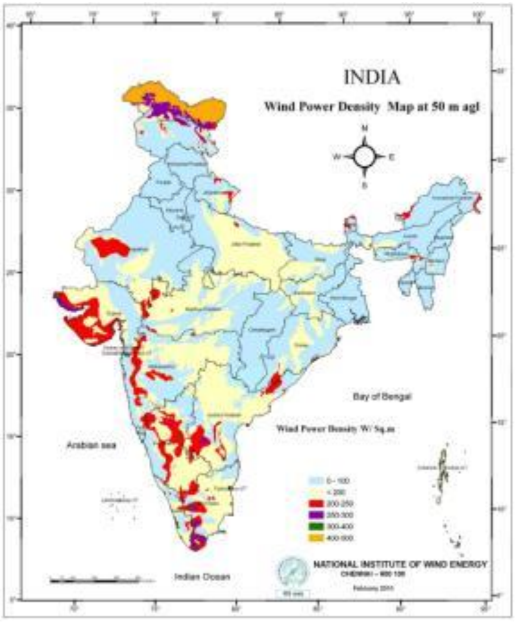
Wind Map of Non-Himalayan regions of India at 120 m height

Source: WinDForce 2013

---

xxvi www.nrel.gov/wind/images/
xxvii WinDForce

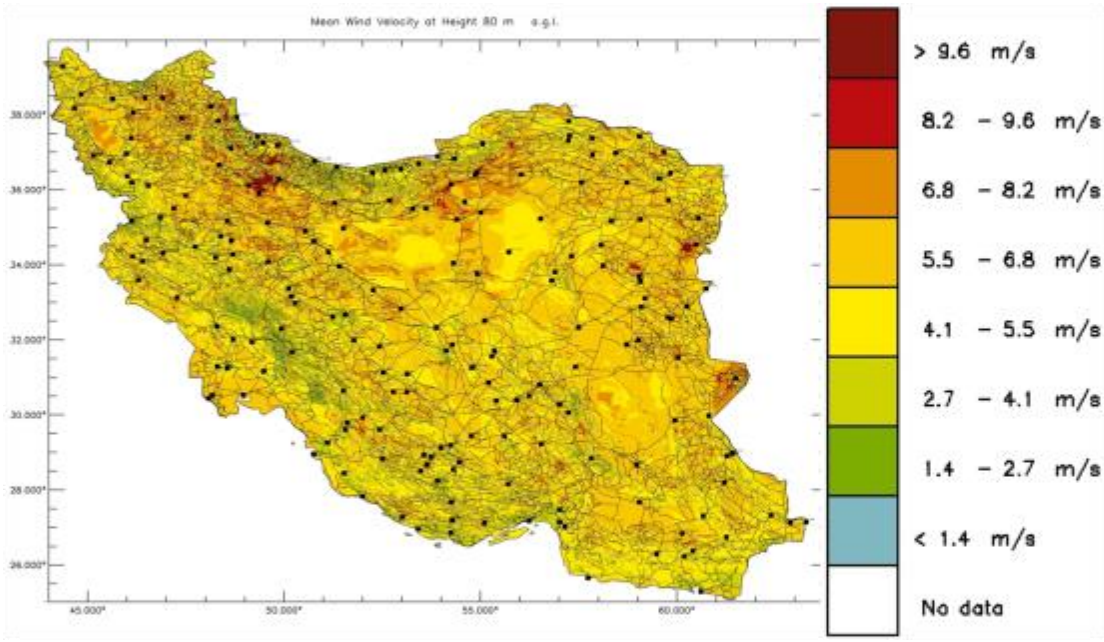
India[xxviii]



WPD Map of India

Source: NIWE (http://www.cwet.tn.nic.in/html/departments_wpdmap.html)

Iran[xxix]

