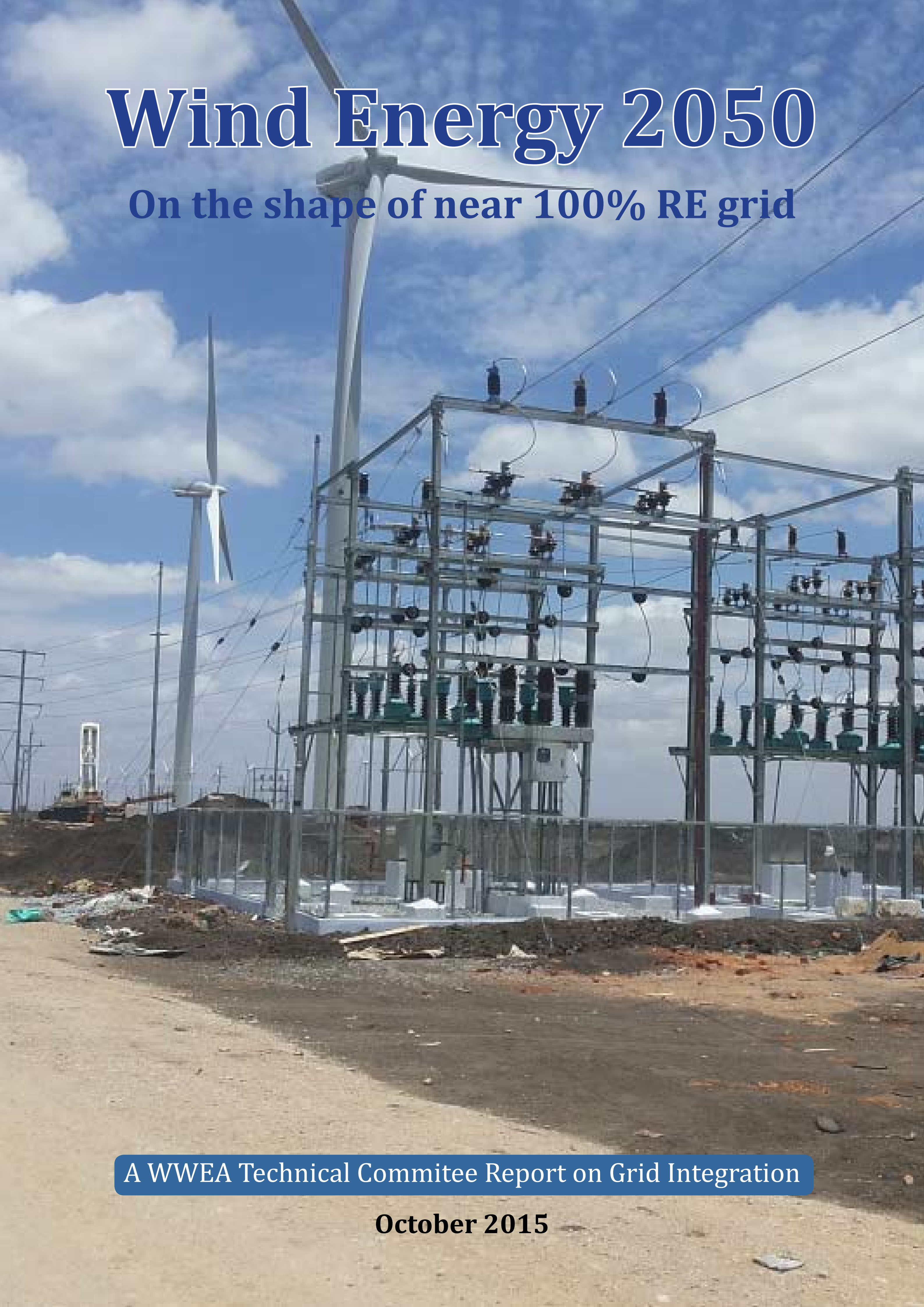
Wind Energy 2050

On the shape of near 100% RE grid



A WWEA Technical Commitee Report on Grid Integration

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Preface

The WWEA technical committee report "Wind Energy 2050: On the shape of near 100% RE grid" (hereafter referred to as WWEA Grid Integration Report) is a futuristic assessment not only of the wind power capacities that can come up by the year 2050 but also about arriving at an understanding of the evolution of the electricity grid in conjunction with evolving wind technologies and other ancillaries and systems and also with the evolution in grid management strategies to deliver uninterrupted power to consumers in a near 100% RE Grid.

The report has 5 main parts – 1) Introductory part that presents the background information and highlights the factors that will continue to provide a thrust to wind technology and deployments 2) An overview of the emerging face of grid and grid integration issues 3) Trends in deployment and technology 4) Assessment of wind penetration levels by 2050 and 5) Evolution of the grid management and the grid model

Wind turbine technology has continued to evolve making an ever deepening impact on the world wide energy system, particularly the grid. While currently 2-5 MW individual wind turbines are being used in Onshore regions and 5-8 MW in offshore regions, this may change in next ten years as many new concepts and initiatives are under research and development. Yet another kind is the small wind turbine of a few kilowatts or less, that too is catching up. The predominant model is a horizontal axis 3 bladed wind turbine. However, this too may change with many technological concepts being experimented.

A lot of analysis presented in this report is done by WWEA technical committee, however, there are also expert inputs from outside the association. Sources of information and data include WWEA but also open data available from The Worldbank , IEA etc.

This report presents a viewpoint of WWEA on the future of Grid, 100% RE and likely scenario by 2050. WWEA's firm belief that wind energy will emerge as one of the major and mainstream sources of energy in a few decades is now supported by concrete data, trends and developments that we have tried to capture in this report. It is important to mention that the report has inputs from a number of wind energy associations across the world and represents these varied viewpoints and perceptions as well. The report should be useful to agencies, utilities, governments, analysts, market players, industry and professionals and academicians.

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Nomenclature

AFDB	African Development Bank
DC	Direct Current
DFIG	Doubly Fed Induction Generator
ERCOT	Electric Reliability Council of Texas
EU	European Union
FACTS	Flexible Alternating Current Transmission System
FiT	Feed in Tariff
GHG	Green House Gas
GIZ	German Society for International Cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit)
GW	Gigawatt
HVDC	High Voltage Direct Current
HVRT	High Voltage Ride Through
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGBT	Insulated Gate Bipolar Transistor
IPCC	Intergovernmental Panel for Climate Change
KfW	Kreditanstalt für Wiederaufbau
KV	Kilo Volt
kWh/yr	Unit of electricity, Kilowatt hour per year
LOLE	Loss of Load Event
LVRT	Low Voltage Ride Through
MERC	Maharashtra Electricity Regulatory Commission
MW	Megawatt
NASA	National Aeronautic and Space Administration

NIWE	National Institute of Wind Energy
NREL	National Renewable Energy Laboratory
PGCIL	Power Grid Corporation of India Limited
PV	Photo Voltaic
RE	Renewable Energy
RES	Renewable Energy Source
RMSE	Root Mean Square Error
SCADA	Supervisory Control and Data Acquisition
SCIG	Squirrel Cage Induction Generator
TPP	Thermal Power Plant
TW	TerraWatt
TWh	Terawatt-hour
VSC	Voltage Source Converter
WEC	World Energy Council
WRIG	Wound Rotor Induction Generator
WWEA	World Wind Energy Association
WWF	World Wildlife Fund

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Executive Summary

Global warming and increasing electricity consumption trends in many parts of the world pose a serious challenge to most countries from a climate change and energy security perspective. Harnessing of wind energy, which is indigenously available in almost every country can be a major mitigating exercise to address both the issues. WWEA in its earlier WWEA Wind Resource Report (2014) (http://www.wwindea.org/wwea-publishes-world-wind-resource-assessment-report/) has assessed the worldwide potential to be of the order of 95 TW, which is more than adequate to meet the electricity requirements of the world in combination with other renewable energy options.

Energiewende or energy transition will result in a high level of penetration of renewable energy in the power systems around the world. Some countries like Denmark and regions like Texas, already have up to 50% or even more penetration of renewable energy. On some days, Denmark receives 100% of its electricity requirements from wind energy. High penetration of renewable energy, in particular wind energy, due to the fluctuating nature of the source, presents many challenges in integrating the wind power generation with the conventional power system or the electricity grid.

In recent times there has also been much interest in 100% renewable energy, which requires a complex grid interface with a varied number of generation devices and balancing ancillaries such as battery banks, pumped hydro storage, other storages, SCADA, capacitor banks etc.

This report from WWEA technical committee is about examining these challenges and solutions to address some of the issues so that we can step off from a Hydrocarbon fossil fuel based energy system and on to a Renewable Energy Platform.

The WWEA Grid Integration report carries a brief holistic overview of the evolution of emerging grid integration issues, smart grid, island grids and the likely shape of grid in foreseeable future. The report also covers trends in wind technologies, trends in wind installations in different regions of the world and expected penetration levels by 2050.

The grid is evolving and it is important to understand that when renewable energy generators get connected to the grid, they become a part of it just like the conventional generators are. The grid is no more – what it used to be. The question then is not so much about how to integrate wind energy with the grid but rather how the various elements of the newly evolved grid must function with a large component of renewable energy including wind energy integrated with it.

There are many different aspects to grid integration of wind energy or renewable energy in general. These aspects vary from region to region depending on local characteristics, generation mix, load patterns, transmission infrastructure and the operation

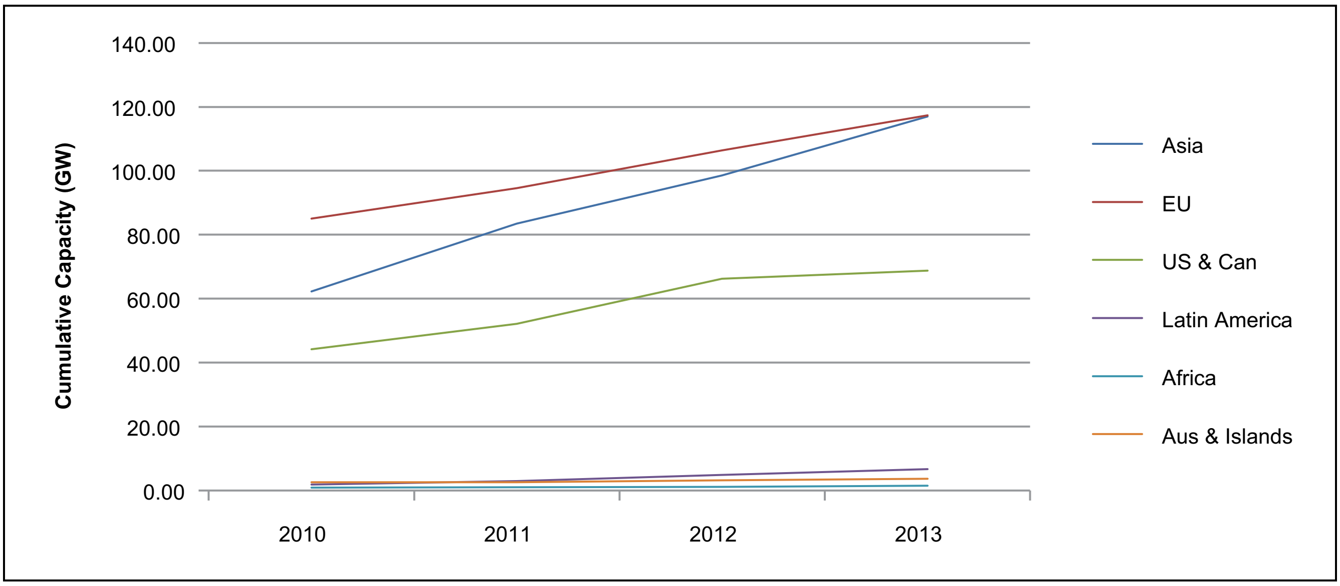
and management practice. In chapter 2.0 we have tried to highlight these different aspects and facets of grid integration issue.

Evolution of wind technologies and the trends in installations are also examined in the introductory section as the technology itself is the change agent. While conventionally there have been large centralized power plants based on fossil fuel, wind turbines that have emerged over the last few decades are significantly smaller machines. These are geographically dispersed meeting local loads as well as feeding electricity upstream in the grid.

Wind turbines are now well entrenched in the grid across the world. Analysis presented in Figure A shows that Asia lead by India and China has emerged as a major market and a hub for technology supply.

The report also presents the 2050 scenarios for wind power penetration levels in total electricity mix over the next 35 years. Taking into consideration the trend of installation from 1971 onwards and studies conducted by IEA and WEC the total electricity production will fall in the range of 40000 to 74000 TWh by 2050. According to WWEA's assessment the wind power generation can be between 8000 TWh to as high as 29600 TWh. The capacities corresponding to different electricity generation scenarios (i.e., Low - 40000 TWh, Likely – 57000 TWh and High – 74000 TWh) assuming capacity utilization factor of 20% are shown in Figure B. The wind capacity scenarios also correspond to Low (20% penetration, Likely 30% penetration

Figure A: Regional trends in installations

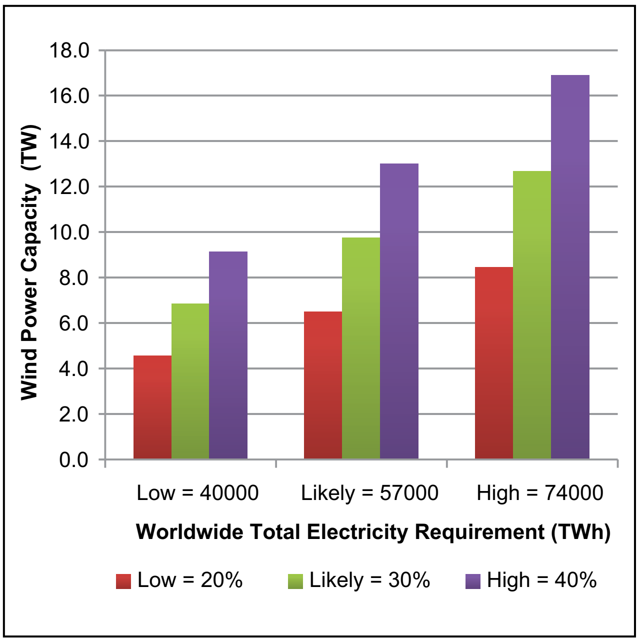


and High 40% penetration). This corresponds to a range of 4 TW to 16 TW. The current installed capacity is 0.37 TW. Therefore, by 2050 on a very conservative and low scenario basis, we expect more than 10 fold increase while on the optimistic side, we expect more than 40 fold increase. In the most likely scenario we expect more than 25 fold increase corresponding to 9.8 TW.

The report has highlighted the evolving aspect of the electricity grid. Across the world, the electricity grids will undergo changes in infrastructure, technologies, structure and management to enable large scale integration of renewable energy, in particular wind energy into the power system. Future electricity grid will comprise of distributed generation as compared to centralized generation. Multiple mega-drivers are set to dramatically change ground realities and the basic assumptions that govern power system design and operation. These drivers are 1) Environment or Decarbonization, 2) Reliability, 3) Distributed Generation with Renewable Energy 4) Transportation electrification, 5) Consumer participation and 6) Deregulation. This evolution should be viewed in the context of the country or region. For example, looking at Africa, which today happens to be the dark continent devoid of a significant network serving it, interconnected mini-grids with distributed renewable energy and hybrid power plants can be a major distinguishing feature from that of the conventional power systems in developed countries.

Whatever, the manner of transition, we will see steady diversification in sources and types of electricity injection devices to include solar, wind, storage systems and demand side resources, etc. This, in turn, would require the grid as a whole to evolve its control capabilities to host the new found and tremendous diversity of loads and generators. The question, therefore, is not of wind variability but of how to evolve with high penetration of wind and to assess the control capabilities of the electricity grid as a whole.

Figure B: Wind Power Scenario - 2050



The already existing suite of control technologies and strategies are set to dramatically change. While existing regulatory codes and standards on grid safety, security and operation will continue to apply to a large extent there will be a greater deployment of control, automation, and information technology. Together, these form the smart grid initiatives that will not only engage with generators but also with consumers and other ancillary units in the grid.

Concluding Remarks

The world energy system, which is predominantly hydrocarbon based must now undergo a transition to make way for a renewable energy based system in which wind energy plays the predominant mainstream role. The planetary environmental concerns, energy access and energy security issues, the geopolitics of oil and resulting conflicts in many parts of the world, all these aspects point towards the urgent need for this transition or *Energiewende* as it is called.

WWEA in its earlier WWEA Wind Resource Report (2014) has assessed the worldwide potential to be of the order of 95 TW, which is more than adequate to meet the electricity requirements of the world in combination with other renewable energy options.

Today with wind contributing nearly 4% of overall electricity generation, 370 GW of installed generation capacity and deployment in more than 100 countries; modern wind turbines have made the transition from a fringe technology to a mainstream electricity generation option. Technology continues to evolve with greater elements of innovation, engineering complexity and technical finesse. We can say a modern wind turbine is a smart wind turbine capable of un-attended operation even in extreme climates such as offshore regions. Many new ideas and initiatives are being experimented with and this may further change the technology landscape.

A major barrier to large-scale wind power deployment is its integration with the conventional electricity grid. We have looked at the entire issue of grid and its management with high penetration of wind and other renewable energy with deep insights but from a broad evolutionary perspective. We conclude that higher penetration of wind in the power systems is not an insurmountable problem and there are specific technological or management practice solutions to each of the problems. We feel with greater component of generation from wind, the grid has evolved and it must undergo further significant evolution to enable 100% RE scenarios. Some of the specific conclusions w.r.t. grid are:

- Need for flexibility in the power system, which implies a lesser capacity based on nuclear and coal and a larger capacity based on hydro or fast response units
- We note that even in the absence of wind, a power system has to deal with many dynamic parameters such as availability of plants and variability in load demand. Wind generation only adds to the dynamics in the system.
- A larger number of transmission links from a high wind resource area to the adjoining areas
- Deployment of DC and HVDC technologies with converters and power electronics that address issues of harmonics and stability
- Need for utility scale storage systems to balance fluctuations
- Need for forecasting power output from windfarms over both, long term (1 week) and very short term (1 hr)
- Need for technological modifications in wind turbines to enable better control and grid friendly operation such as LVRT, HVRT, curtailed operation or power factor adjustments. Technologies are also required to interface with storage systems with wind turbines or independent of wind turbines
- We also conclude that in large scale wind generation, variabilities are evened out and pose less of a problem at system operation level. However, local variabilities may cause surge or dip voltage and frequency.
- Smart grid options need to be explored for better communication in different parts of grid and better control
- Proliferation of battery storage systems in vehicles, power back ups in domestic, industrial and commercial establishments can be leveraged to achieve high penetration of wind energy and other renewable
- Hydro capacity with the ability to ramp up and ramp down in a matter of minutes is a good combination with wind energy. Pumped hydro capacity in the system has the same effect.

1.0 Introduction

Modern industrial civilization, built over the last 300 odd years has made huge transition from a predominantly agrarian society to an industrial one. The journey to machine age has been most miraculous and makes for an amazing story. Energy has been a key element of this story. Beginning with the first coal based steam engine developed in the 17th Century; energy has been at the centre stage of this evolution. Mankind was fortunate to stumble upon huge reserves of hydro-carbons across the world that has fueled modern civilization in an unprecedented way. One could say that our civilization is built on a hydrocarbon platform, its constituents being coal, oil and gas. Be it transport, industrial, commercial, non-commercial, domestic sectors – As of today, our machines need hydrocarbons to keep the show going.