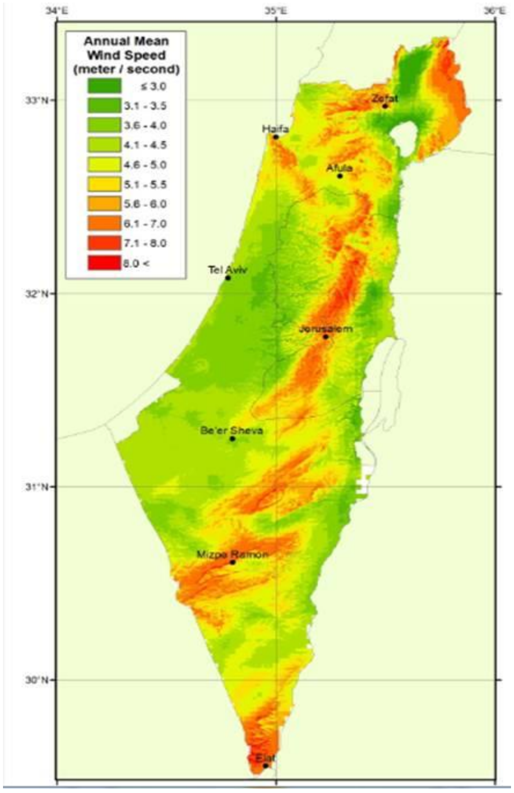


---

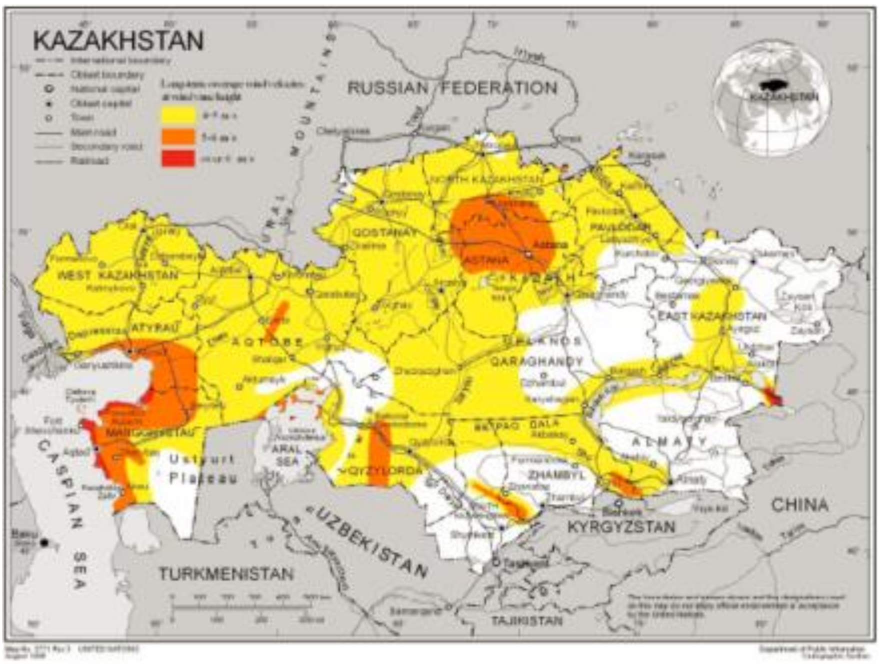
xxviii NIWE, Chennai (previously CWET)

xxix A Presentation, Renewable Energy organisation of Iran (SUNA). Islamic Republic of Iran

Israel, including Golan Heights and West Bank[xxx]



Kazakhstan[xxxi]

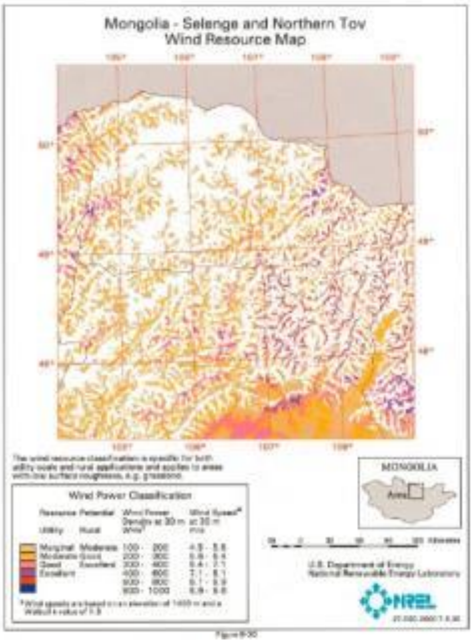


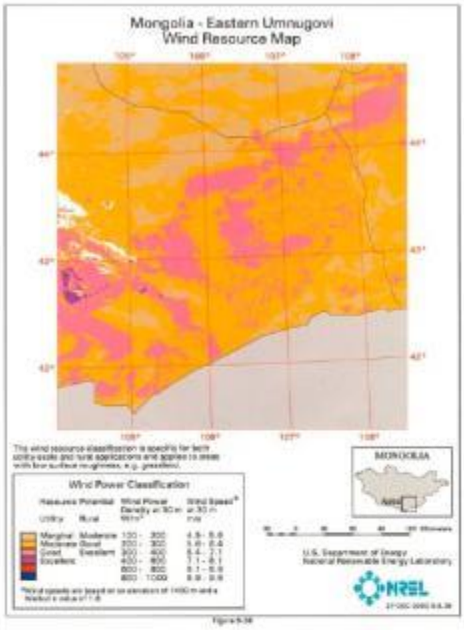
---

xxx Israel Meteorological Service- IMS and Israeli Wind Energy Association – ISRAWEA

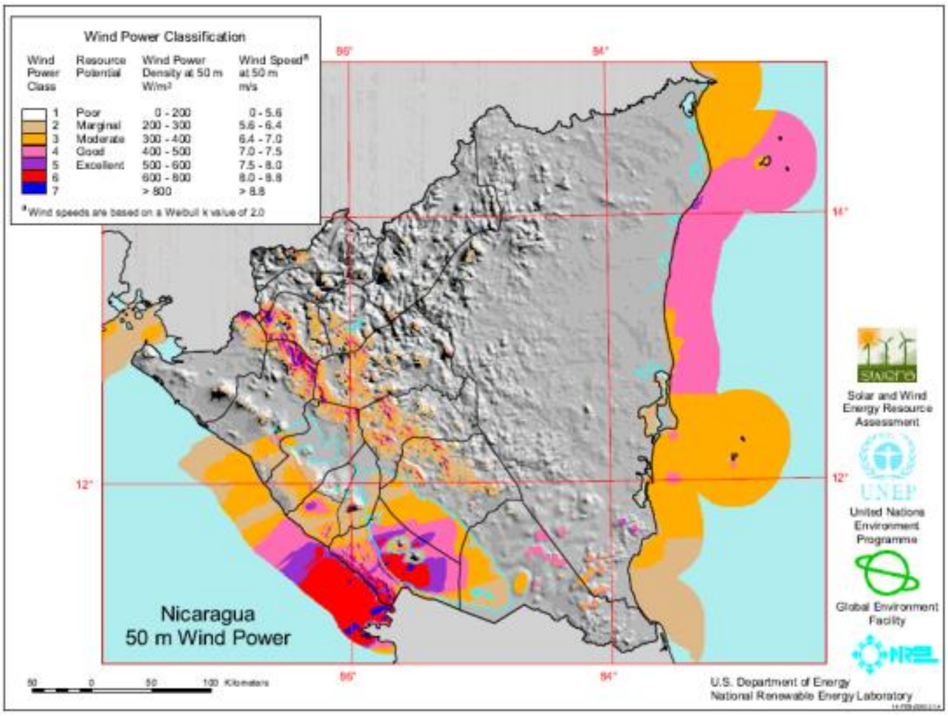
xxxi UNDP/GEF and Government of Kazakhstan project "Kazakhstan- Wind Power Market Development Initiative"

Mongolia[xxxii]



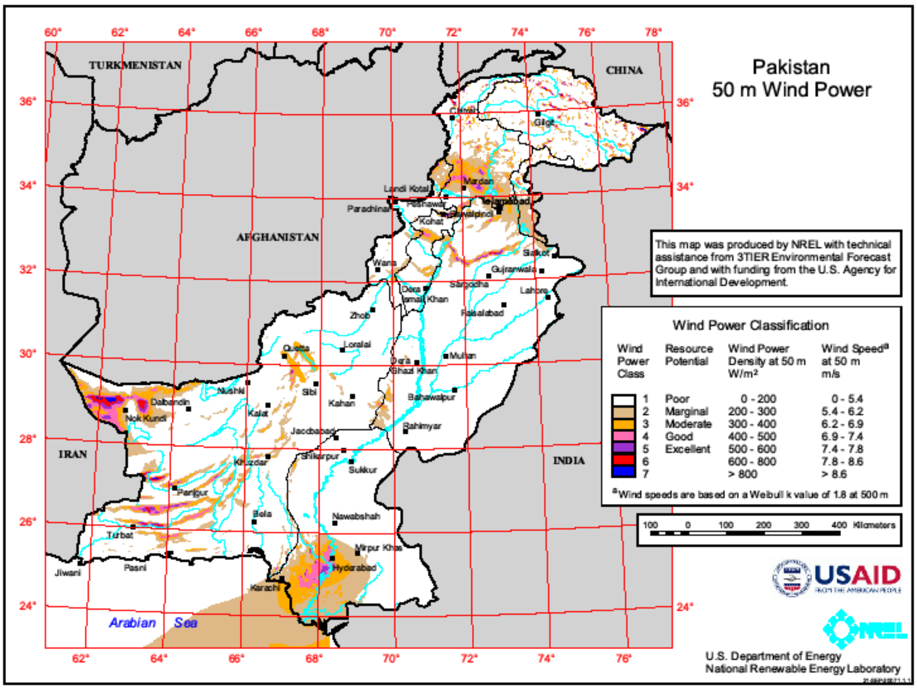


Nicaragua[xxxiii]

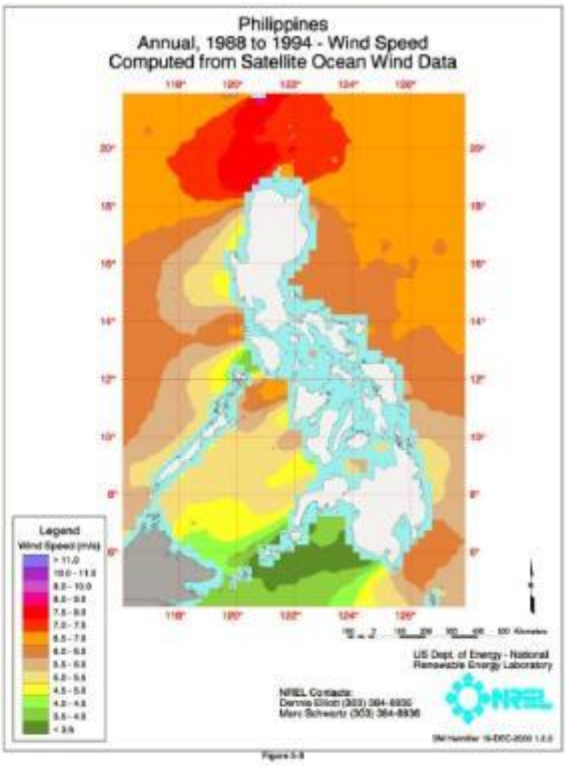


xxxii D. Elliott, M. Schwartz, G. Scott, S. Haymes, D. Heimiller and R. George. 2001. Wind Energy Resource Atlas of Mongolia. NREL Report. NREL/TP-500-28972
xxxiii www.nrel.gov/wind/images/