Though today we still have discovered and undiscovered reserves of hydrocarbons in huge quantities, we stand on crossroads. On the one hand, we have the relentless and massive extraction of these minerals and substances (fossil fuels) that have been formed through millions of years of natural pro-

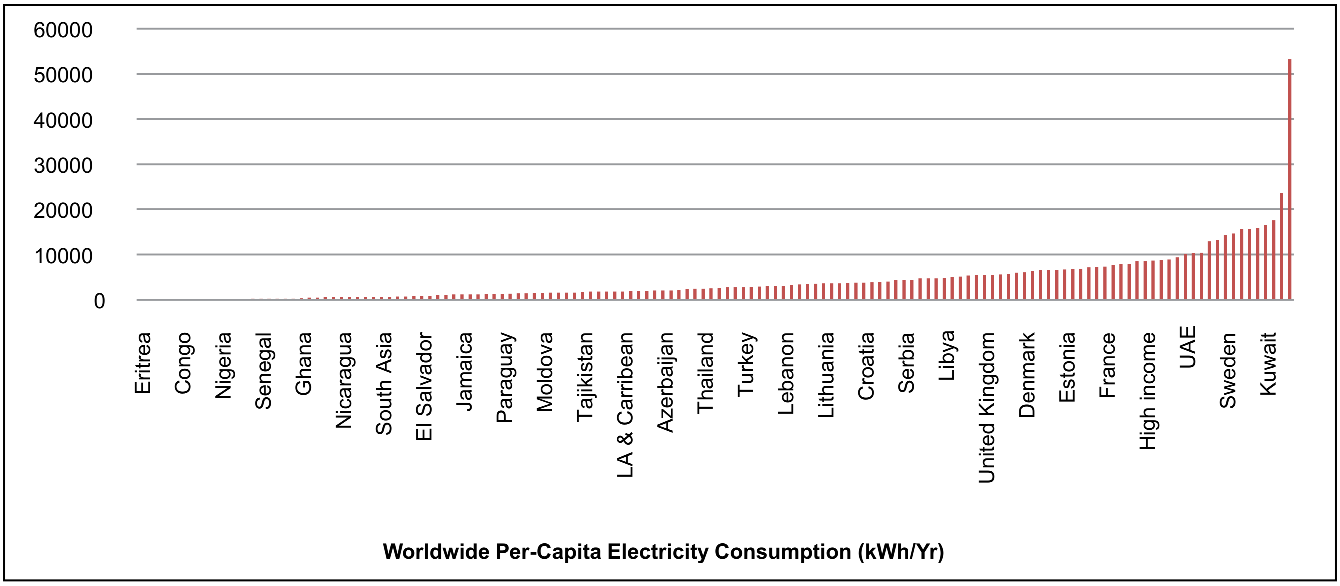
cess in Earth's surface, in just about 300 years. On the other hand, we have Green House Gas (GHG) emissions from burning of Hydrocarbons in Transport, Industry and Power Generation that has created a situation where we are already hitting the roof as far as these emissions are concerned. GHG emissions are causing global warming and if no preventive measures are taken, average global temperatures could rise upto 4 deg C in the long term (source: IPCC, RCP8.5 scenario). This implies large-scale climate change resulting in changes in atmospheric and oceanic systems such as monsoons; increased frequency and severity of cyclones, storms, droughts and floods; sea level rise and inundation and loss of millions of square kilometers around the world; melting of glaciers in polar regions resulting in a change in pH of oceans with associated impact on plankton existence- the basic food source for all marine life, oceanic circulation, currents and the melting of glaciers in Himalayas with associated impact on the rivers that emanate from Himalayas. According to an estimate, livelihoods of nearly 4.5 billion people living in different countries are linked to rivers that emanate from Himalayan Glaciers. Though many people are skeptical about global warming and its impact, it stands to reason, that if we continue to intervene in natural systems in an unnatural way consistently, the outcomes are going to be disastrous.

It is now an established scientific fact that anthropogenic activities are at the root of global warming and even if GHG emissions were neutralized completely, the inertia of the climatic system will result in average global temperatures rising well into the next century. In its latest report, IPCC[1] commenting on future risks emanating from Climate Change has said:

Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks.

Climate change is undoubtedly a major driver of wind power development. In 2004 burning of fossil fuels in Industry and in general for electricity

Figure 1.1: Per-capita Electricity consumption in different countries (2013)



Source: Worldbank database

generation accounted for nearly 45% of the total emissions[2].

Access to electricity is another major driver. Today, it is estimated that nearly 1.3 billion people in the world do not have access to electricity, which is as much as the population in OECD countries.
(Source:http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/).

Electricity consumption is directly related to the quality of living. In 2013, as shown in figure 1.1 more than 38 countries had per capita electricity consumption less than 1000 kWh/yr including some of the most populated regions and all countries of South Asia accounting for 1.7 billion people and about 50% of the world has per-capita consumption below 2000 kWh/yr. The world average is around 3000 kWh/yr and the European countries typically have per capita electricity consumption of more than 5000 – 7000 kWh/yr. This shows that there is great potential to add generation capacity across the world. According to an assessment, the electricity requirements are expected to grow by 43% in next 20 years.

Electricity generation has grown in most parts of the world; however, maximum growth has taken place in developing and even under developed countries.

Wind energy deployment has also been on a rise and while regions like China, US, Europe and India are mature wind energy markets, there are many countries that are emergent markets or potential future markets, these include south-east Asia, Africa, Latin America, middle East and central Asian and East European countries.

In recent years, Germany and many other European countries have made a serious effort towards energy transition, to step off from the Hydrocarbon platform and to create a Renewable Energy Platform. This movement also known as *Energiewende,* is about transition of the national energy portfolio to renewable energy and a significant reduction or an end to hydrocarbon fuels. Many other countries outside of Europe including China, India, US, Brazil and Canada are also making a serious effort to bring about significant renewable energy capacity addition. *Energiewende* or energy transition will result in a high level of penetration of renewable energy in the power systems around the world. Some countries like Denmark and regions like Texas, already have upto 50% or even more penetration of renewable energy. On some instances, Denmark and other countries, receive 100% of their electricity requirements from wind energy.

High penetration of renewable energy, in particular wind energy, due to its fluctuating nature, present challenges in integrating it with the conventional power system or the electricity grid.

In an earlier report, WWEA has assessed the worldwide potential for utilization of wind energy at 95

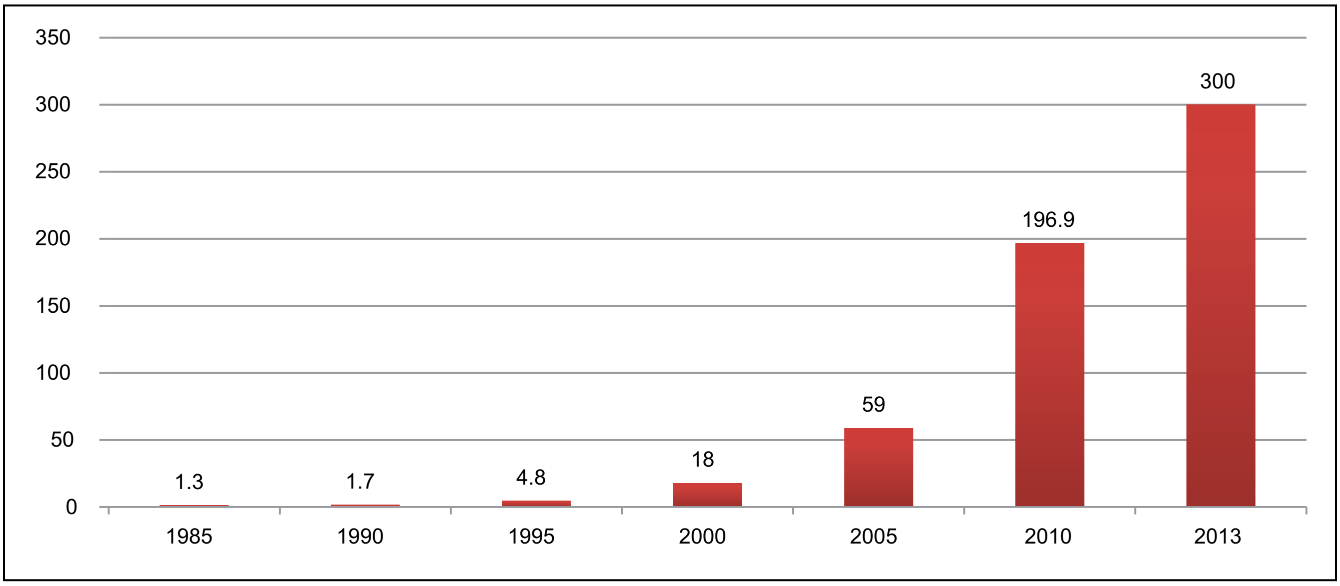
TW (http://www.wwindea.org/wwea-publishes-world-wind-resource-assessment-report/). Such assessed capacity is more than enough to build a worldwide 100% RE scenario in a foreseeable future. Wind power penetration in the conventional power system is still quite small at 4% (Source: WWEA). It is imperative that significant additional contribution to the grid from this renewable energy resource, would pose serious technological and even policy and regulatory challenges. Many of these challenges, have been worked upon across the world in various institutions, research establishments and among the grid operators.

In this report, first and foremost, we present an overview of the grid integration issues to highlight the fact that most of these issues are technology and grid management related, have been partially resolved and are indeed surmountable. We then look at trends in electricity generation across the world to arrive at low, medium and high renewable energy scenarios by the year 2050. The report is prepared with the objective of supporting all other worldwide initiatives towards 100% RE so that indeed we can step off from the Hydrocarbon platform and on to a Renewable Energy Platform.

1.1 Wind Power Growth

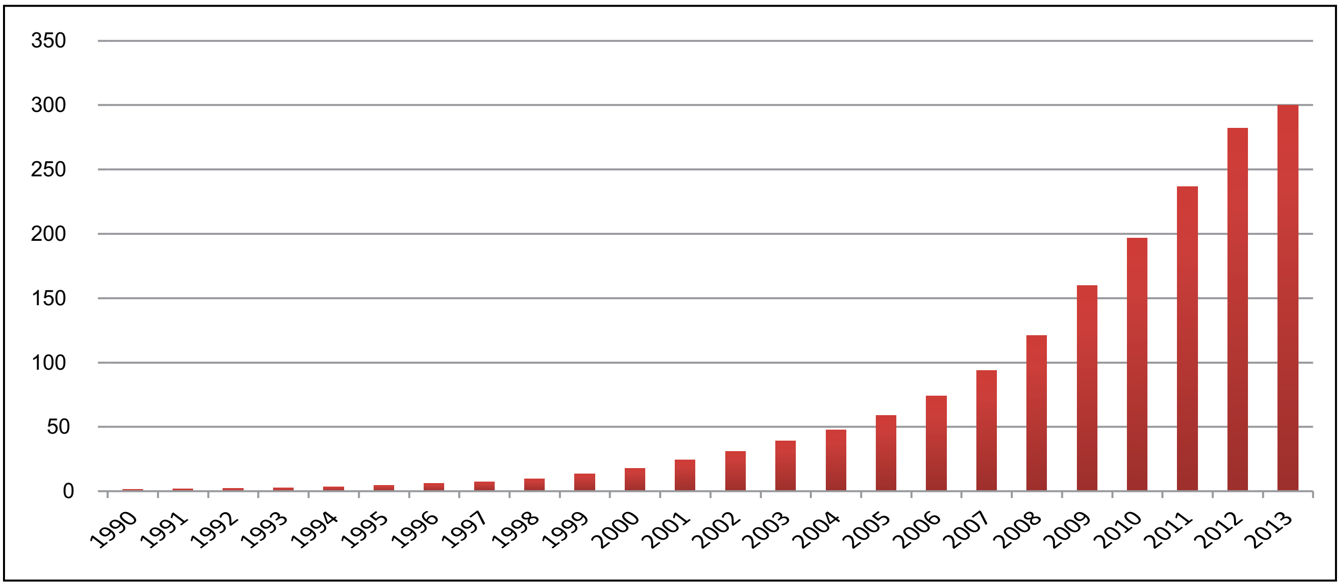
Exponential growth in wind power development across the world, particularly in the last few years, has lead to wind energy occupying a prominent position in the power sector. Continued technological development and innovation in design and manufacturing has resulted in wind turbines being deployed on a large scale in onshore projects and to a significant extent in offshore projects. Today with wind contributing nearly 4% of overall electricity generation, 393 GW of installed generation capacity and deployment in more than 100 countries (Source: WWEA); modern wind turbines have made the transition from a fringe technology to a mainstream electricity generation option. The main drivers for this very significant thrust in technology, innovation and worldwide deployment are energy security, climate change and energy access while employment and economic development are added benefits.

Figure1.2: Half decadal cumulative wind farm installations (1985-2013) (GW)



Source: (Derived from WWEA data)

Figure 1.3: Annual cumulative installation of wind farms (1990 – 2013) (GW)



Source: (WWEA)

1.2 Technology

The drivers mentioned above have also lead to the evolution of wind turbine technology, matured to a point where it can operate as a reliable machine in a near "unattended" situation and interface with a complex electricity grid to feed grid quality electricity.

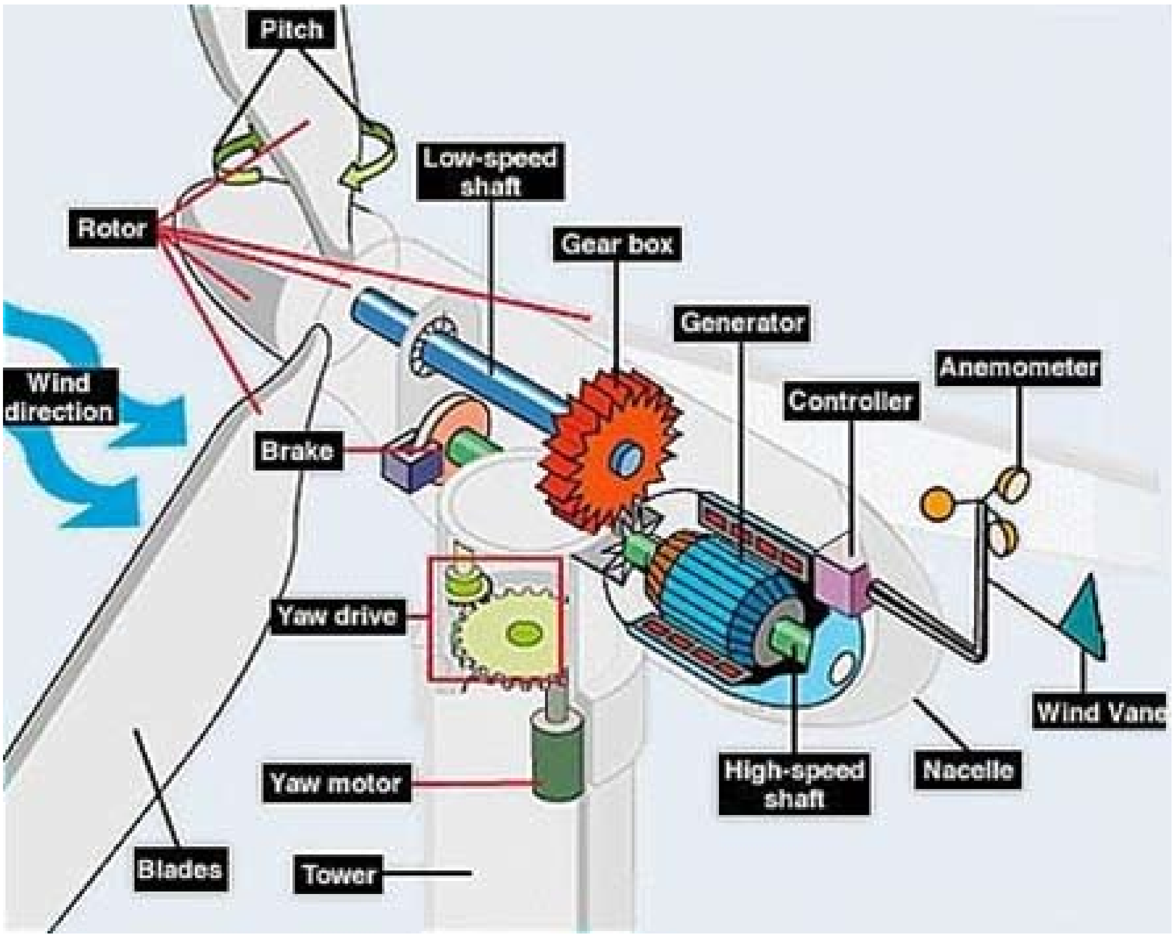
Thus wind resource, which we have shown to be abundantly available in the world (WWEA Wind Resource Report, 2014), can play the most significant role in offsetting GHG emissions from the power sector and in mitigating global warming.

Though there is a general trend towards larger wind turbines, in more recent times, the trend is more

Figure 1.4: A typical Offshore wind farm

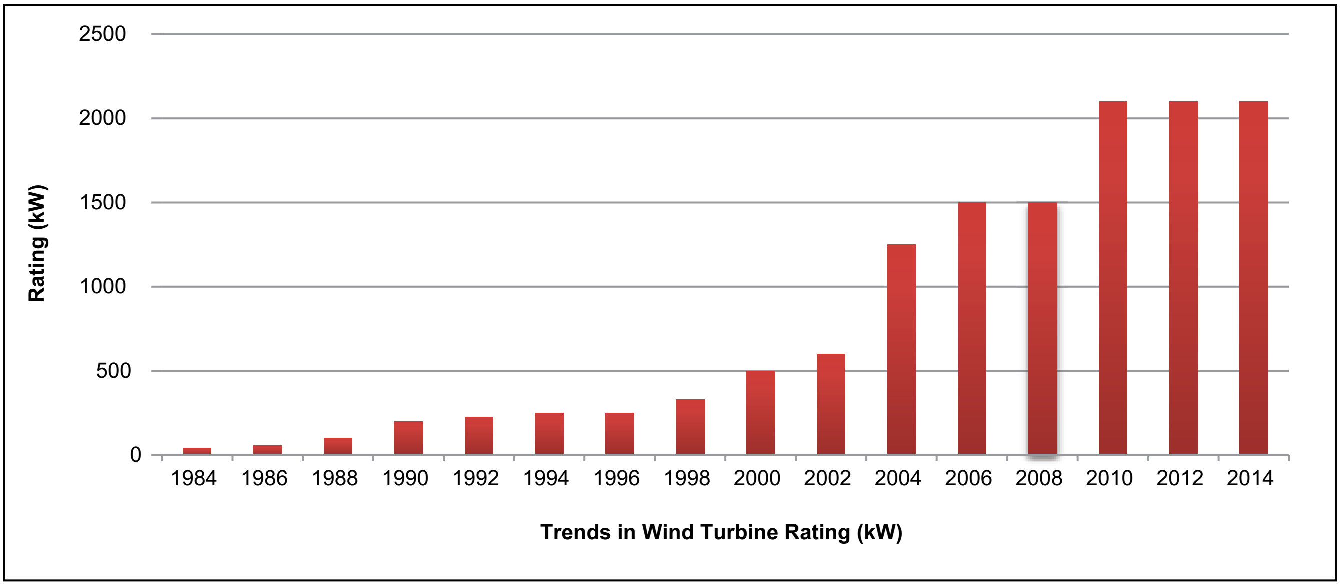
Source: http://ultimateskirmish.co/tag/wind-farm-wallpapers

Figure 1.5: Wind turbine components



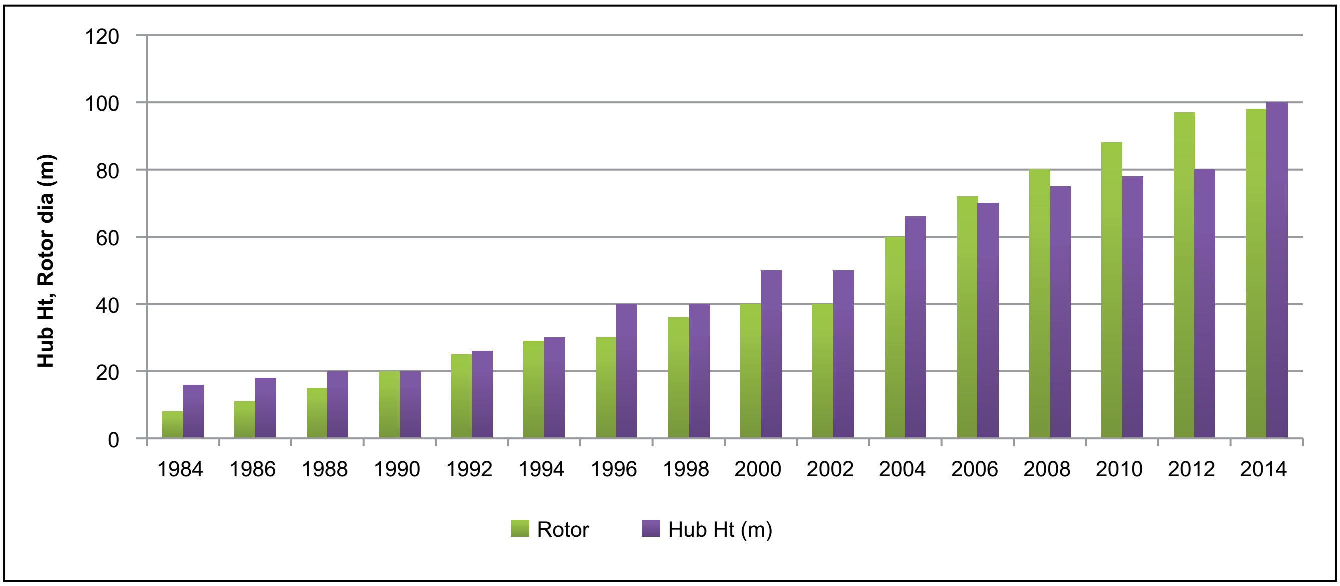
Source: http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/how-wind-energy-works.html#.VcLy-POqqko

Figure 1.6: Trends in ratings of wind turbines



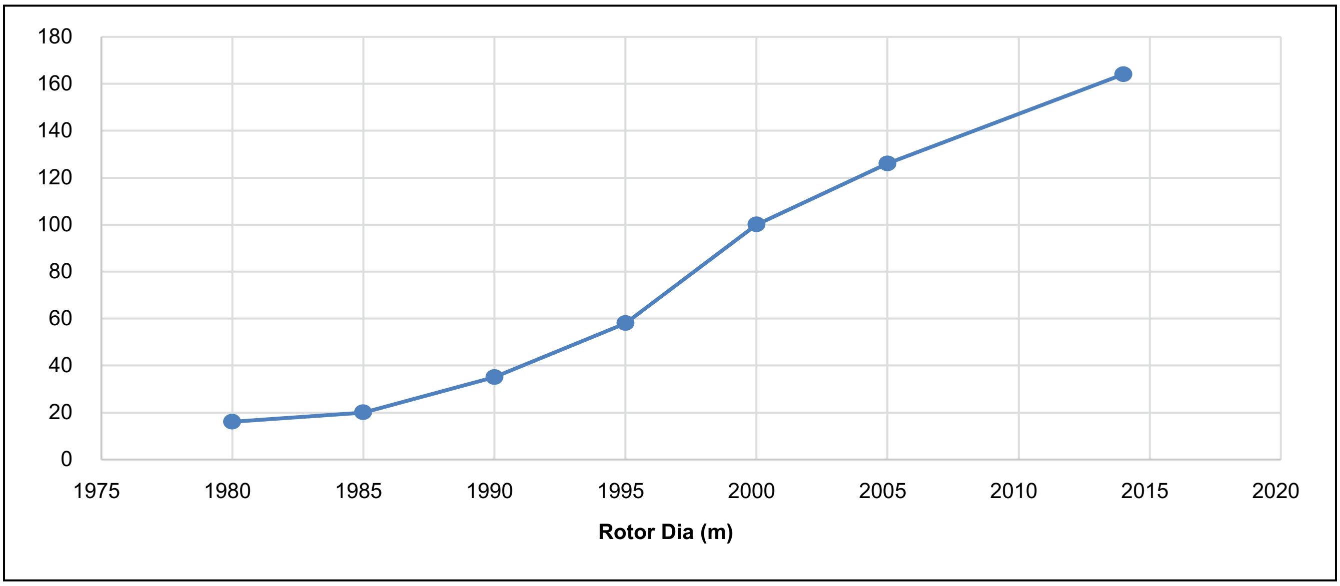
Source: (WinDForce database)

Figure 1.7: Trends in Hub height and Rotor diameter (m) for predominant turbines



Source: (WinDForce database)

Figure 1.8: Trends in largest Rotor diameter (m)



Source: (WinDForce database)

towards increased rotor size and tower height of the wind turbine for optimal energy capture. The implication is that regions with mediocre wind speeds that were not feasible for setting up windfarms earlier, are becoming viable. Thus wind technology suitable for vast areas of the world is increasingly getting established. This, also is a trend towards mainstreaming of wind in the energy sector.

On another front, knowhow on Offshore wind power technology continues to evolve. Foundations present a major challenge and a "cost head" in case of offshore wind farms. Currently most of the offshore projects come up either in the inter-tidal zone or in the shallow seas with a maximum depth of 40 m. Some projects are planned in depths up to 80 m. However, for shores where the continental shelf drops off steeply such as most coastal regions of India or Western US, offshore wind farms are a difficult proposition. However, currently trials are on in a few projects with floating type of wind turbines that may minimize the foundation costs and also resolve other logistic issues around off-shore projects. Northern Europe with nearly 6 GW capacity has maximum offshore projects in the world. China has installed 500 MW capacity in the intertidal zone. Offshore wind farms, though not necessarily the most favored option today, in times to come could unfold as yet another huge opportunity.

1.3 Grid Integration

As more and more windfarms get commissioned across the world, and thus more electricity generated by wind is getting pumped into the electricity grids alongside other forms of distributed generation such as solar and biomass, new challenges arise, as the character of the grid itself is undergoing a change to support this distributed and fluctuating generation.

The grid is fundamentally a network with interconnected power system elements. In the very recent past (about a decade back), it used to comprise of a few large generating stations based on coal, nuclear or large hydro plants generating electricity in a centralized manner and the electricity generated was being transmitted over large distances, sometimes hundreds of kilometers, on high voltage lines (220KV to 1000 KV). In the last few years, this has changed in many parts of the world. Large but distributed wind based generation capacity has come up in US, Europe (Germany, Denmark, Spain, and UK), India and China.

The power system or the utility manager who used to manage the load dispatch functions with large power plants to meet a geographically distributed load demand on the system, now has to deal with not only the variability of load demand but also the variability of geographically dispersed wind based generation, , on which he has little control. Apart from wind energy, there are increasing amounts of solar generation capacities connected to the grid. Solar energy, though it does not vary in the same manner as wind, is also subject to variations, with other resources with different levels of variability and availability.

As world leaders and organizations become more aware of the need for transition to renewable resources, due to the policies pursued, many countries start experiencing higher share of variable distributed generation, to levels approaching 50% and beyond. As per IEA statistics[3], nearly 30% of the electricity requirement of Denmark was met by

wind in the year 2012. Some of the other countries with significant amount of wind power penetration, in terms of energy generated, are Portugal 20%, Spain 17.8%, Ireland 14.5%, Germany 7.7%, and UK 6%. Among relatively larger countries, US had penetration level of 3.5% and China 2%. India, which is not covered by IEA reported 2.7% generation from wind for the year 2011-12[4]. In larger countries, though overall penetration levels are relatively lower, at regional levels, where there is concentration of windfarms like Texas, Tamil Nadu, Inner Mongolia Autonomous Region, the penetration levels are of the same order as those in high concentration areas of Europe like Denmark, Spain, Germany, etc. Texas, for example, has reached over 10% from wind in 2014[5], while the West Zone of the Texas in fact seems to have a very high penetration level of 85%[6] according to ERCOT[7] and can get to over 100% in some months.

We can thus conclude that in parts of the world, the electricity grid has undergone a transformation. The constituents of the grid network are not the same anymore and neither are the issues that a utility manager faces today to ensure secure power supply to consumers. With many countries planning large wind farms (of over 100 MW), this transformation seems to be the trend that utilities across the world will follow.

It is now widely accepted among policy makers, academia and industry that wind as an economically exploitable resource is present in almost every country though in varying degree and strength. At the same time technological developments in the industry indicate that new designs of wind turbines with higher hub-heights and large rotors, enable harnessing of wind energy even in areas that were earlier not considered suitable for setting up wind farms. At the same time new technological and management approaches such as forecasting of wind energy output from windfarms, efficient use of storage capacities in the power system, remote controls over wind turbine operation as well as the transmission linkages to other regions and systems, in the foreseeable future, can quiet significantly enhance the ability of the conventional power system to accept more wind energy.

In many parts of the world, we are currently managing the power system with wind penetration of the order of 40% - 50% (Denmark, Texas, Tamilnadu etc.). According to WWF in its report The energy report 100% renewable energy by 2050 (http://wwf.panda.org/what_we_do/footprint/climate_carbon_energy/energy_solutions22/renewable_energy/sustainable_energy_report/), we could get all the energy we need from renewable sources. The first recommendation of this report is

Promote only the most efficient products. Develop existing and new renewable energy sources to provide enough clean energy for all by 2050

Therefore, efficiency goes hand in hand with 100% RE concept and coupled with other measures such as smart grid and other renewable energy systems, we have a case for a near 100% renewable energy powered grid. Given that we have only 4% wind penetration today (source:WWEA) and combined with 16% of hydro (Source: worldbank 2011) we have nearly 20% RE penetration today. The energy transition is likely to happen over a time horizon of 30 – 40 years. In this report, we are looking at a scenario of 40% wind penetration worldwide by 2050. This prospect throws up many interesting questions:

- What needs to be done to reach this high penetration point of 40%?
- What are the implications for the electricity grid and its management and how will it evolve?
- What kind of wind power capacity are we talking about?
- Will renewable electricity flow beyond the grid to transport sector?

These are diverse and complex questions covering energy sector, power systems engineering and management as well as technological evolution with smart and IT enabled solutions.

We do not necessarily see the complete end of fossil fuel based generation, but it could have a significantly less important role in the overall scheme in the power sector. In terms of transition, the next decades would indeed be very exciting and would undoubtedly define the future energy system for the world.

In next few chapters, we present an overview of grid integration issues and subsequently country specific aspects, 2050 scenario and the evolving face of the grid. We try to answer some of the questions, capture the picture of not too distant a future and try to gain clarity on how grid integration of wind energy and other renewable energy systems will bring about paradigm shift in the way grid exists today.

Some of the chapters have been written by experts and some of it is our own analysis. All of this feeds into wind energy scenario 2050!

2.0 Wind Energy Grid Integration – An overview

A power system or the electricity grid, is a network of interconnected generation loads, consumption loads and transmission and distribution infrastructure – spread over a very large geographical area either covering a province or state or an entire nation or many nations. The only purpose of the grid is to supply quality electricity to the loads connected to it under all circumstances. In trying to achieve this, a grid operator has to deal with many uncertain events such as sudden increase in load demand or breakdown of a power system element also termed as 'outage'. A power system element could be a generating plant, a transformer or a transmission link or any of the ancillaries/ elements in the supply chain that brings electricity from the point of generation to the point of consumption. When such an outage occurs and the system is not able to meet some of the load demand connected to it, a Loss of Load Event (LOLE) is said to have occurred. The purpose of the grid operation, therefore is to avoid LOLE or to keep it to a minimum. A LOLE happens essentially because of uncertainties around some of the elements of the power system such as reliability of the power plants or fluctuations in load demand or sudden weather changes that can cause breakdowns or sudden spurts in load demand. Therefore, management of the grid is essentially about coping with these uncertainties.

There are many ways in which these uncertainties can be addressed – one of them is to keep certain reserve capacity in the system to meet any eventuality caused by these fluctuations. The reserve capacity itself could be cold (that is not running but available) or warm (spinning reserve) that is running but at minimum possible load or part load but with the capability to quickly ramp-up or ramp-down generation. Modern power systems work on the concept of load dispatch or unit commitment, i.e., committing availability of a unit to meet generation loads or scheduling power generation in advance.

Given that the grid is an interconnected system over a large geographical area, it is also possible to divert excess electricity generation from one region to another region that is deficit in generation and in this manner too, the grid operator can manage some of the uncertainties in the system. The operator also has to track load demand and have a forecast of load based on past trends, weather conditions or even events such a football world cup being played when the TVs are likely to remain switched on across regions or countries and hence a peak load occurs, so that generation units can be accordingly committed or kept in reserve.

The grid as it has evolved with conventional elements in it, typically has large centralized power stations based either on coal, nuclear or hydro and some gas or diesel generators to cope with sudden fluctuations or to meet the peak load. These gen-

erators are classified as base load plants or peaking plants. The base load plants run nearly all the time to meet the base load. Large coal based plants, or nuclear plants or sometimes hydro plants are operated as base load plants. The main reason to run coal and nuclear plants as base load plants is the fact that these plants cannot be easily switched on and off and take more time to ramp-up. On the other hand, peaking plants like gas engines, diesel plants or even hydro plants can come on-line in a matter of minutes and can also ramp-up quickly.

The grid, across the world, has evolved with major generation capacity based on large coal based plants or nuclear plants that often transmit electricity to very large distances. Often coal plants are set up near coal mines, so that they have uninterrupted supply of coal. Which, however means very long transmission lines to the load centers, which are in urban and industrial areas.

In short, the grid is a dynamic system operating in a dynamic environment, with various parameters that govern system operation, fluctuating all the time.

Now when we talk about integrating wind energy or other fluctuating renewable energy with the grid, the immediate reaction from people used to the idea of conventional power plants is that wind is variable and fluctuating and hence will pose very serious problems in the operation of the grid. However, they seem to forget that management of the grid is all about managing uncertainties. More wind energy or more renewable energy connected to the system just means additional dynamic parameter to be dealt with.

On the other hand, the variability part of wind energy appears to be more hyped-up than it actually is. No doubt, output from any given wind turbine varies over timescale from minutes to hours to days and seasons. However, aggregated output from many wind turbines shows less variance, therefore output of a windfarm with 100 wind turbines will fluctuate less over short time scales than the output of a single wind turbine and similarly output from many windfarms in a region will show-up less short-term variance and when we are talking about windfarms spread out over large geographical areas, the variance is further diminished.

When we are looking at large-scale integration of wind energy and in fact wind energy in combination with other renewables such as solar energy, small or micro hydro – all of which are fluctuating at the resource end, we have to look at the problem and the system holistically.

With many drivers in place that we have discussed, large scale renewable energy injection into the grid is emerging as more of a necessity than a choice. It is important to understand that when renewable energy generators get connected to the grid, they become a part of it just like the conventional generators are. The grid is no more – what it used to be. The question then is not so much about how to integrate wind energy with the grid but rather how the various elements of the newly evolved grid must function with a large component of renewable energy including wind energy integrated with it? Given that renewable energy fluctuates, what attributes should be there in the balance of the grid elements to cope with these fluctuations? These questions further lead us to issue of planning capacities in the grid – How should we plan future expansion and management of the grid so that we can have large component of wind energy / renewable energy in it. Perhaps even 100% renewable energy.

Wind energy grid integration also has to be viewed from different perspectives depending on the country, region, load demand and the size of the grid. It is important to keep in mind here that load demand on the system brings its own element of variability and uncertainty and the wind variability only adds to that. Grid operators are used to making load forecasts or managing with that kind of variability. This may differ from country to country. In developed nations, there is excess generation capacity and grid electrification is nearly 100 per cent. Therefore, grid in developed countries is geared to meet any demand on the system. However, in developing countries, the peaking generation capacity is often less than the peaking demand and system is managed by switching off some of the loads. This practice often leads to shutting down of wind farms as well if the grid operator is not able to manage the variability. In countries with sparse or no grid such as countries in parts of Africa and some parts in Asia, grid integration aspect may emerge somewhat differently. It could be, that we have a number of small/ mini/ micro grids with wind generation and interconnections between these different grids. Although some believe that Wind or load demand forecasts may not be required in case of small grids such as those in islands yet by scheduling an ongoing analysis and forecasting, remote communities and islands could become self sustained communities with electricity availability which matches generation with consumption.

The grid management aspects with high penetration of wind energy can be categorized as discussed in following sections:

2.1 Policy & Regulatory

How wind energy injection and associated issues and infrastructure is treated in the system is determined by the policy guidelines of governments to the utilities, the grid regulations and the grid code. If the policy specifically requires that wind generation must be accepted by the system at all times, then the planning for capacity addition and rest of the grid elements must evolve to accept more and more wind power. This would mean more fast response units, management practice that enables greater penetration of wind energy, transmission links, storage, pumped hydro, wind power forecasting etc. The policy and regulatory mechanism should also enable market players to play out their role through mechanisms such as electricity trading, open access, energy exchange, renewable energy exchange, renewable portfolio obligation etc. The manner in which deviation from a wind power forecast or generation schedule is treated in the system or the allowable deviation has an overall impact on wind energy. Storage systems and regulations around different possible business models involving storage systems, their grid connection and net-metering also need to be covered in the overall framework. Appropriate financial and tarrif mechanisms should be designed to incentivize increased storage systems in the grid.

2.2 Wind Turbine Technology

Wind turbine technology has evolved enormously over the last three decades. In the context of grid friendliness – we have moved from fixed speed wind turbines with Squirrel Cage Induction Generator (SCIG) to variable speed synchronous, ring or permanent magnet generators. The associated electronic, power electronic and control systems have also changed dramatically – a modern wind turbine is well on its way to being an '*intelligent wind turbine*'

The fixed speed wind turbines have very limited ability to operate over a varied rpm range of the wind turbine rotor. This means that any change in wind speed is directly translated into a corresponding change in power output. SCIG also consume reactive power from the grid that has to be compensated.

However, in case of variable speed wind turbines, depending upon the control strategies followed, an increase in incident wind speed, depending upon the control strategy, can also lead to higher rpm – i.e., the rotor by speeding up can absorb short-term variations in wind speeds. The predominant modern wind turbines today are quasi variable speed wind turbines such as wound rotor induction generator (WRIG) which can cope with 10% variations in rpm and doubly fed induction generator (DFIG) in which up to 40% of injection to the grid is through a insulated gate bipolar transistor (IGBT) power converter and thus enables 40% variation in rpm. The fully variable wind turbines have 100% of the power

going to the grid through the IGBT converter. Variable speed wind turbines are more desirable from a grid integration perspective as they have greater ability to cope with short-term wind fluctuations. Such variable speed wind turbines with IGBT converters also have the capability to manage reactive power. These control systems can supply electricity leading, lagging or at unity power factor. Many features that are possible with advanced power electronics and controls have not been fully exploited for grid integration. Low Voltage Ride Through (LVRT), High Voltage Ride Through (HVRT) or curtailed power output or switching down of some wind turbines to limit power injection at bus-bar are some of the possibilities. In case of grid disturbance or a problem with one of the generators or sudden increase in load demand, one can experience voltage and frequency variations and normally wind turbines shut down if these variations go beyond 10% of the nominal value. A large wind capacity going out of the system can create major disruption in the grid with cascading effect and many of the conventional power plants can start after tripping. This can cause a complete grid failure. Such situations can be tackled if wind turbines are equipped with LVRT or HVRT features. This way the wind capacity does not get disconnected from the grid and in fact helps the grid tide over the disturbance.

Variable speed wind turbines can also interface well with storage systems. We can think of wind turbines with some built-in storage and depending upon spot prices of electricity, grid frequency tracking or the time of the day, excess wind generation can go to a battery bank or the battery controls could be programmed to enhance the generation in case of certain shortfall in wind. Many of these features though not necessarily available on all wind turbines today, are technical solutions that can help bring about greater integration of wind energy.