Pakistan[xxxiv]



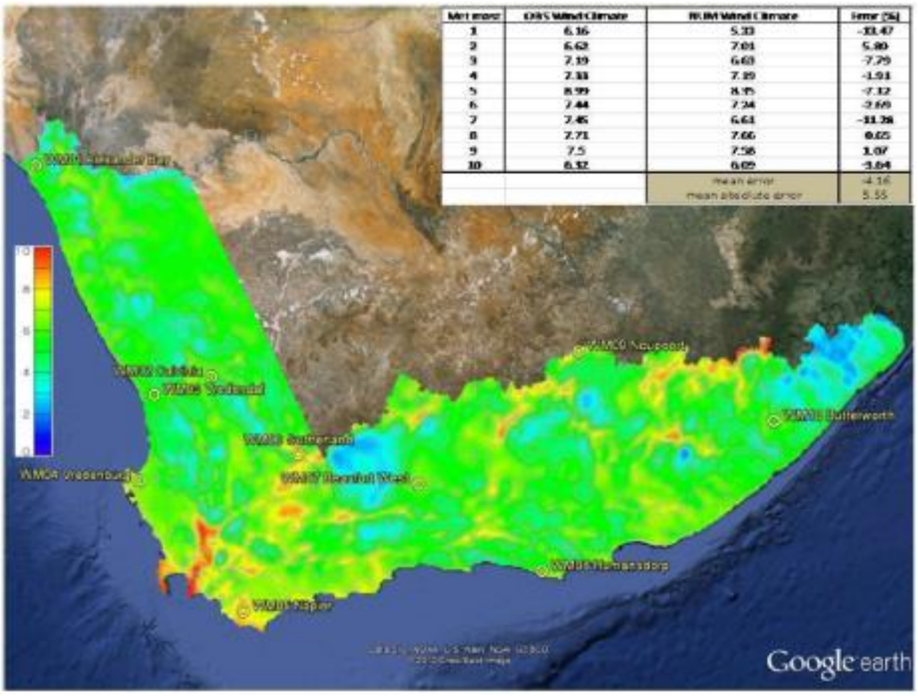
Philippines[xxxv]



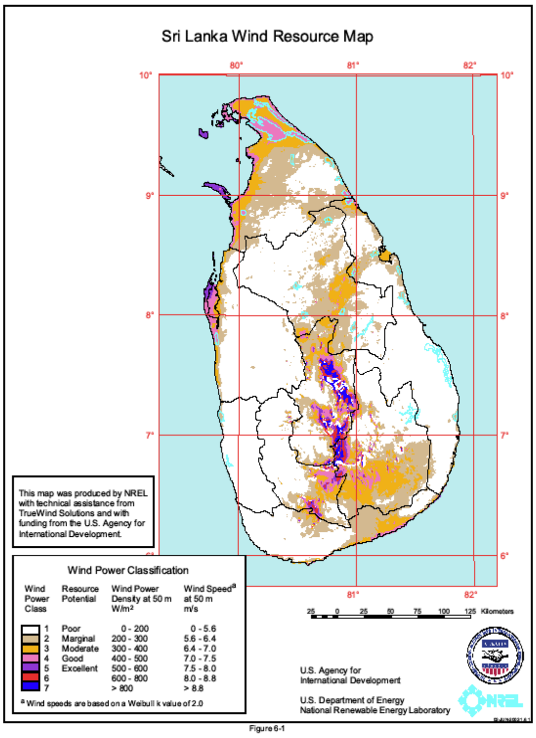
xxxiv www.nrel.gov/wind/images/

xxxv D. Elliott, M. Schwartz, G. Scott, S. Haymes, D. Heimiller and R. George. 2001. Wind Energy Resource Atlas of Mongolia. NREL Report. NREL/TP-500-26129

South Africa[xxxvi]



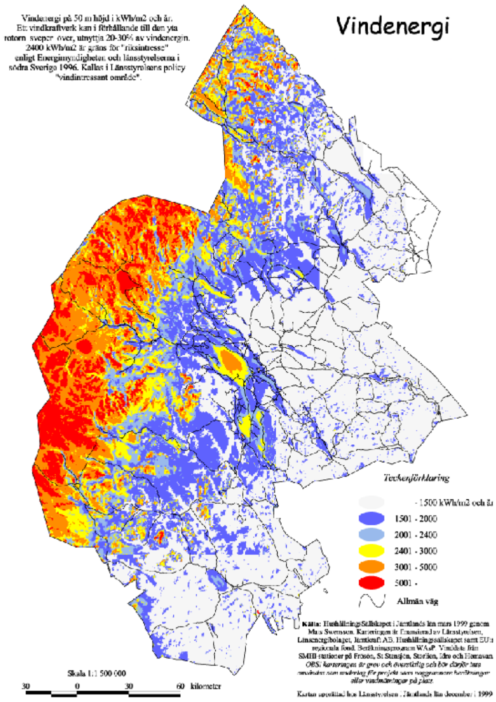
Sri Lanka[xxxvii]



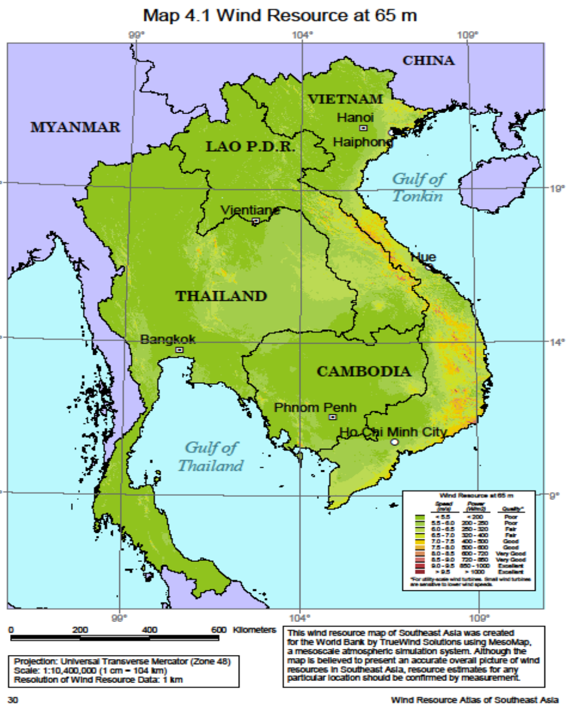
xxxvi Wind Atlas for South Africa (WASA). 2010

xxxvii www.nrel.gov/wind/images/

Sweden[xxxviii]

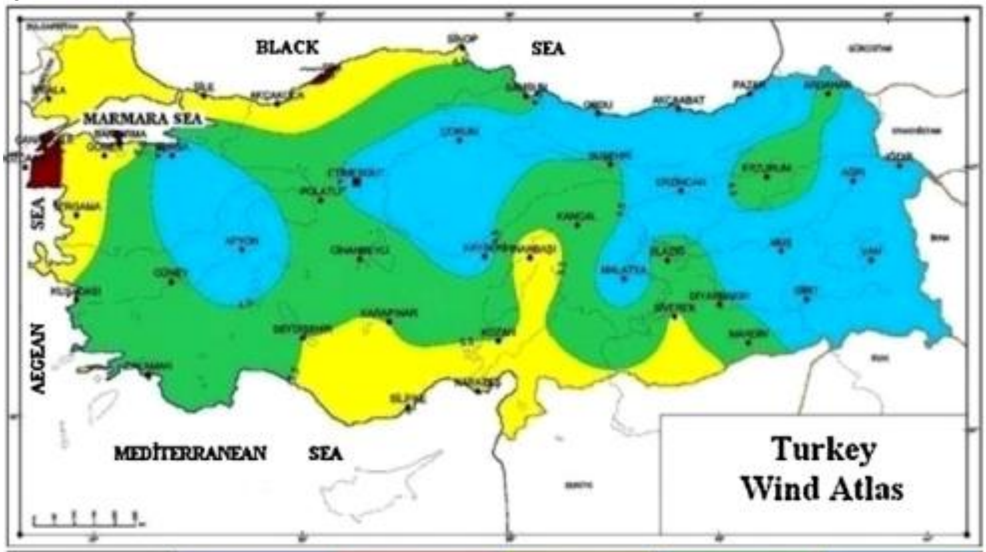


Thailand, Cambodia, Vietnam[xxxix]



[xxxviii] http://130.226.56.150/extra/web_docs/windmaps/vindresurs_jamtland.pdf
[xxxix] WIND ENERGY RESOURCE ATLAS OF SOUTHEAST ASIA, The World Bank, Asia Alternative Energy Program

Turkey[xl]