Forecasting of wind speeds is generally undertaken at a macro level or at windfarm level. However, appropriately designed forecasting system can also work with wind turbine controller – to provide a day ahead forecast of generation for that wind turbine. It should also be possible through the SCADA systems for the load dispatch center (the grid operator) to directly control the wind turbine output or even to shut it down. Many of these possibilities of resolving part of the problems of grid integration at the wind turbine are already available.

There is whole area of technological interventions and advances at the wind turbine level in controls, communication and power electronics that can not only reduce the adverse impacts of variability on the grid but also to actually support the grid when it faces low or high voltage instances or reactive power compensation.

2.3 Wind Forecasting

Forecasting of wind power output has become an important aspect of the management of the grid. Forecasting wind power essentially caters to short –term and medium term fluctuations. The medium term forecasts are typically provided by weather data providers for the next 48 or 72 hours and the machine characteristics (power curve) as well as a windfarm simulation models can be used to forecast power output from the windfarm and injection at bus-bar. Historical records of numerical weather prediction and actual generation can be used to further train the model to arrive at more accurate results. Today, the level of accuracy being achieved is around 10% (RMSE) of the rated power. Short-term prediction, 1 - 2 hours ahead, can be more accurate and can also enable the operator to make final revisions to the schedule. It may be possible to forecast wind power more accurately in the short term because the weather condition in terms of its parameters is already evolved and the models present a better picture of what kind of generation might happen from windfarms in the near future. In general, forecasts are more accurate in near future i.e., closer to the present and become less and less accurate farther in future.

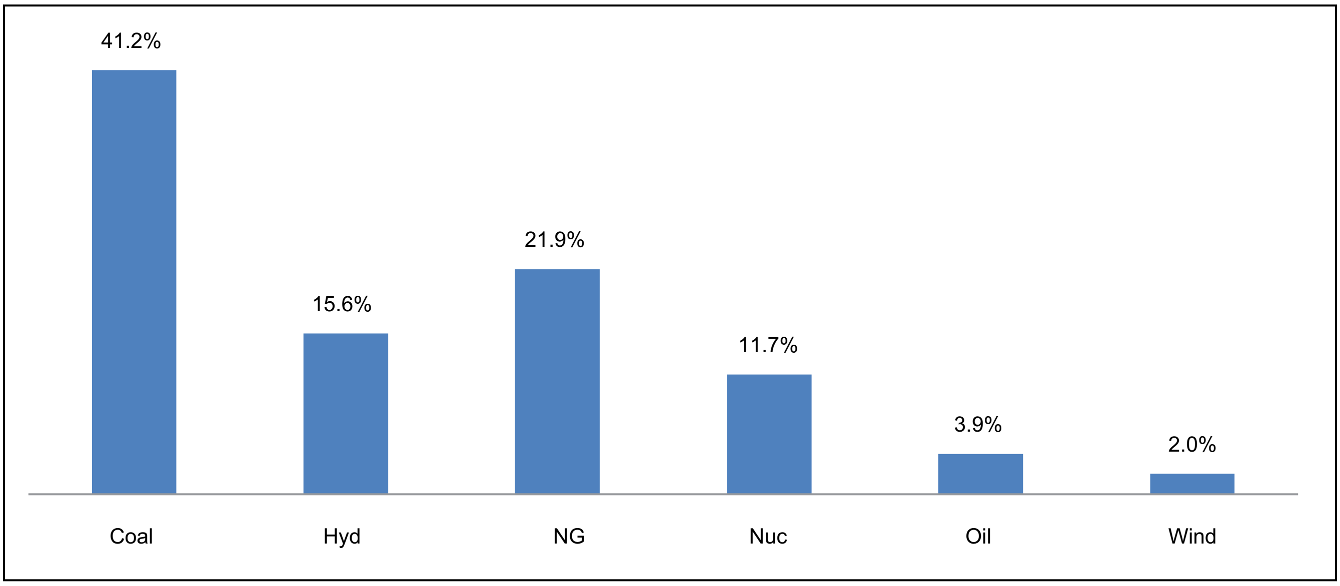
Forecasts can only address part of the problem, with wind or other renewable energy, variability is inherent to the source and type of generation and even with a forecast, the operator has to deal with variable generation.

Another important question, that we need to keep in mind is – does large wind capacity also imply large variation? Though this requires examination of data that already must exist with grid operators in many countries, we feel that in case of large wind capacity, which must be spread out over a large geographical area, the short-term variability at aggregate level will get diminished. However, mid term and long term variability such as seasonal variability or even over a couple of days, the variations would be linked to weather patterns and hence even large variability is possible. This may be so, in case of provincial or state level grids, however, where there are national or transnational grids – the variability at the system level may be less pronounced. In case of really large scale utilization of wind energy at regional, national and transnational levels a very different scenario may emerge – where electricity flows from multiple high wind zones to load centers.

2.4 Rest of the Grid

When the wind capacity is a small percentage of the overall generation capacity, it does not result in a major challenge for the grid operator. However, as we scale up wind power, variability and uncertainty on different timescales imposes certain requirements of flexibility on rest of the system components. If we look at 2011, World electricity generation (figure 2.1) shows that wind penetration was of the order of 2% and hydro is of the order of 16%. Nuclear and coal together account for nearly 53% of generation at global level in 2011. Now both Nuclear and Coal power plants offer limited flexibility in the system to enable large renewable energy integration, on the other hand hydro capacity, which may be in the form of large hydro projects offers much greater flexibility and possibility to ramp-up generation from zero generation to full rated generation in 10 minutes or so. Moreover, hydro projects offer storage in the form

Figure 2.1: World Electricity Generation



Source: (Worldbank and WWEA data)

of reservoirs, which can be leveraged to enhance renewable energy penetration in the grid. These reservoirs need not be close to the windfarms and can be geographically far removed. However, at the system level, they offer storage capacity. There could be limitations of seasons, rainfall, non-power requirements such as irrigation or flood control due to which it may not be always possible to operate hydro projects in the manner desired.

It is desirable to phase out coal and nuclear power plants due to climate change and risk perception associated with nuclear after some of the major nuclear mishaps that have taken place. While discussing higher penetration of renewable energy it is important to keep in mind that these sources are directly in conflict with coal and nuclear capacity. A large coal or nuclear capacity in the system implies rigidity while what we need is flexibility. Therefore, from the renewable energy perspective, lesser the coal and nuclear plants, the better it is for renewable energy.

Oil and Natural gas plants have high ramp up and ramp down capability and a certain capacity in the grid should be based on these fast response plants.

2.4.1 Transmission

Transmission linkages and transmission capacities are yet another important aspect of large scale grid integration strategy. We all know that the regions that experience high winds are not necessarily close to the load centers. For a high renewable energy grid, transmission planning must take into account major wind corridors in a country or a region. The second important role that transmission links play is in balancing wind variability by transmitting surplus wind power to far off load centers or to draw power from other regions, if wind generation or load demand do not happen as per the forecasts.

According to NREL (2011) in its report Eastern Wind Integration and Transmission Study

long-distance (and high-capacity) transmission can assist smaller balancing areas with wind integration, allowing penetration levels that would not otherwise be feasible

Both AC and DC transmission linkages are being used for large scale wind generation transmission, National or regional linkages are increasingly being planned with high voltage DC (HVDC) lines. Modern high voltage direct current (HVDC) systems can transmit up to three times more megawatts across the same linkage and wires as an AC transmission system. Significantly, with HVDC it would be possible to deploy reserves from one area to another, thus bringing in greater reserve capacity to address variability resulting from wind.

HVDC systems can also address transient stability and reactive power issues due to the use of Voltage Source Converters (VSC). HVDC-VSC is increasingly being looked upon as a means not only for long distance transmission but also to address issues related to power quality, harmonics, voltage and frequency variations within AC networks.

2.4.2 Power quality issues

Different wind turbine types can cause different kinds of power quality problems. Fixed speed wind turbines can result in problems such as voltage fluctuations and reactive power consumption and variable speed turbines can cause problems related to harmonics. Frequent changes in power injected can also lead to variations in frequency. For such problems there are technical solutions that need to be deployed such as filters, reactive power compensation, converters etc.

2.5 Energy Storage

Energy storage is emerging as an interesting component both, from the renewable energy grid integration perspective as well as energy and power system efficiency. In itself, energy storage is full of diverse possibilities on types and scale of storage. There is a great opportunity, waiting to be tapped, within Renewable Energy-Storage-Energy Efficiency area, which is fueling research and development in the storage systems.

Some of the large companies have already made commitments to electric storage systems, GE and TESLA are among them. Tesla has set up a factory in California (also called Gigafactory) and has introduced two products – Powerpack and Powerwall, for homes and utilities respectively and is looking at business in multi billion dollars 2-3 years from now. (http://fortune.com/2015/08/10/tesla-grid-battery/). GE has come up with wind turbines with a certain storage capacity.

When it comes to electric storage, it is the day to day battery or cell as we call it that comes to the mind. However, when we look at the grid, there can be diverse forms of storages, beginning with the rotating machines themselves. On the other hand, we can think of large scale storage in the form of hydro reservoirs. The rotating machines like a flywheel store energy in the rotational inertia. This can be used to smoothen short term variations in the grid (from micro seconds to a few seconds). However, in case of windfarms, leveraging this very short-term storage in the system would require that wind turbines be variable speed or quasi-variable speed so that fluctuations can either add to the rotational inertia or draw from it. The inertia of the rotating rotors could benefit the grid using the active power control, which, while sensing a drop of grid frequency, could increase the energy delivered to increase and stabilize the grid frequency or vice-versa.

One can also think of thermal energy storage both in forms of cold storage and heat, which can charged or stored in off-peak hours (normally in the night) and again used during the day to offset air-conditioning

loads in buildings. As long as there is a charging and discharging mechanism, any storage capacity can be leveraged to enhance renewable energy penetration in the system.

2.7 Transport Sector

The potential to use electric vehicles is a vast area that on one hand can lead to reduction in pollution and GHG emissions and on the other hand, by providing storage, can enhance renewable energy penetration. At the time of parking, an electric vehicle can be plugged to the grid and depending on the requirement of the grid can either result in charging or discharging. This would require smart grid kind of applications that can enable the grid to charge or discharge according to its state and the state of the battery. Imagine parking hubs turning into small backup and balancing plants. Similarly, one can imagine, residential as well as commercial premises using power back-ups contributing to grid stability.

Compressed air, lithium-ion batteries, hydro reservoirs present a great opportunity to enhance renewable energy or wind energy penetration in the grid.

In all these concepts with storage systems, there can be varied business models in the form of energy service companies that should be allowed to have a play in the regulatory mechanism.

2.8 Smart Grid

Smart grid is the use of automation, information technology, sensors, databases etc. in real time to manage different control aspects of the grid. These control aspects cut across all the themes we have discussed. Since in a modern grid there is a requirement to manage more complexity emerging from many more sources than what used to be in the con-

ventional grid, the need for greater use of control, automation and online communication between different components in the grid has increased and has also become critical from the viewpoint of 100% RE.

Forecasting of wind power, conversion of forecasts to schedules and frequent revisions as permissible as well as settlements are now almost entirely automated with minimum human interference.

Be it energy efficiency, that calls for switching of devices by means of sensors and controls or optimal performance of a wind turbine generator w.r.t. to grid parameters or curtailed generation from wind energy when desired by the grid operator – all of these functionalities and many more aspects get covered under smart grid concept.

The concepts of storage that we have discussed above can be implemented effectively only by smart grid options.

What we call smart grid is the evolved power grid of tomorrow that has got to be smart to cope with all the complexities emanating from different sources of generation, loads, transmission system, national and international transfer of power etc.

Smart grid is the evolving face of the conventional grid and is essential for achieving 100% or near 100% RE.

2.9 Island Grids

(This section is authored by Prof. Conredo Moreno, Vice President WWEA, Havana, Cuba)

Island grids pose interesting challenges in integrating wind energy. Most of the islands are far from the main island or continent and therefore, are not connected to the electric grid of these territories. An island grid essentially means a local grid isolated from the main grid.

The islands have the necessity of autonomous and reliable power systems that in general are based on internal combustion engines (ICE) and thermal power plants (TPP) that produce electricity by means of fossil fuels (diesel, fuel oil, etc). However, ICEs and TPPs are polluting in nature and are characterized by a high emissions.

Moreover, these generators are highly dependent on the supply of the fuel from long distances. The energy model of islands is therefore highly sensitive to the fuel variation costs which includes the cost of transporting these fuels over large distances.

The issue of increasing the peneration of Renewable Energy Sources (RES) in the local grid of an island becomes a very different problem in comparison to the penetration in large territories such as a country within a continent. To make a case analysis it is necessary to keep in mind the impact of the electricity generation using Renewable Energy Sources (RES) such as wind and PV in these local electric systems. The impact depends on several factors, most important being the technology used. For example, if the solution is based on wind energy, the type of wind turbine and the strength of the electric system are important. Fixed speed wind turbines or variable speed wind turbines have different kinds of impacts. Moreover, these impacts will be different if the electric grid is strong or weak. For the calculation of the limit of wind generation, it is important to know these operating conditions of the system.

The per cent contribution to the grid of wind generation with respect to the total generation will be limited. This limit is due fundamentally to the climatological dependence of wind energy and because generation varies through the day. This aspect defines a maximum per cent of penetration and integration with the grid keeping in view grid stability and its frequency.

To solve the penetration of RES in these kind of electric grids, typical in islands, many solutions have been proposed by several experts which have to take into account the increase in the penetration.

A group of Cuban experts led by Daniel Stolik are researching the matter of the RES penetration and they have proposed a set of measures, some of which are presented here.

2.9.1 Electric generation along grid periphery

To increase the electricity coming from wind and PV, getting injected at the periphery of the grid, in low and medium voltage in such a way that the injection is less in high voltage.

2.9.2 Highly dispersed distributed generation

To increase the number of RES electricity installations dispersed and distributed intelligently along the regions to flatten the variations in electric power generated.

2.9.3 Windfarms near load centers

To modernize the quality state of the grid: In order to increase the penetration of renewable, the electric grid should be more reliable and secure.

To use internal combuston engines (ICE) and TPP together with RES as an intelligent hybrid system: The electricity coming from classical systems (ICE and TPP) is very expensive but when the system is operated as an hybrid, the cost of the generated energy diminishes notably and the capital cost can be recovered in a few years.

To use RES for captive or self-consumption: To consume maximum possible electricity generated by RES for self consumption in large consumers. In this kind of approach, a smaller part of electricity is injected in to the grid. In practice, RE systems should be built near high electricity consumers.

To combine wind with other renewable energy sources

To maximize automation: To introduce automation in different aspects and parts of grid until distribution. Load Dispatch Centers and the grid should be ready for automation as the number of locations at which wind systems connect with grid will be increase with time.

2.9.4 Microgrids & other aspects

To include micro grids: To develop intelligent micro grids in certain regions of the island, without the necessity of injecting electricity to a bigger grid. This solution will enable an important increment in the global penetration of the island.

To introduce the "smart generation" with flexible plants: To install new flexible plants using fossil fuels (smart generation), to increase the penetration of RES. Nowadays hundreds of MWs based on ICEs are in the market which start up in 5 sec. and achieve the full capacity in 5 min.

To mitigate fluctuations of the grid using inverters: To use inverters in order to mitigate fluctuations in voltage and frequency of the grid.

To develop the storage systems: At this moment, diverse types of electricity storage systems are being researched and developed. However they are somewhat expensive but gradually their costs continue to diminish. These systems will participate in a growing way in the accumulation of electric power that would address the intermittent character of the RES, mainly wind and PV.

Submarine transmission: Today, transmission of electricity by submarine High Voltage Direct Current (HVDC) cables is a reality. For island close to a bigger island or continent, this could be a long term solution.

3.0 Status of the Top & Emerging Markets

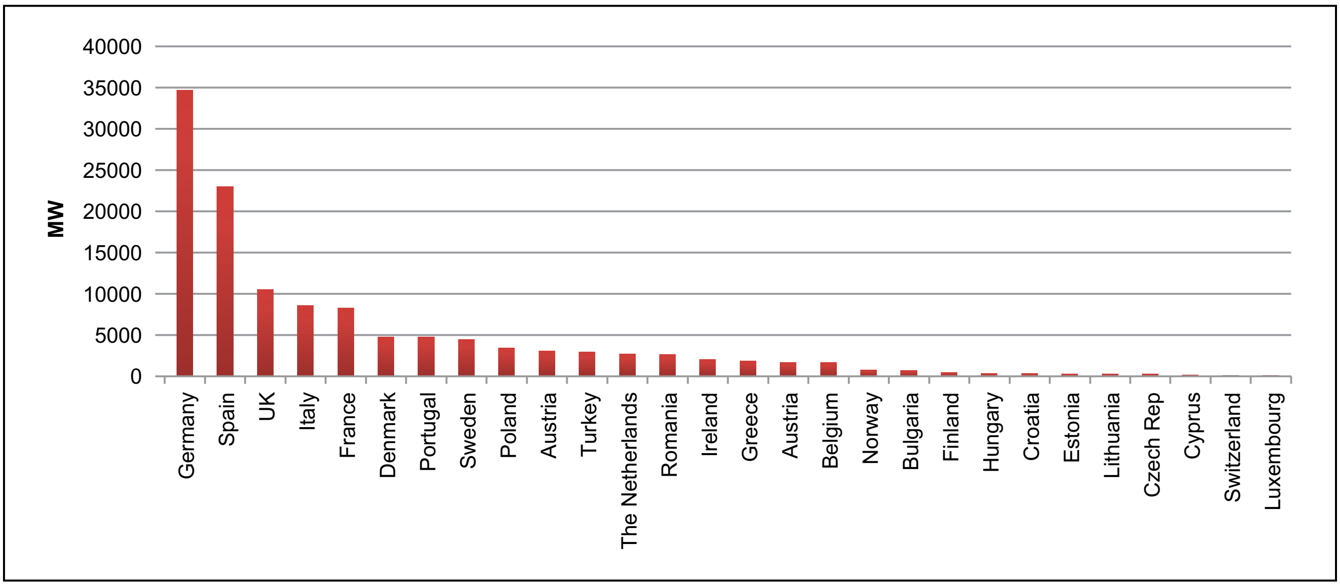
In order to arrive at a picture of power system with high penetration of wind energy, we summarize the current state of wind energy development in the top and emerging markets of the world.

As per WWEA database, nearly 97% of wind farm installations in the world have taken place in the top and emerging markets namely - EU, US, China and India. An overview of wind power development in the context of overall energy mix and grid integration aspects in each of these regions can lead to interesting conclusions from a global perspective.

3.1 European Union Region

The European Union (EU) region has the highest installed capacity and concentration of wind farms in the world. Figure 3.1 shows cumulative installed capacity in different countries in Europe. EU is also the region that has seen the most intense development of wind energy related activities at all levels i.e., research & development, technology, manufacturing, wind resource assessment techniques, meteorology, project execution, off-shore projects, financing and policy. It still remains hub of activities leading to technol-

Figure 3.1: EU Cumulative Installations 2013



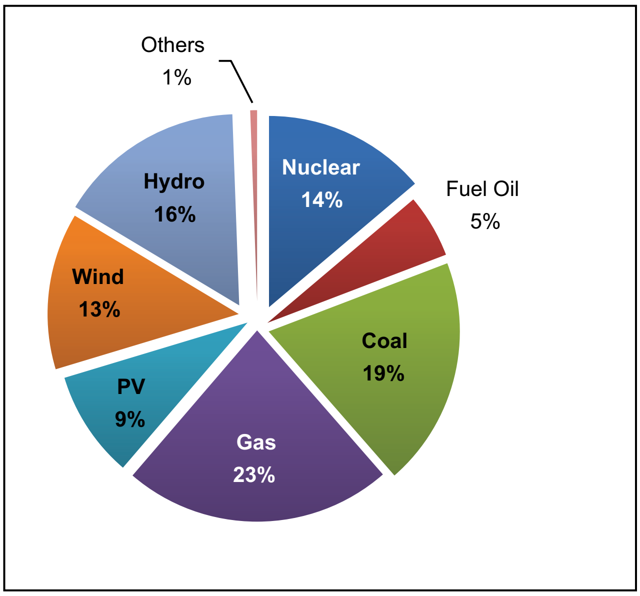
ogy development and export of knowhow across the world. Most of the modern wind turbine technology today, that is being deployed across the world has emanated originally mainly from Denmark & Germany. The largest wind turbine manufacturing base in Europe is also in these countries.

At the end of 2013, EU had achieved cumulative installed wind farm capacity of 117.3 GW of which 110.7 GW is onshore and 6.6 GW is offshore. These wind farms can generate up to 8% of the electricity consumption in EU. The installed capacity in entire Europe including Norway, Russia, Iceland, etc. was nearly 121.5 GW at the end of 2013. The top five countries within EU with a total installed capacity of 84 GW at the end of 2013 account for 71% of the total installed capacity (Figure 3.2).

In a total electricity generation capacity of nearly 885 GW in EU, wind accounts for 13.3% as shown in Figure 3.3 below.

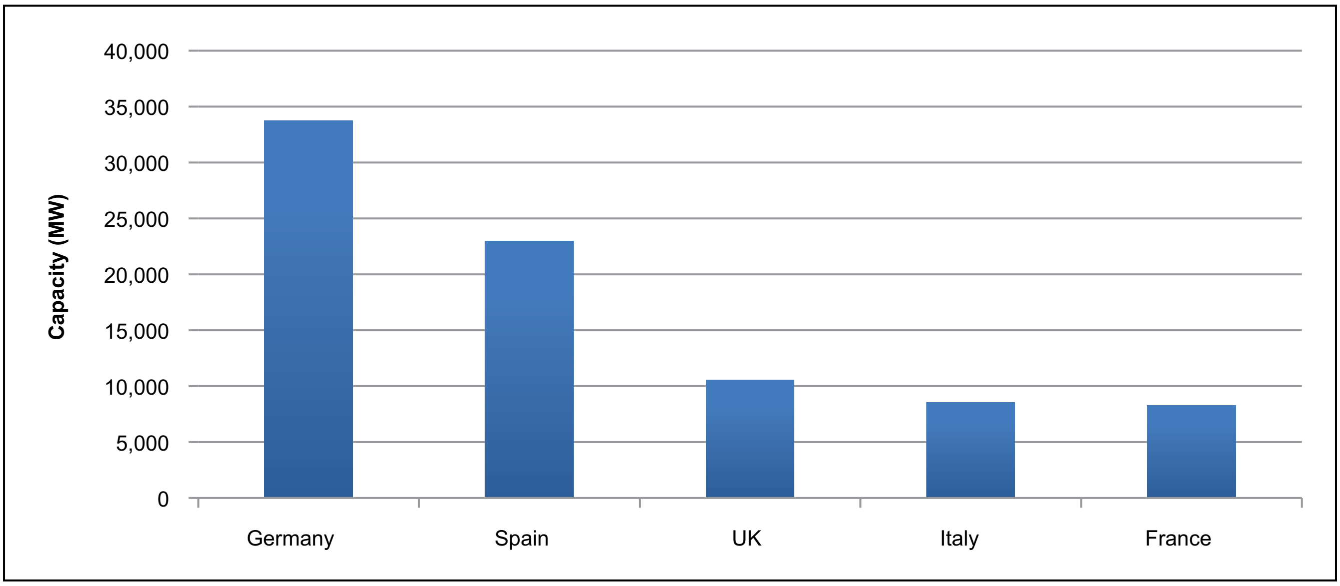
It is worthwhile noting that gas accounts for 23% of electricity generating capacity and while gas due to its fast response is suitable in a generation mix containing high component of wind energy, it also poses a major risk perception in Europe with regard to its supply from Russia. Nuclear is an option which perhaps after Fukushima and Chernobyl earlier may not find social and political acceptance. The total Renewable Energy capacity accounts for 38.5% including hydro power. Therefore, it is obvious that the way forward for EU is Renewable Energy in which wind will continue to be a major component.

Figure 3.3: EU Generation Mix end 2013



(Others include CSP, Ocean, Geohermal and Peat)

Figure 3.2: EU Top 5 - Cumulative Installations ending 2013



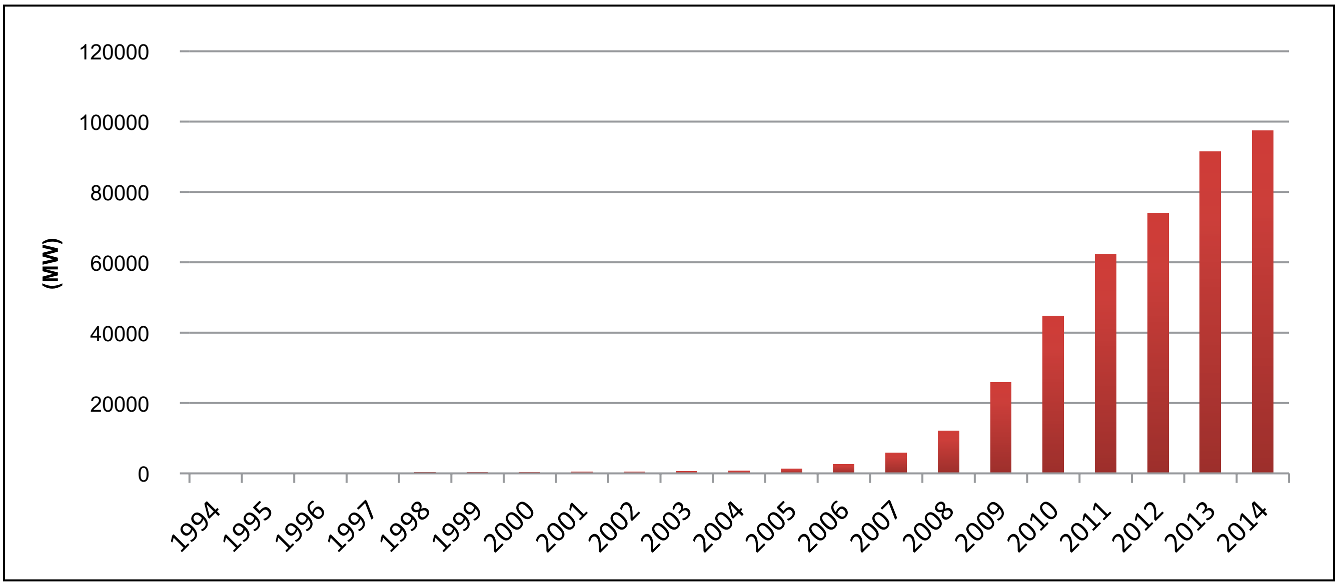
Source: (WWEA)

3.2 China

(This section is mainly authorised by Prof. Shan de Chang of Chinese Wind Energy Association). At the end of 2013, China[1] with 91.4 GW of installed capacity stood tall in the worldwide wind energy market. By the end of 2014, the country crossed the 114 GW figure with more than 23 GW of new capacity installed in 2014. China has overwhelmed the world with the pace at which it has added wind power capacity. In 2013 & 2014, Chinese wind power industry continued to grow faster in comparison with other major markets, notably USA, Europe and India. New installations in 2013 and 2014 have grown at a rate of nearly 25% year by year after 2012. Cumulative installed capacity at the end of 2013 is presented in Figure 3.4. Apart from these huge installations in China, by the end of 2014, more than 1760 MW of wind turbines manufactured in China were also exported to many countries. Thus China has also consolidated its position as the manufacturing hub of wind turbines.

The stupendous growth in China follows enactment of the Chinese Renewable Energy Law in 2005. The

Figure 3.4: Cumulative Installed Capacity China



[1] This part of the article is written with support from Prof. Shen de Chang of Chinese Wind Energy Association.

law, apart from enabling financial and tax incentives, requires power grid operators to purchase electricity from registered renewable energy producers. The impact of such a policy measure is clearly visible in the developments that have taken place. Annual growth rates in cumulative capacity (Figure 3.5) show two peaks, one in 1997, when the capacities were very small and more than 100% growth was possible and the second one in 2007, a direct result of the 2005 RE Law. The compound annual growth rate (CAGR) in cumulative wind farm installations between 1995 and 2013 is 54.8%.

In 2014, 20.16 GW of new wind farm capacity was connected to the public electric grid in China and by the end of 2014, the total accumulated capacity of wind turbines connected with public grid in China was about 97.32 GW, constituting 6.2% of the total electricity generation capacity in the country.

China's onshore wind energy resources are mainly in the "Three Norths" (Northwest, Northeast & North China), accounting for more than 90% of China's total wind energy resources. Two-thirds of the power requirement in China is concentrated in the eastern and central regions.

The regions of western Inner Mongolia, eastern Inner Mongolia, Gansu, and northern Hebei have highest wind power installed capacity in China. However due to small electricity load centers only 10% of the total electricity produced can be consumed. Figure 3.6 presents an interesting picture of wind generation vis-à-vis consumption as a percentage of the total national electricity consumption in these regions.

At present, the predominant models being installed in China are in the 1.5- 2.0 MW range. In the new installations, the 1.5 MW and 2 MW wind turbines constituted 81% and 83% respectively of the accumulated installation capacity by the end of 2014.

Off-shore wind farms are also being set up, some of them in the inter-tidal zone. By the end of 2014, more than 657 MW of offshore wind farms had been installed and connected to the grid. Doubly fed 3 MW WTGs, 2.5 MW direct drive WTGs and 4 MW WTGs have been used in the off-shore wind farms. Several 5 MW and 6 MW WTGs are also being tested in offshore projects. In 2014, among Chinese markets of onshore and offshore wind power, domestic WTGs accounts to 98.3% and foreign WTGs accounts for 1.7%.

Figure 3.5: Annual growth rates of cumulative wind farm capacity

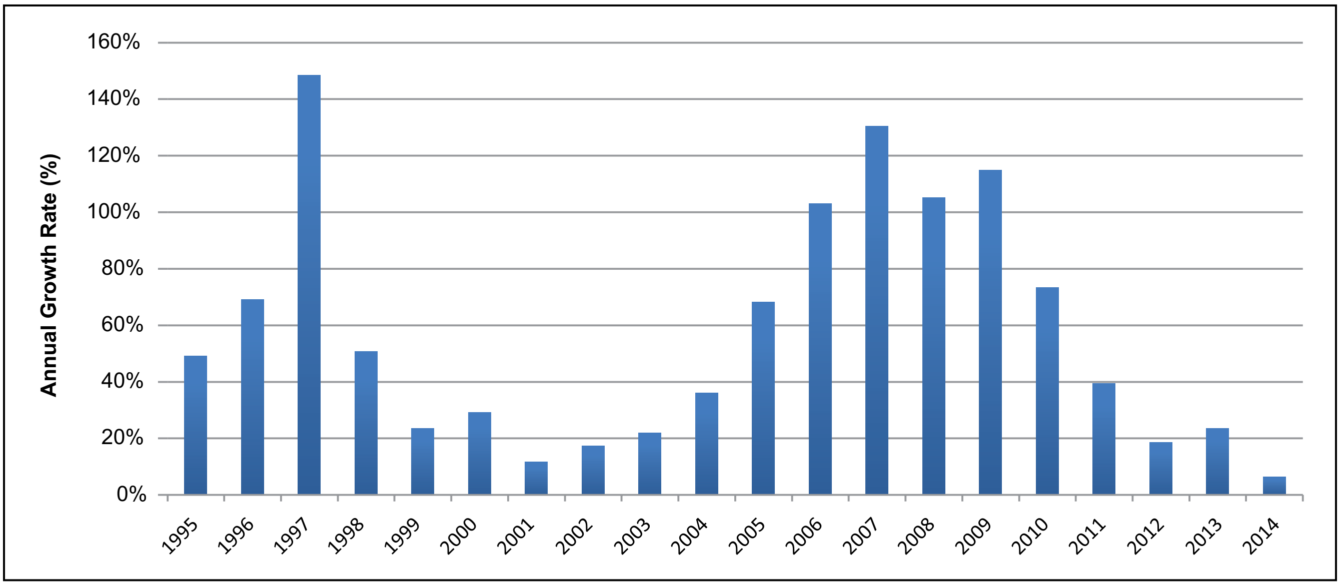
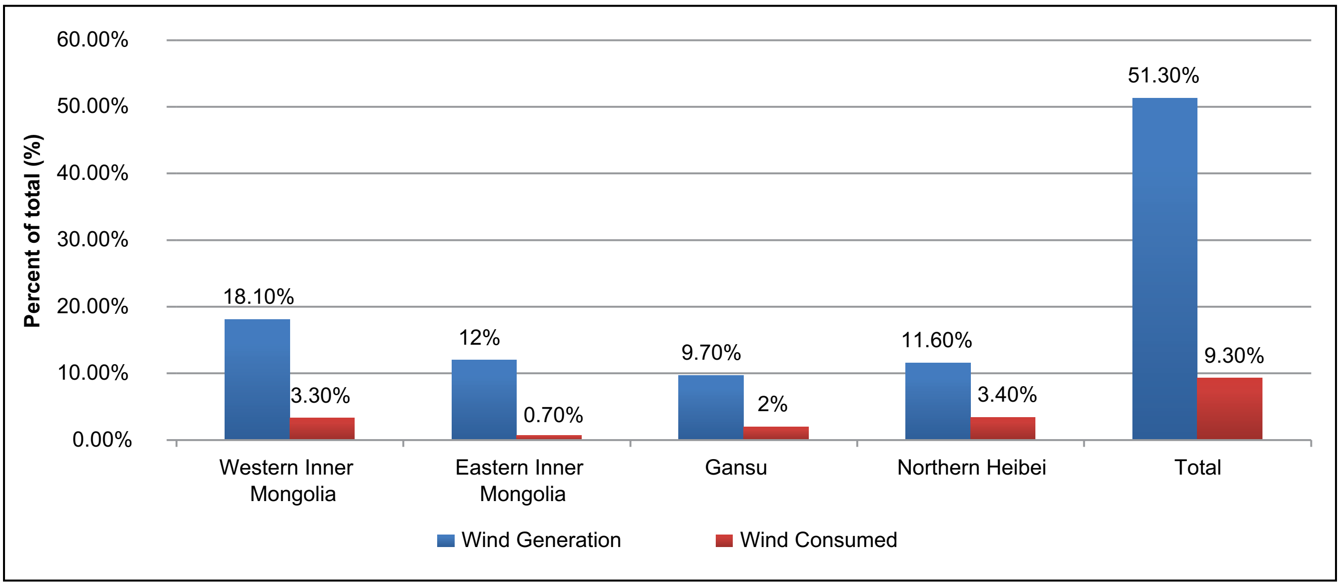


Figure 3.6: Wind generation v/s consumption of wind generated electricity (% of total) [8]



With regard to grid connectivity in the country, high voltage power transmission lines are under construction and they will enable wind power transmission from north-west areas to south-east areas, where there are more load centers.

The key elements of a wind power roadmap for China are:

Construction of large-scale high potential wind farm zones

- Construction of high voltage long-distance transmission lines and an expanded power grid system.
- Connection of local loads and a gradual increase in local electricity consumption in the vicinity of wind farms and quickening of the pace of construction of transmission line from west to east
- Greater attention towards off-shore wind farm construction

Construction of decentralized wind farm projects New capacity of 18 GW is expected to be added every year- taking the total capacity to 200 GW by the end of 2020. Trends in electricity generation from renewable (including hydro and wind) as a percentage of the total over the years are presented in Figure 3.7 and the trends in wind penetration as percentage in total generation in Figure 3.8

Figure 3.7: Trends in electricity generation from renewable energy as Percent of total electricity generation

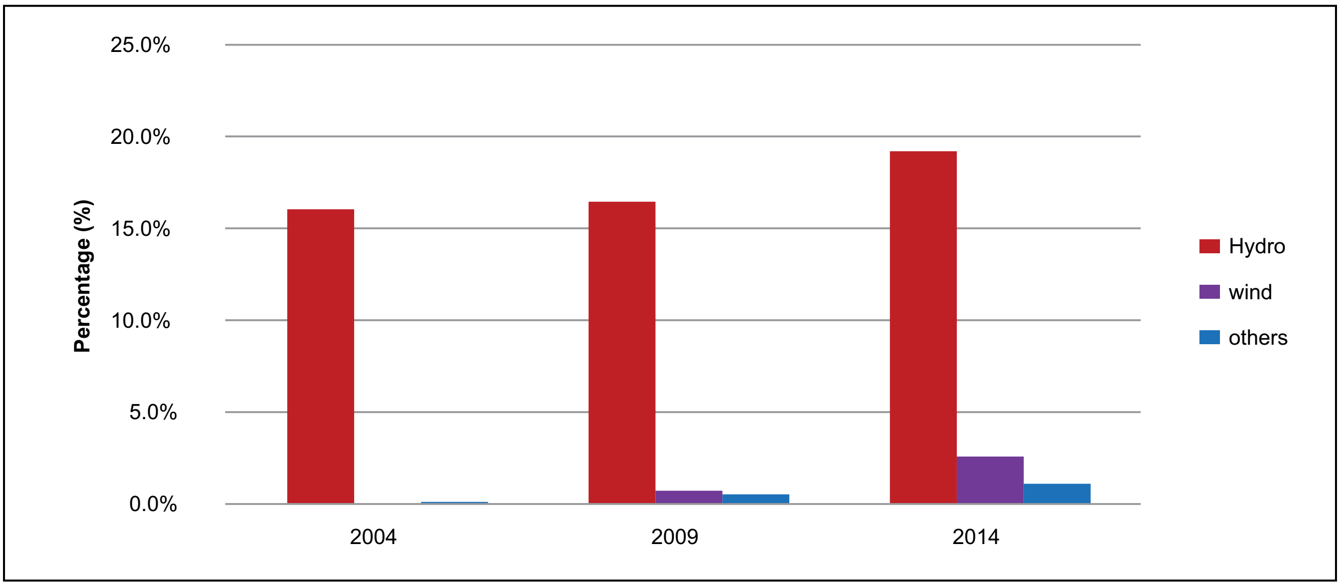
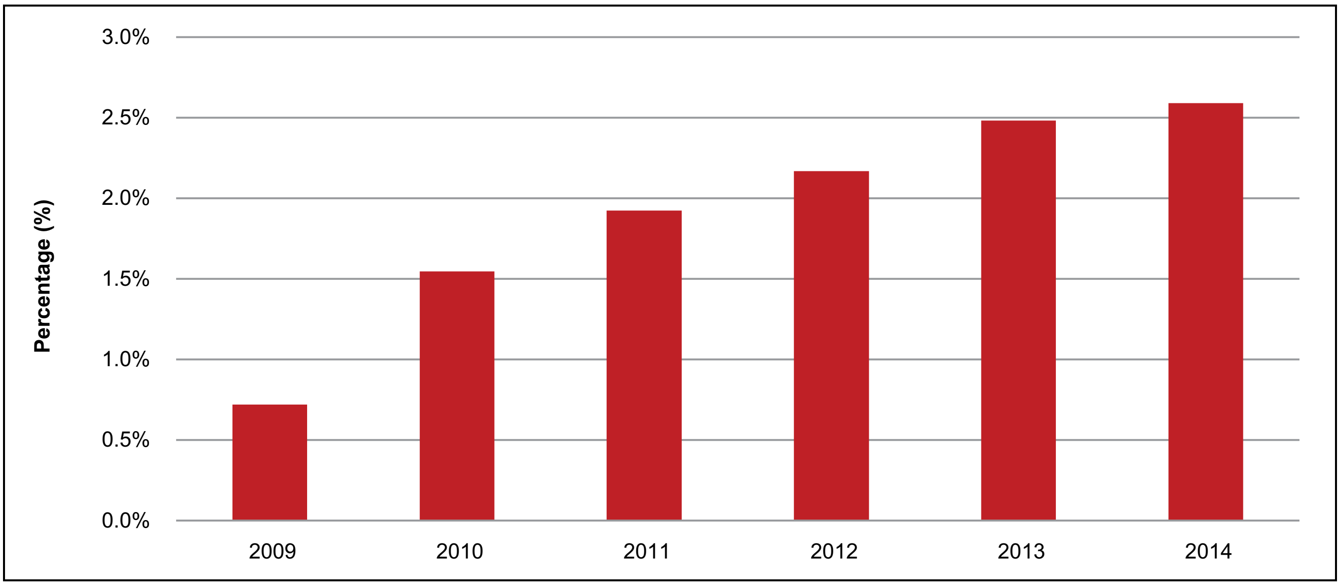


Figure 3.8: Trends in wind penetration as percent of total electricity generation



3.3 United States

At the end of 2014, USA had nearly 66 GW wind power capacity and is ranked second after China. The country has played a great pioneering role in the establishment of wind energy markets and the industry as well as in technological development over the last several years.