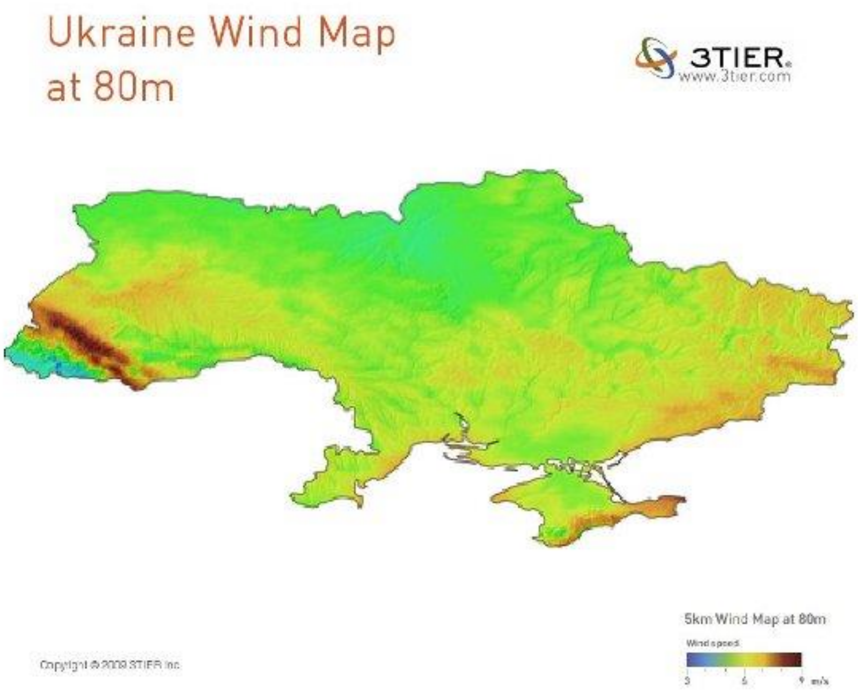


V (m/s)	> 7.5	6.5 - 7.5	5.5 - 6.5	4.5 - 5.5	< 4.5
P (W/s²)	> 500	300 - 500	200 - 300	100 - 200	< 100

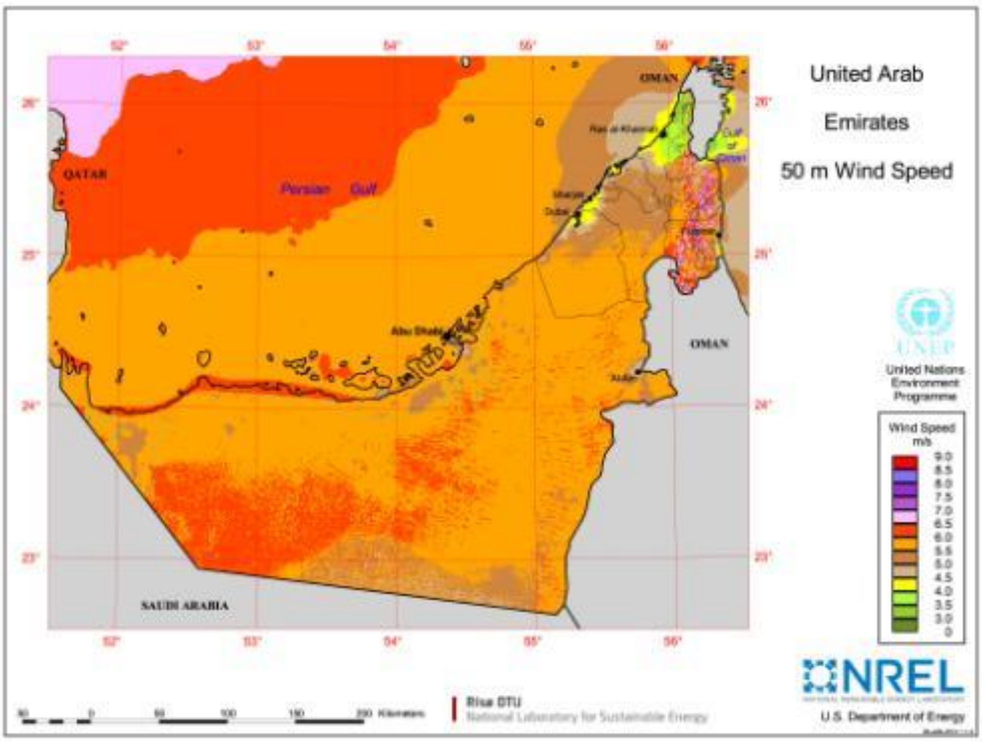
The United Kingdom[xli]

[xl] Cumali I˙lkilic, (2012) Wind energy and assessment of wind energy potential in Turkey, Renewable and Sustainable Energy Reviews 16 (2012) 1165– 1173
[xli] https://restats.decc.gov.uk/cms/assets/SiteFiles/NOABL_wind_speed_map_June_2008_small.jpg

Ukraine[xlii]