The first wind farms with modern wind turbines in grid connected mode first came up in US in California in early eighties. This was a pioneering development that lead to wind farm activity in many other countries in Europe and Asia (India at that time), creating a worldwide wind turbine market and a push for further technology development.

Even prior to the first wind farm, after the oil crisis and between 1974 and 1980, the US government worked with industry to advance the technology and enable large commercial wind turbines. NASA through its Lewis research centre in Sandusky Ohio

Figure 3.9: Shanghai East Sea Offshore wind farm

Figure 3.10: Huitengxile wind farm of Inner Mongolia

(Now the Glenn Research Centre) was assigned the task of coordination of development by large contractors such as General Electric, Westinghouse, United Technologies and Boeing. The first wind turbine under the program was a 100 kW, 2 bladed machine (Mod 0), which was set up at Sandusky Ohio. Subsequent models (Mod 0A, Mod1, Mod 2, Mod 5B, WTS4) went upto 4 MW capacity and pilot plants were set up.

In 1980s, California provided tax rebates for wind power. These rebates resulted in first major installations of large scale wind farms. In 1985 half of the world's wind energy was generated at Altamont Pass (North California). By the end of 1986 about 6,700 wind turbines, mostly less than 100 kW, had been installed at Altamont, at a cost of about $1 billion, and generated about 550 million kWh/year.

Today (end of 2014) US has nearly 66 GW of installed capacity and the experts[9] are of the view that the new wind farms can produce electricity at 5-8 cents/kWh, making them cost competitive with conventional power.

Major Wind farm capacities in US are in Texas, California, Iowa, Illinois & Oregon (see Figure 3.11)

3.4 India

India, with nearly 24 GW of wind power capacity ranks 5th in the world and very soon is likely to take over Spain in the 4th position (Figure 3.12). Capacity addition in 2015-16 is expected to be around 4000 MW. Growth in wind power development has been exponential as can be seen in Figure 3.13. The government has ambitious plans to achieve 40 GW of installed capacity by 2020 and a Wind Mission is being considered by the government to bring the capacity to 100 GW.

Like Europe and US, India too has been a pioneering nation in wind energy and the first wind farms that were set up India in 1986 were also the first wind farms in Asia. After the first demonstration projects, the Government of India launched a wind energy program with seriousness and many policy measures and currently a FiT regime in most of the states continues to create an enabling environment in wind energy investments. India is also perhaps the only country that has dedicated a full fledged ministry to renewable energy.

Today, there are nearly 20 wind turbine manufacturers in India with about 52 turbine models certi-

Figure 3.11: States in US with major installations

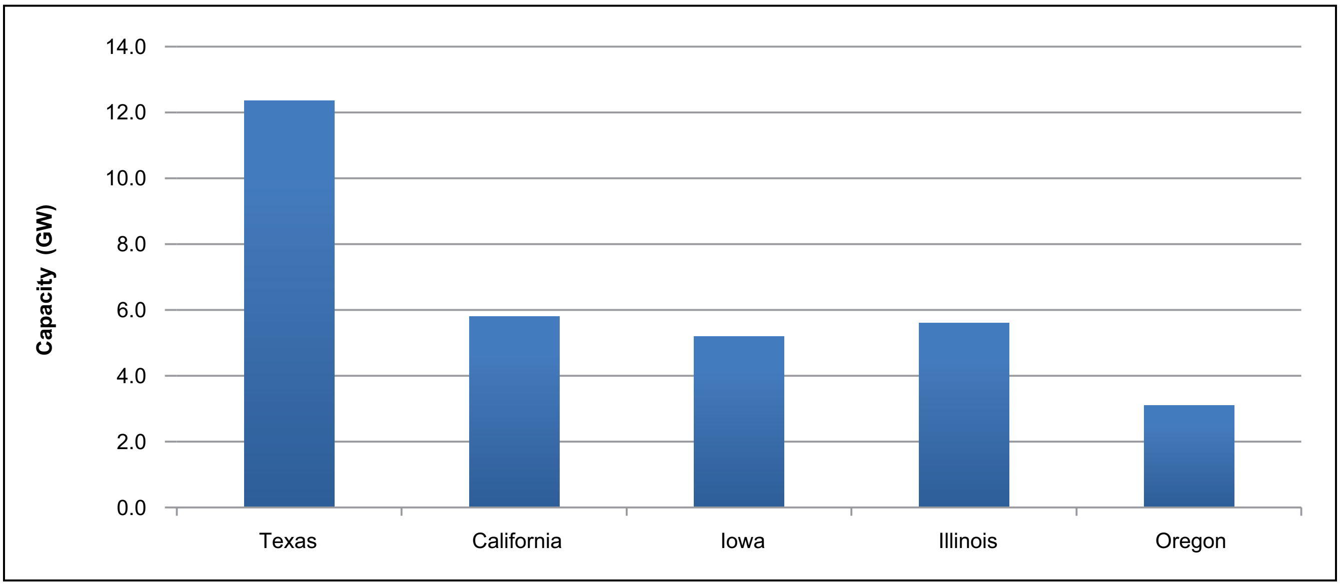
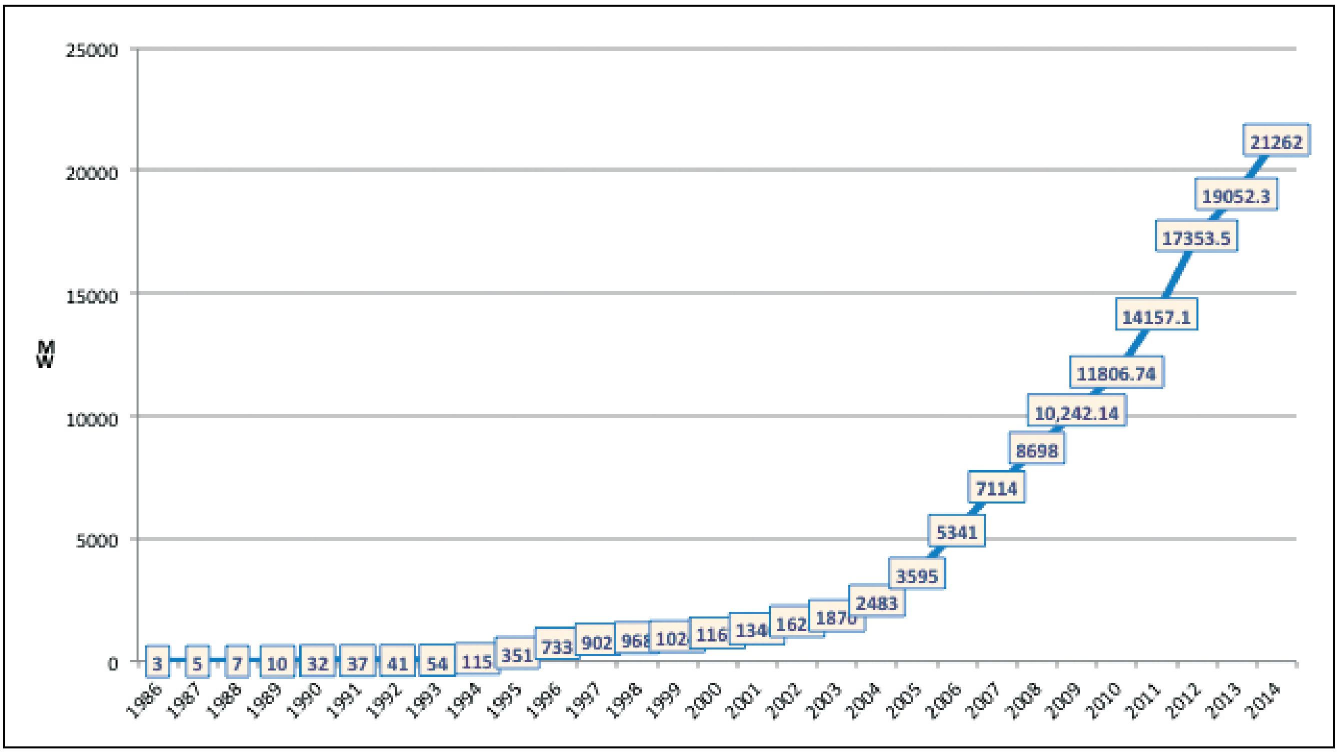


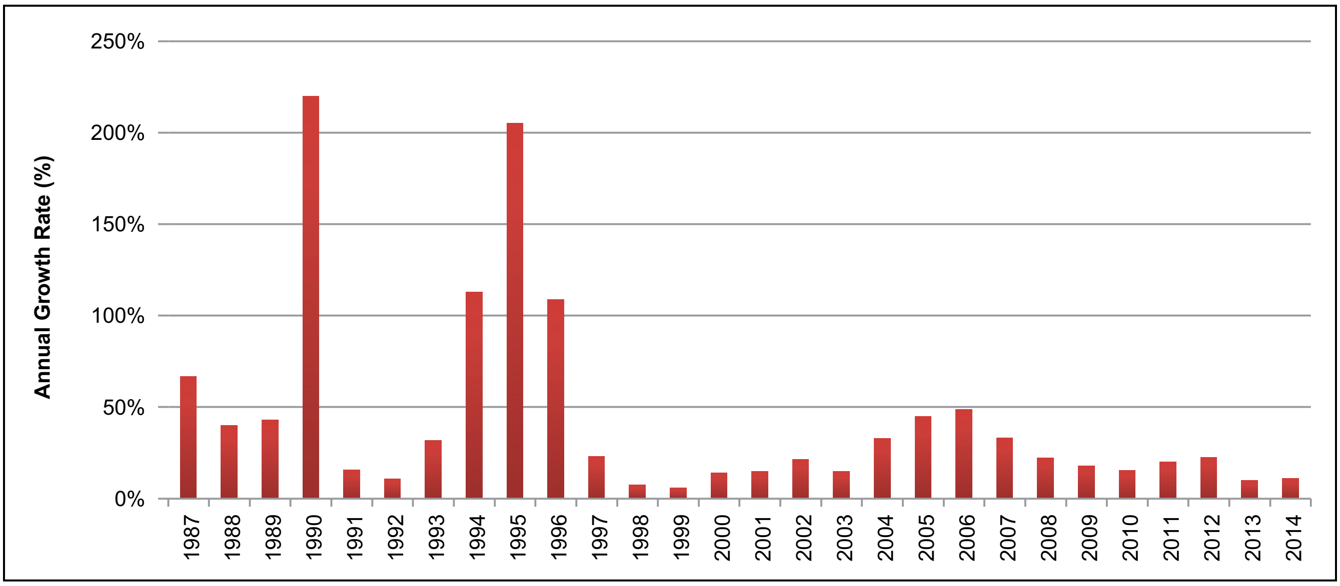
Figure 3.12: Growth of Installed wind power capacity in India



fied by National Institute of Wind Energy (NIWE) for grid connection. The total manufacturing capacity established in the country is about 10,000 MW / year.

In 2003, after the enactment of the Electricity Act 2003, Maharashtra Electricity Regulatory Commission (MERC), after a process of stake-holder consultation, came up with a landmark regulation on wind and set the tariff for wind farms at Rs. 3.5 with an escalation clause. This opened up the wind market in Maharashtra. Subsequently State Electricity Regulatory Commissions have become active in nearly all the states and based on the wind regime in

Figure 3.13: Annual growth rates of cumulative wind farm capacity (India)



the state and consultations with stake holders, tariffs have been set.

A recent assessment of the potential for wind energy utilization in India (Hossain 2011 and LBNL 2012) has indicated a possibility of almost 2000 GW of onshore wind farm potential with wind turbines at 80 m height and nearly 1000 GW of offshore potential.

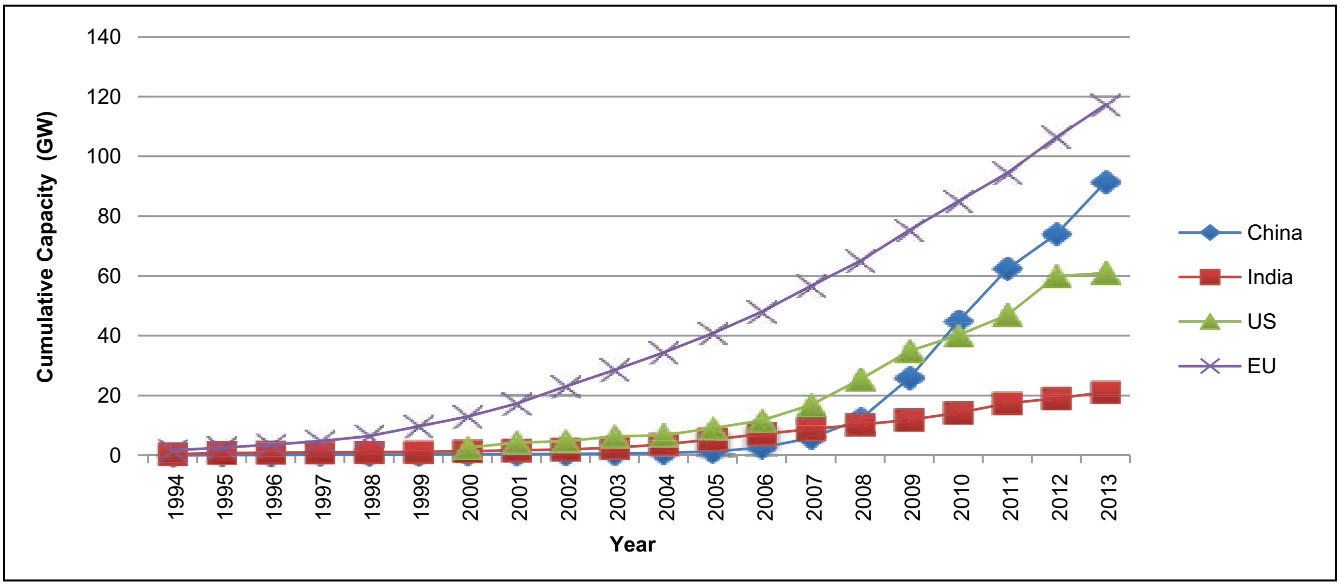
Annual growth rates presented in Figure 3.14 show high growth rates in initial years when the capacities were very small and subsequently in 1995 and 2006 due to policy announcements or introduction of FiT. After a record installation of 3200 MW in the financial year 2011 – 2012, the growth rate dropped due to the expiry of accelerated depreciation benefit and generation based incentive schemes. Both measures have been reinstated now and the government is very keen to see a capacity addition of the order of 10 GW/yr.

The Power Grid Corporation of India Limited (PGCIL) which is responsible for maintaining high voltage transmission network in the country is working on development of a so called “green corridor” which will essentially lead to strengthening of transmission network in high potential regions of the country. PGCIL is working closely with state utilities and the respective state governments. Development agencies such as USAID, Development (KfW) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) are also involved in a technical assistance role.

3.5 Africa

Energy Access happens to be the most important issue in Africa and this will drive the wind energy market in the coming years. The continent is faced with the challenge of generating more power to meet existing and future demand as more than 500 million people on the continent lack access to electricity. Many countries in Africa, particularly North Africa and Sub Sahara region have rich wind resources. According to an AfDB study[10,11] at least eight African nations are among the developing world’s most endowed in terms of wind energy potential. A study over Kenya (2013) has also indicated vast potential in this Sub-sahara country. Somalia, Ethopia, Egypt, Morocco, Nigeria, Tunisia, Libya, Chad Sudan, Madagascar have excellent wind resources and potential. However, this potential has been tapped in a very limited way so far.

Figure 3.14: Trends in cumulative installed capacity in different regions



Ethopia, Tunisia, Egypt, South Africa and Morocco account for nearly all the wind power capacity in Africa.

The first wind project in Africa was a pilot wind farm of 400 kW (4 X 100) capacity set up at Ras Gharib in Egypt, near the Gulf of Suez, in 1988. Between 1993 and 1996, a second project of 5.4 MW capacity came up at Hughada city. Till 2000, the total wind farm capacity in Egypt was nearly 6 MW. Egypt's first commercial wind project was the first phase of the Zafarana wind farm (30 MW) commissioned in 2001. Seven subsequent phases of Zafarana have since been completed, bringing the farm's capacity to 545 MW as of 2010.

There are currently three ongoing developments on the Gulfs of Suez and El Zayt which are expected to add another 200 MW capacity each, and the expansion of the Hurghada wind farm which is expected to have an installed capacity of 1,100 MW at completion.

Morocco added 203 MW in 2013, bringing its total installed capacity to 495 MW at year end. Alstom 1.67 MW turbines make up the 101.9 MW at Akhfenir, while the remaining 101.2 MW is split equally between Foum el Oued and Haouma, powered by 2.3 MW Siemens units.

Due to the vast potential and the need to provide energy access, Africa is likely to be an important and perhaps a hot market in next few decades. The key issues will be bankability, political certainty and power evacuation infrastructure. The model for wind power development may not be entirely in grid connected mode as is the case in nearly all other parts of the world. It may be possible, that Africa experiments with mini-grids and suitable load and grid management technologies including storage devices.

3.6 Analysis

Trends of growth in wind power installations in different regions of the world presented in Figure 3.15 are interesting. A sudden spurt in growth is seen in the cumulative installation in China as it overtakes India in 2008 and afterwards emerges as Numero Uno country in wind farm installations. Cumulative installed capacities by regions presented in Table 3.1 below and Figures 3.15 to Figure

Figure 3.15: Regional trends in wind power installations in recent years

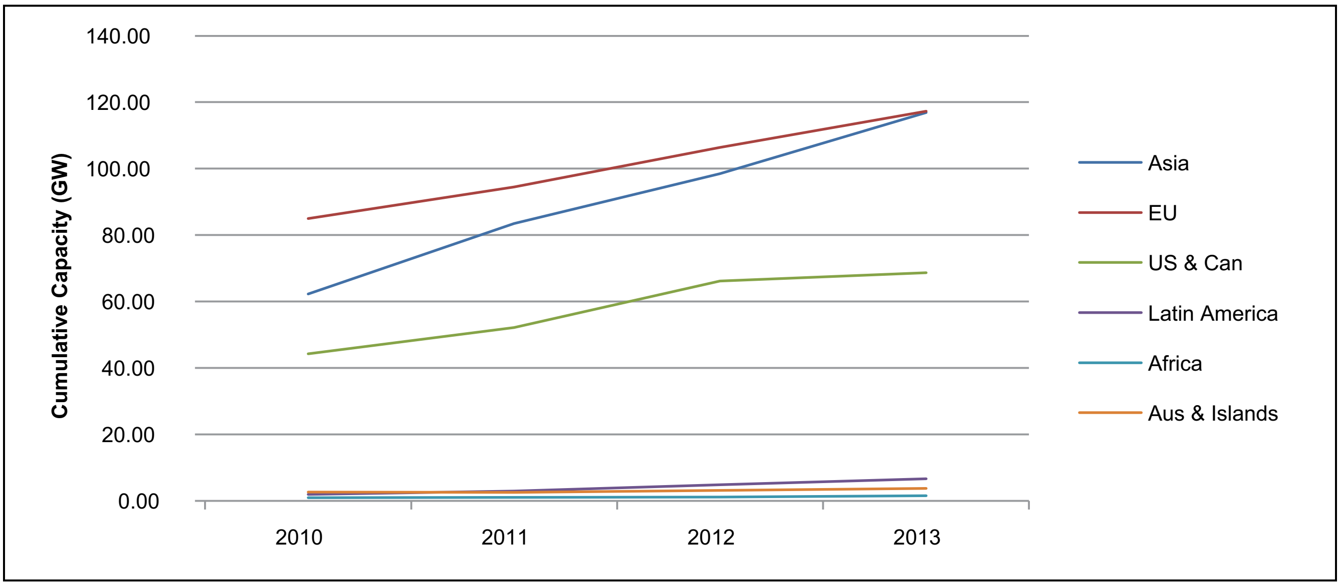
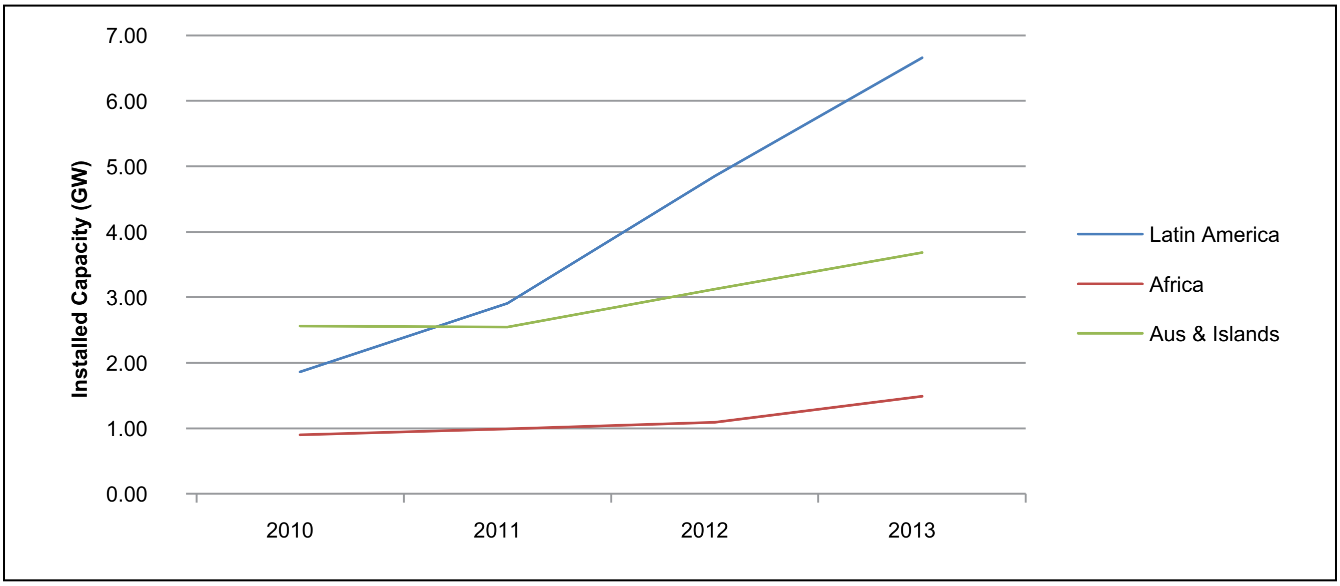


Table 3.1: Regional Wind Power Installation trends in last 4 years

Yr	Asia	EU	US & Can	Latin America	Africa	Aus & Islands
2010	62.30	85.00	44.21	1.86	0.90	2.56
2011	83.45	94.50	52.17	2.91	0.99	2.55
2012	98.50	106.40	66.20	4.85	1.09	3.13
2013	116.94	117.30	68.70	6.66	1.49	3.69

Figure 3.16: Trends in installations – LA, Af, Aus



3.16 also tell a story of the geographic expansion of wind technology and of Asia catching up with EU in 2013. That Latin America has been through very high growth rates can be seen in Figure 3.16. Africa, a continent with vast potential is yet to install any major capacity. However, over the last few years there has been a spurt of activity in Egypt, Ethopia, Morocco, Tunisia and Kenya. The main issues in Africa are on bankability of wind farm projects and availability of grid. As mentioned in the earlier section of Africa – the way forward in this continent could be vastly different from that of other continents. It is almost essential that a mix of grid connected as well as Mini and Micro Grids with substantial wind penetration and possibly with storage devices along with solar or biofuel form the basis of energy system for communities and industry in Africa. This is also be true for many parts of Asia and Latin America.

With wind power development picking up in many countries of Asia such as Thailand, Vietnam, Philippines, Malaysia, Pakistan, Japan as well as the central Asian countries and parts of the MENA region, Asia, in all likelihood will surpass Europe and US in total installed capacities. We feel the coming decade shall be a decade of growth of wind power development in Asia.

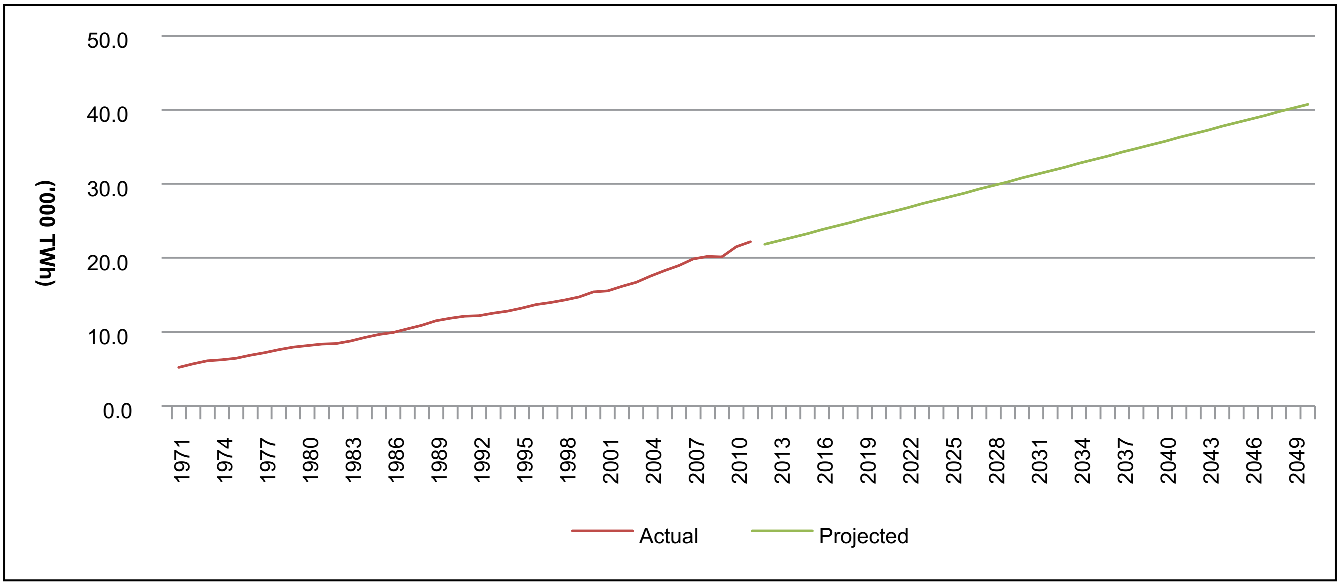
4.0 Future Scenario 2050 Energy Mix

In this report we are examining a significantly enhanced role of wind energy in the future energy-mix of the world. The future electricity generation from wind would depend on the total world electricity production in future as well as the energy mix. Data provided by the World Bank[12] till 2011 on total electricity production projected in future, as shown in Figure 4.1, indicates that going by trends from 1971 onwards, the electricity production by 2050 is going to be around 40 thousand TWh. However, if we examine growth in consumption for different regions of the world, we find that the fastest growth has taken place in Asia and if the growth in Asia is modeled separately, we arrive at an annual consumption level of 74 thousand TWh. Differential growth in electricity consumption for different regions is discussed later in this chapter.

Different agencies such as IEA or WEC, though their modeling exercises have come up with different scenarios of total electricity production by 2050 but most of them are comparable and fall in the range of 40000 TWh – 74000 TWh.

In the WWEA wind resource report, we have seen that the world has vast wind power potential. The constraints to its utilization may emanate from

Figure 4.1: World Electricity Production till 2050



Source: World Bank database

grid, social & environmental and land pressure constraints. The pressure on lands may get eased somewhat by technological developments that result in more and more efficient turbines, optimized to wind regimes, with larger rotors and higher towers and also if offshore wind farming is taken up seriously and picks up on a large scale. However, the modern power system and its ability to accommodate large wind energy capacity in the total energy mix can be a greater limiting factor. To a large extent, grid integration issues can be addressed by a combination of grid management strategies, technologies, power transmission infrastructure etc. We know today that many parts of the world like Denmark, parts of Texas and Northern Germany have wind penetration levels as high as 40%. Wind penetration would depend upon future energy mix, economic considerations, transmission connectivity between regions and technology. By 2050, we assume that various technological options and strategies would enable high penetration levels of at least upto 40% in the power systems all over the world. Therefore, the role of wind energy and the extent of its utilization would mainly depend upon the future energy mix, total electricity production and economic considerations.

Table 4.1: WEC Scenarios

Jazz	Symphony
As an energy scenario, Jazz has a focus on energy equity with priority given to achieving individual access and affordability of energy through economic growth.	As an energy scenario, Symphony has a focus on achieving environmental sustainability through internationally coordinated policies and practices.
Total Electricity Production	
53.6 thousand TWh	47.9 thousand TWh
Share of Renewable Electricity	
46%	70%
Generation from wind	
4.51 thousand TWh	4 thousand TWh

4.1 Different Scenarios

When looking at future, there can be many possible scenarios. For example, World Energy Council (WEC) has developed two scenarios[13], one of them Jazz scenario and the other Symphony scenario. The two scenarios are described as follows:

Under Jazz scenario WEC forecasts, world electricity production at 53.6 thousand TWh and under Symphony scenario, 47.9 thousand TWh. The projections vary according to the policy and technology thrust in different areas.

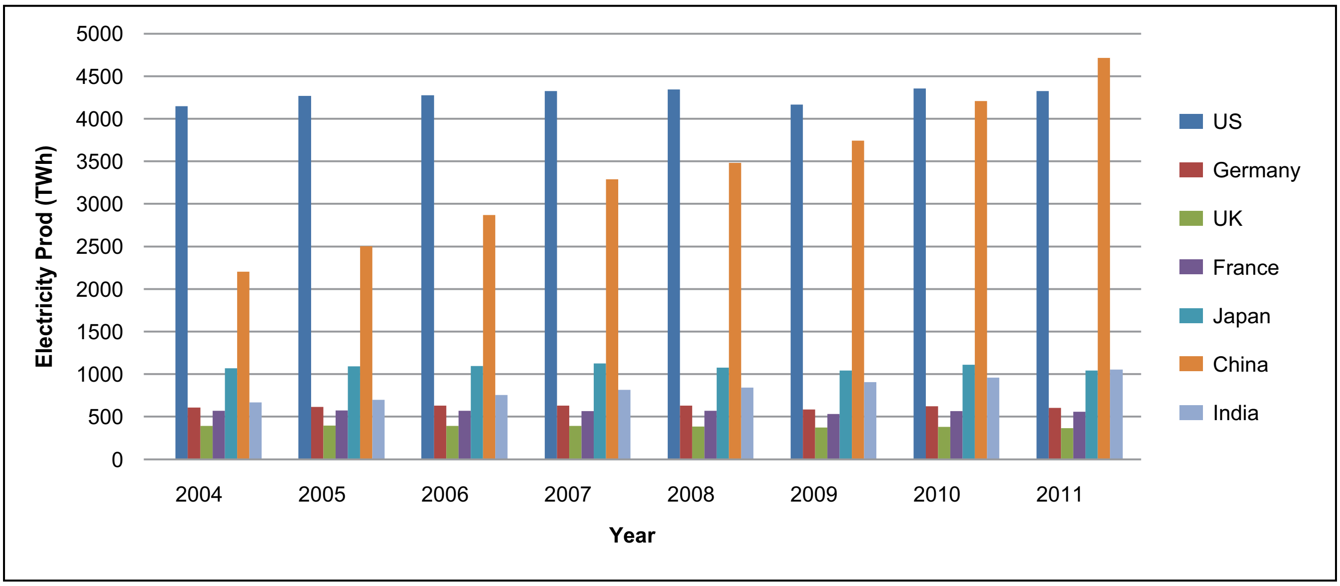
According to International Energy Agency (IEA)[14], in its outlook extending up to 2050, in two of its climate friendly scenarios, 2DS and hiRen, total electricity production is of the order of 42 - 40 thousand TWh with variable renewable energy comprising of solar, onshore and offshore wind and ocean energy contributing 22% to 32% electricity generation. In its wind energy technology roadmap 2013[15], IEA for the year 2050 has indicated a total share of wind at 14% of the total in 2DS and 18% in hiRen, amounting to 5.9 and 7.6 thousand TWh respectively. Somewhat higher than the World Energy Council estimate.

International Renewable Energy Agency (IRENA) in its report REmap 2030 has indicated that of the total electricity production in 2030, estimated at 37 thousand TWh, wind energy will account for 12%, i.e, 4.4 thousand TWh. Wind contributes nearly 43% of all renewable energy by 2030. If we look at trends and projection in Figure 4.1, in year 2030, world electricity consumption is likely to be 32 thousand TWh

Intergovernmental Panel on Climate Change (IPCC) in its report has indicated that in two of its scenarios, Median and Ambitious, by 2050, wind energy could account for 13-14% and 21-25% of global electricity generation respectively.

Studies cited above project scenarios with different levels of RE or wind energy use. The other factors and parameters that can be used to define these scenarios include greater policy thrust, greater energy efficiency, more economic development, technological innovation etc. There can be a number of scenarios.

Figure 4.2: Trends in Electricity Production

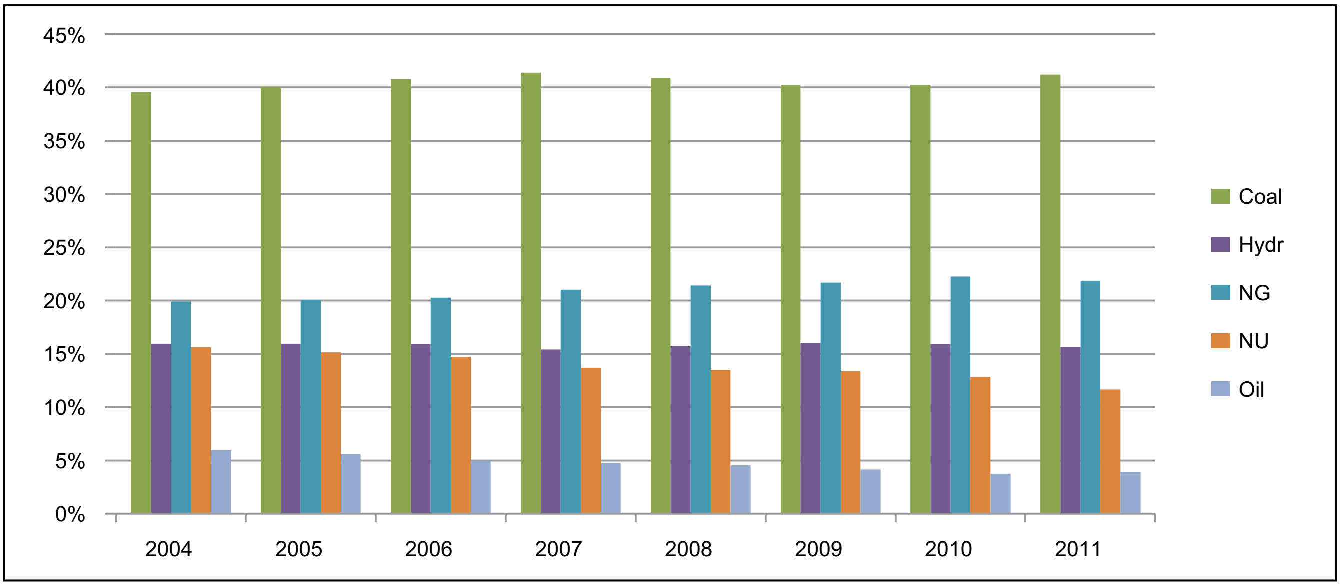


Source: World Bank database

One line of thinking on scenario building is that all the stake-holders involved with electricity generation i.e., policy makers, industry, consumers, academicians and politicians have been increasingly made aware of RE, EE, climate change and technologies and have been aware of these options since early nineties and, therefore, world electricity production projection in 2050 based on data from last 30 - 40 years is a realistic assessment. In any case, irrespective of any assumptions in scenario building, actual trends cannot be ignored and present a realistic picture. Therefore, Figure 4.1 presents a realistic picture and in terms of order of magnitude is in close agreement with projections.

An examination of electricity production trends in select developed and developing countries (Figure 4.2) shows that while electricity production in developed countries like US, Japan has remained stable, in developing countries it has been on the rise.

Figure 4.3: World Electricity mix trend (%)



Source: World Bank database

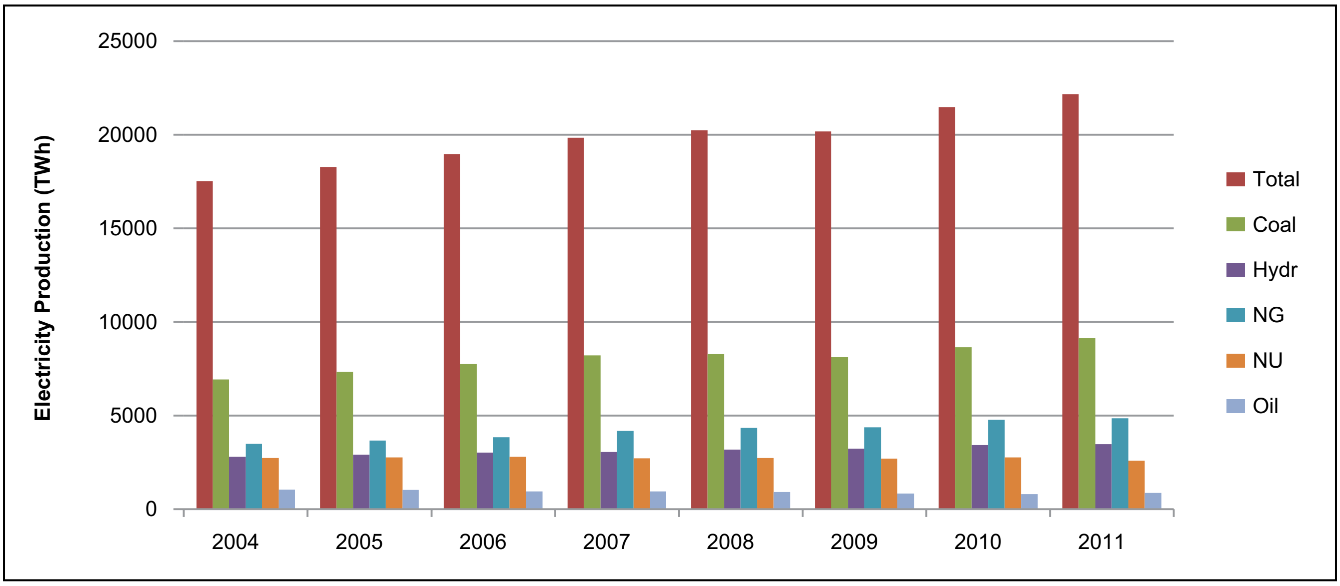
Most interesting and exceptional is China, which surpassed US in 2011. Interestingly, China is also the country with largest wind farm capacity. A less pronounced trend is in India, which also has the second largest wind farm capacity in Asia.