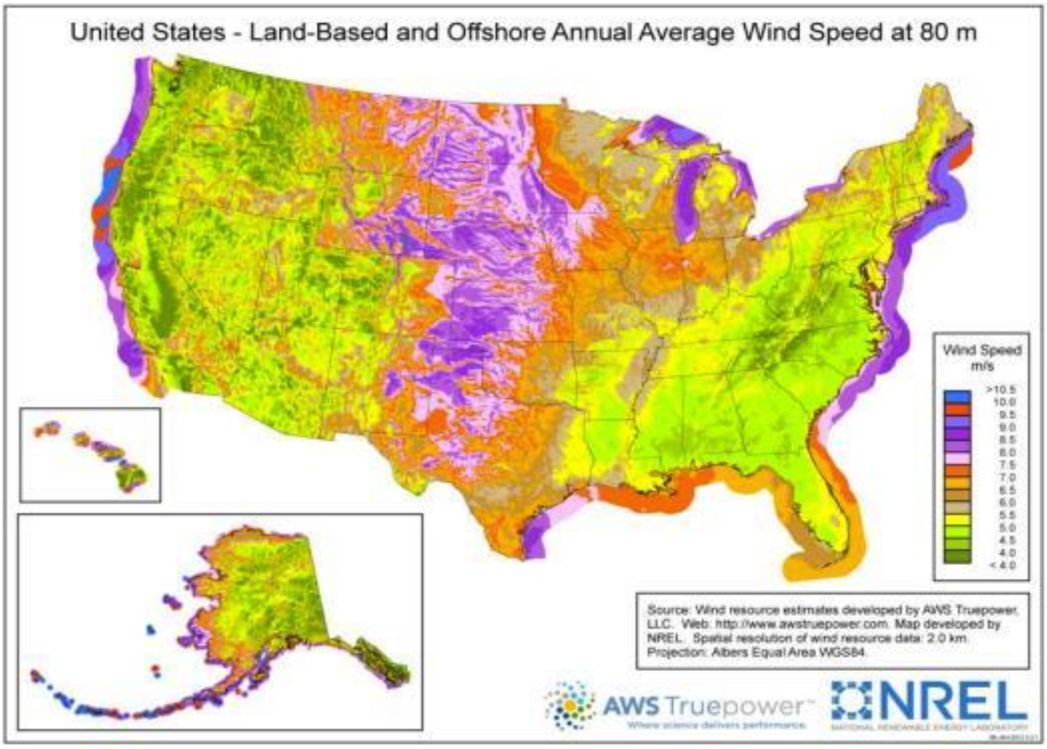


United Arab Emirates[xliii]



xlii http://www.3tier.com/
xliii http://www.nrel.gov/wind/images/

United States of America[xliv]



xliv http://www.nrel.gov/gis/images/80m_wind/awstwspd80onoffbigC3-3dpi600.jpg

References

[1] International Energy Agency, “Energy Balances of non-OECD Countries 2014”, 2014, IEA, ISBN: 9789264217072

[2] US Energy Information Administration http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=7 , accessed on 20 November 2014

[3] http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch1s1-3.html , accessed on 15 July 2014

[4] CO2 emissions from fuel combustion: Highlights, IEA STATISTICS, International Energy Agency, 2012

[5] <http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_SPM.pdf>

[6] <http://www.theguardian.com/world/2014/oct/24/eu-leaders-agree-to-cut-greenhouse-gas-emissions-by-40-by-2030>

[7] < http://www.epa.gov/climatechange/ghgemissions/sources/electricity.html

[8] http://www.iec.ch/renewables/wind_power.htm

[9] Lysen E H, “Introduction to Wind Energy,” SWD, the Netherlands, (1982).

[10] James F. Manwell, Jon G. McGowan, Anthony L. Rogers, “Wind Energy Explained: Theory, Design and Application,” 2nd Edition, December 2009, ISBN: 978-0-470-01500-1

[11] www.weibull.com

[12] Jami Hossain, Suman Sharma, V V N Kishore, “Multi-peak Gaussian fit applicability to wind speed distribution”, Renewable and Sustainable Energy Reviews 34 (2014) 483–490

[13] E. Kalnay, M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell,S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds (NCEP Environmental Modeling Center); M. Chelliah, W. Ebisuzaki, W.Higgins, J. Janowiak, K. C. Mo,C. Ropelewski, J. Wang (NCEP Climate Prediction Center); Roy Jenne, Dennis Joseph (NCAR), “The NCEP/NCAR 40-Year Reanalysis Project,” Bulletin of the American

Meteorological Society, March 1996;
<http://rda.ucar.edu/datasets/ds090.0/docs/bams/bams1996mar/bamspapr-bm.pdf > accessed on Aug 20 2014

[14] http://www2.mmm.ucar.edu/wrf/users/model.html

[15] Kate Marvel, Ben Kravitz, & Ken Caldiera, "Geophysical limits of global wind power," Nature Climate Change 3, 118-121 (2013), doi:10.1038/nclimate1683, < http://www.nature.com/nclimate/journal/v3/n2/full/nclimate1683.html>

[16] Cristina L. Archer and Ken Caldeira, "Global assessment of high altitude wind power," Energies 2009, 2, 307-319; doi:10.3390/en20200307, http://www.awec2010.com/public/img/media/archer_caldeira.pdf

[17] < https://www.cia.gov/library/publications/the-world-factbook/rankorder/2236rank.html>

[18] Michael Kenward, "Potential Energy: Analysis of World Energy Technology", Cambridge University Press, 1976

[19] Cristina L. Archer and Mark Z. Jacobson, "Evaluation of global wind power," Journal Of Geophysical Research, VOL. 110, D12110, doi:10.1029/2004JD005462, 2005

[20] Lu, Xi, Michael B. McElroy, and Juha Kiviluoma. 2009. Global potential for wind-generated electricity. Proceedings of the National Academy of Sciences of the United States of America 106(27): 10933-10938. doi:10.1073/pnas.0904101106

[21] Hossain J, Sinha Vinay & Kishore V V N, "A GIS based assessment of potential for wind farms in India," Renewable Energy, Volume 36, Issues 12, December 2011, Pages 3257-3267; doi:10.1016/j.renene.2011.04.017

[22] Jami Hossain, "A GIS based approach to reassessment of potential for wind energy utilization in India,"A PhD thesis, TERI University 2013

[23] Mohammad Ziaulhaq Ansari, Deepshikha Sharma, Neelu kumar, Jami Hossain, "Offshore wind power development in India,"Windpro Journal of Indian Wind Power Association, Jan 2014

[24] South Asia Regional Initiative for Energy Co-operation and Development
http://www.nrel.gov/international/pdfs/afg_pak_wind_june07.pdf

[25] Italian Ministry for Environment, Land & Sea (IMELS) with CETMA Consortium

http://www.taskforcecee.com/files/presentations/Albania/WERA_Ex%20Summary_en.pdf

[26] Wind Energy Resource Atlas of Armenia – D. Elliot et. al., NREL. Prepared under task no. WF7C0202 http://www.nrel.gov/docs/fy03osti/33544.pdf

[27] SWERA project for UNEP

http://en.openei.org/datasets/node/713/.pdf

[28] Center for Wind and Solar Energy Resources Assessment/CMA, China Wind Energy Resource Assessment in High Resolution, Wind Energy, August 2011, 16-22.

[29] Resource Assessment by NREL for SWERA project for UNEP

http://en.openei.org/datasets/node/716/.pdf

[30] Resource Assessment coordinated by NREL & sponsored by US DOE & USAID

http://www.nrel.gov/wind/pdfs/27602.pdf

[31] I. Lütkehus, H. Salecker, "Onshore Wind Energy Potential in Germany," Umweltbundesamt, Germany < http://www.dewi.de/dewi_res/fileadmin/pdf/publications/Magazin_43/05.pdf>

[32] Resource Assessment by NREL for SWERA project for UNEP

http://en.openei.org/datasets/node/717/.pdf

[33] "IRENA Case Study 2013 – Wind Atlas Kazakhstan" by UNDP-GEF http://globalatlas.irena.org/UserFiles/casestudies/IRENA_Case_Kazakhstan.pdf

[34] Wind Data Analysis and Prospectus Development Programme. A Report submitted by WinDForce Management Services (P) Ltd to World Bank. 2013

[35] Resource Assessment coordinated by NREL & sponsored by US DOE & USAID

http://www.nrel.gov/wind/pdfs/28972.pdf

[36] South Asia Regional Initiative for Energy Co-operation and Development http://www.nrel.gov/international/pdfs/afg_pak_wind_june07.pdf

[37] http://www.nrel.gov/wind/pdfs/26129.pdf

[38] Report by Grigori Dmitriev, VetrEnergo for Gaia Apatity and INFORSE-Europe First Part - June 2001 http://www.inforse.org/europe/wind_RU_en.htm

[39] Resource Assessment by NREL for SWERA project for UNEP http://en.openei.org/datasets/node/719/.pdf

[40] www.fossil.energy.gov, February 2005

[41] "Europe onshore and offshore wind energy potential - An assessment of environmental and economic constraints", European Environment Agency 2009. ISSN 1725-2237

[42] Hossain J, Sinha Vinay & Kishore V V N, "A GIS based assessment of potential for wind farms in India," Renewable Energy, Volume 36, Issues 12, December 2011, Pages 3257-3267; doi:10.1016/j.renene.2011.04.017

[43] Jami Hossain, "A GIS based approach to reassessment of potential for wind energy utilization in India,"A PhD thesis, TERI University 2013

[44] Amol Phadke, Ranjit Bharvirkar, Jagmeet Khangura, " Reassessing Wind Potential Estimates for India: Economic and Policy Implications" LBNL report, July 2011 < http://ies.lbl.gov/sites/all/files/lbnl-5077e_0.pdf >

[45] Action Plan for Comprehensive Renewable Energy Development in Tamilnadu, 2012 http://shaktifoundation.in/wp-content/uploads/2014/02/tamil%20nadu_re%20action%20plan_jan%202013.pdf

[46] Integrated renewable energy resource assessment for Gujarat, A TERI Report for Shakti Foundation, 2012 < http://shaktifoundation.in/wp-content/uploads/2014/02/final%20report_irerag_v1.pdf >

[47] http://www.cstep.in/node/219

[48] Mohammad Ziaulhaq Ansari, Deepshikha Sharma, Neelu kumar, Jami Hossain, "Offshore wind power development in India,"Windpro Journal of Indian Wind Power Association, Jan 2014

[49] Alli D. Mukasa, Emelly Mutambatsere, Yannis Arvanitis and Thouraya Triki, "Development of Wind energy in Africa", Working Paper series, African Development Bank Group, March 2013.36.

World Wind Energy Association
Charles-de-Gaulle-Straße 5
53113 Bonn – Germany

www.wwindea.org