Going by trends for India and China, one can conclude that the countries with pronounced growth trends in electricity production will also have large wind farm capacities in the future. By the year 2050, many countries in Asia and Africa including India and China will have larger wind farm capacities.

Analysis of trends in global electricity mix (Figure 4.3) shows that overall the generation mix has been stable throughout the years. There has been a slight annual rise 3-4% in total electricity consumption as well as the component of electricity generated by coal. The growth in wind power over these years, though manifold, is still so small at overall electricity consumption level that it does not seem to make a perceptible difference to the total picture.

In Figure 4.1 earlier, we have shown that linear extrapolation of world electricity production, indicates 40,000 TWh of electricity production by 2050. However, there is differential growth in different

Figure 4.4: World Electricity mix trend (TWh/yr)



Source: World Bank database

regions of the world. Therefore, between 1990 and 2011, while in Asia electricity production has grown 3-4 times over the base year 1990, in Europe the growth has been only 1.16 times. In general, developed countries have lower growth rates in electricity production than those in developing countries. Therefore, US, Europe, Australia have lower growth rates in electricity production and India, China, Brazil and other developing countries in Asia and Africa have higher growth rates.

Figure 4.5 shows differential growth in electricity production in different regions of the world. Linear extrapolation of each of these differential growth rates results in a total electricity generation of 40,000 TWh by year 2050. In Figure 4.5, it can be seen that Asia is branching out in a high growth mode and the linear fit is not the best fit. However, Asia is best modeled as a binomial function (Figure 4.6) and results in a global total electricity consumption of nearly 74000 TWh in 2050.

Figure 4.5: Differential growth in electricity consumption in different regions

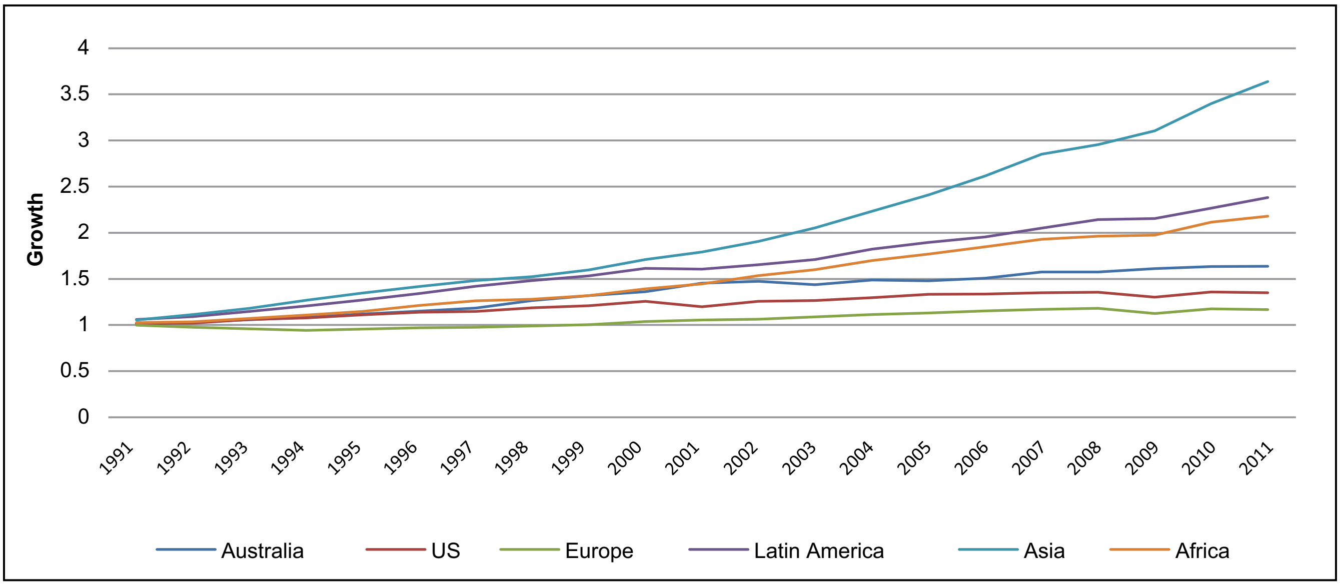


Figure 4.6: Linear growth model

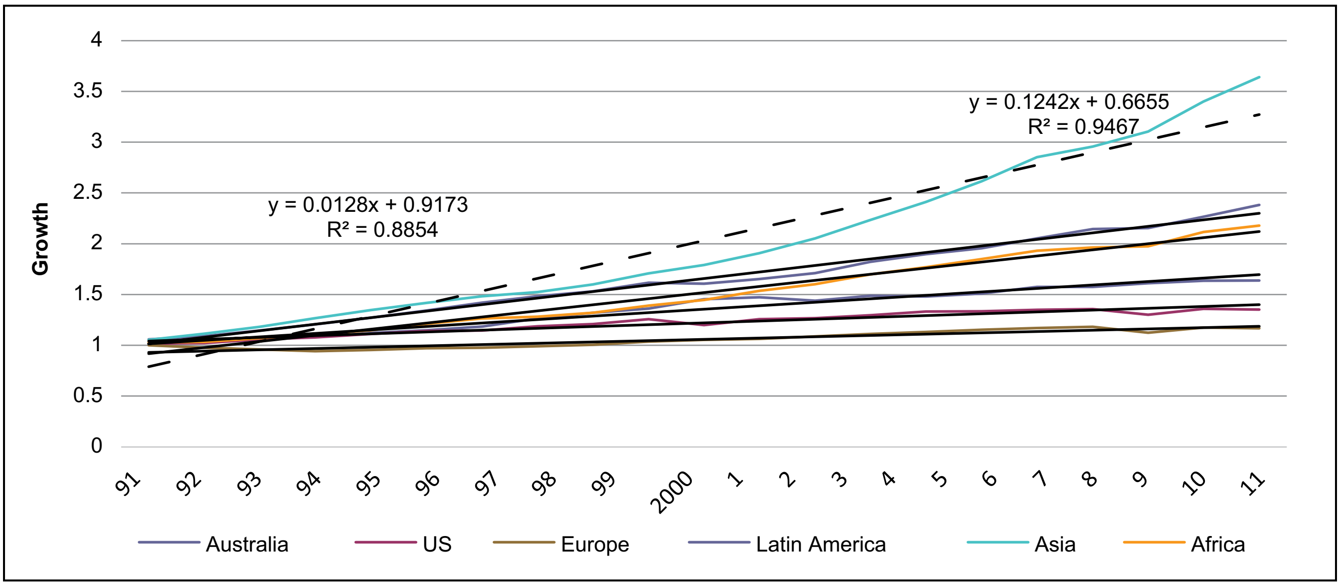
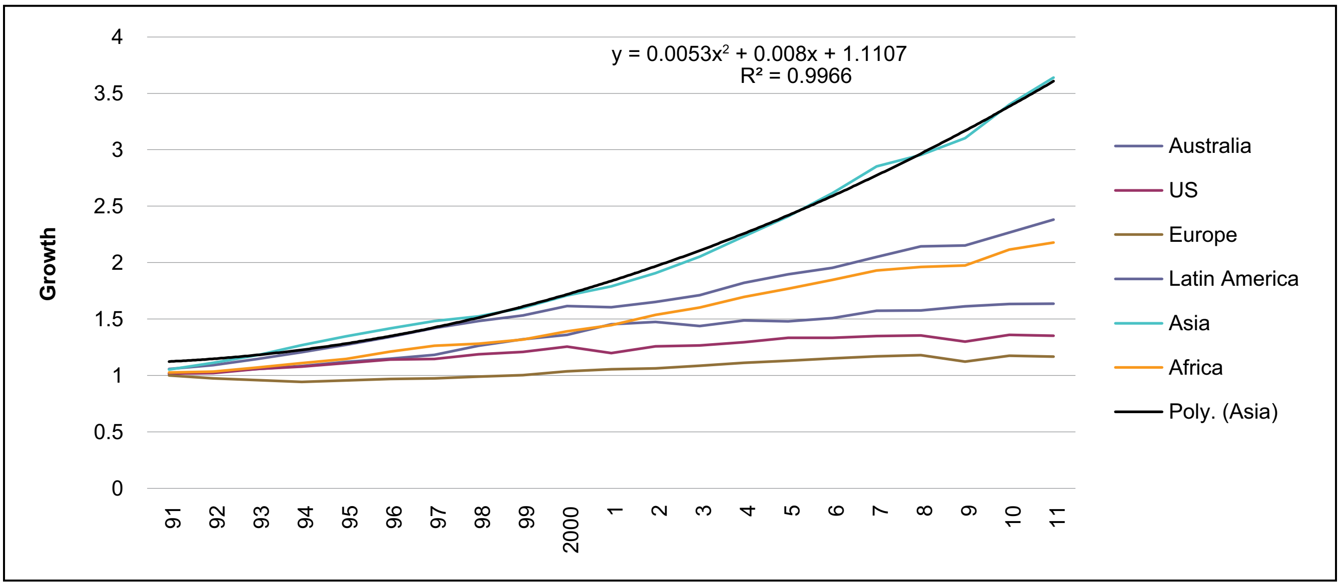


Figure 4.7: Binomial growth model for Asia



4.2 Wind Energy Future 2050

Today wind energy has achieved a global penetration level of around 4%. Developments in global and national policies, technological developments and global environmental and energy security concerns indicate that these penetration levels will get enhanced significantly. There are many cities and countries that have pledged to 100% renewable energy system, in which obviously wind will be an important component with hydro and solar. The electricity grid itself and its management practice will evolve around absorbing maximum wind power into the grid, while retaining stability in power system and power supply. In Chapter 4.0 later in this report based on work by Farid et. al, we examine how the transition in electricity grid is taking place.

An interesting test of how a power system could survive massive fluctuation in renewable energy happened in March 20, 2015, when Europe faced near total Solar Eclipse.

Germany has more Renewable Power installed, including Solar of 38.5 GW and a similar capacity of wind power, more than any other nation in Europe. There was a great concern that the solar eclipse would lead to a collapse of the electricity grid.

On the day solar eclipse was scheduled to occur, Engineers operating the grid were concerned with a massive, sudden drop in solar electricity input - followed by a massive increase when the eclipse came to an end later in the morning. This was going to be the test of the newly evolved German grid with high renewable energy penetration. There had never been such a massive and rapid drop and rapid increase in solar power before in Germany.

The eclipse cut off 65 to 80 percent of incoming sunlight. It was a "stress test" for the Energiewende - the country's massive shift toward renewable energies. It was an opportunity to show that it's possible to deal successfully with large-scale fluctuations in renewable energy input, whether from sudden increases and decreases in solar energy or in wind power.

At the time of eclipse, solar power dropped from 14 GW to 7 GW and then rose to 20 GW as the eclipse ended. However, the grid operators (TSOs) managed to keep the power system stable.

A question often posed – of grid security with high penetration of renewables had been successfully addressed through actual demonstration under massive fluctuation, which is not encountered under day to day operations

Looking at the overall policy and development scenario, plans in different countries and the technological evolution, up to 40% wind penetration can be safely assumed for the year 2050. However, when looking at future, one has to allow for many possibilities and scenarios that can take place. It is possible that worldwide electricity consumption does not increase to as high a value as 74000 TWh/yr as mentioned in the scenarios discussed above but remains at a low of 40000 TWh/yr. This can be due to some of the following or more reasons:

- Significantly increased energy efficiency, that would result in curtailing electricity consumption at demand side
- Climate change
- Significant variations in trends due to social, political and economic reasons
- Technological development and other competing technologies etc.

Due to the same reasons, wind power generation could also possibly vary from the highest expected point to a rather low point. The different scenarios that we have considered are LOW, LIKELY, and HIGH both in total electricity requirements and wind penetration levels. These levels are summarized in Table 4.2 below.

Table 4.2: World Electricity Demand scenarios 2050

Worldwide Electricity Demand (TWh/yr)				
LOW (40000 TWh)	**LIKELY (57000 TWh)**	**HIGH (74000 TWh)**		
8000	12000	16000	LOW= 20%	W I N D
11400	17100	22800	LIKELY = 30%	
14800	22200	29600	HIGH = 40%	

**All figures in TWh*

Figure 4.8: Wind power scenarios 2050 (TWh/yr)

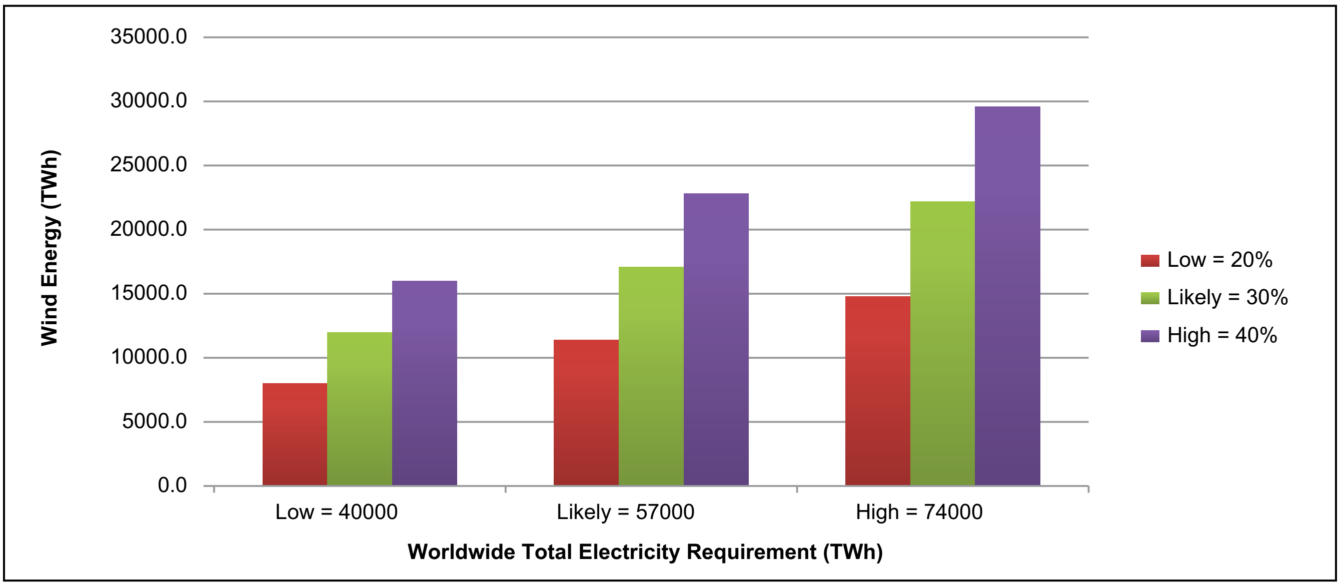
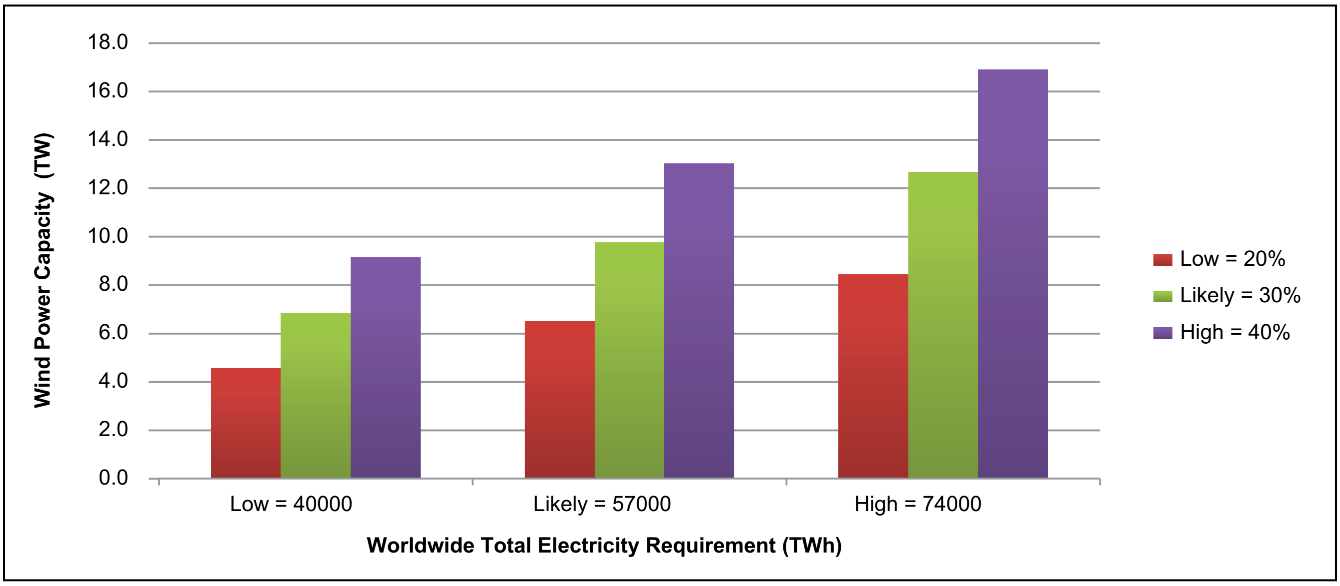


Figure 4.9: Wind power scenarios 2050 (TW)



Figures 4.8 and 4.9 indicate the scenario assessments arrived at. In arriving at Figures in TW in Figure 4.8 we have assumed a Capacity Utilization Factor of 20%.

From Figure 4.9 it can be seen that the possibilities range from a low of 8000 TWh/yr or 4.6 TW of wind power to high of 29600 TWh/yr or 16.9 TW. In these scenarios, we feel renewable energy in combination with hydro and solar could possibly reach 100% RE mix for some regions of the world and 50% RE for most of the world in terms of energy met.

This would mean complete transformation of the grid and needs parallel efforts with solar energy, smart grid options, transmission links, energy efficiency, mini and micro grids, storage systems and bio energy. These areas are the new areas that are fast emerging as significantly important components of the power sector.

In the WWEA Wind Resource Assessment Report we have reported a worldwide wind energy potential of 95 TW based on various national and regional studies. Even this, we have mentioned in the report is rather conservative. The capacity to be installed to free this world of fossil fuels is of the order of 1/20th to 1/6th of the assessed potential. New technological developments in wind energy such as Makani wind turbine[16], which was acquired by Google in 2013 and can access wind speeds at up to 350 m above ground, while reducing most of the heavy structural aspects of conventional wind turbines have the promise of harnessing winds in most areas of the world in a more cost effective manner. Such developments in wind technology and many more that can surface over a time horizon of 35 years can significantly alter even these scenarios to a High Wind, High Renewable Energy Scenario.

5. Evolution of Electricity Grid

(This chapter is based mainly on the work of Amro M. Farid Dartmouth/MIT)

Worldwide growth and expansion in wind power installations has led to nearly 370 GW of installed capacity by the end of 2014. With many countries and regions having ambitious plans to add wind power to their power grid, this capacity is likely to grow manifold in the coming years. In the previous chapters, we have highlighted the environmental, energy access and energy security issues that will continue to drive wind and solar power generation. On the other hand, new technologies and approaches that bring about greater efficiencies in energy generation, transmission and consumption are poised to play a very important role in energy saving. All this means that the focus in the power sector shifts from large centralized thermal or nuclear generating plants to small distributed generation, demand side management, consumer play and evacuation of power from these distributed plants.

In the last few years, wind and solar energy have emerged as a mainstream energy options for the grid and in order to absorb inherently fluctuating energy from these sources, the conventional power grid itself has to undergo a dramatic change. This aspect must be looked upon as a part of Energiewende (or Energy Transition). This paper, drawing upon some of the ideas presented in the work of Farid et. al[17], ponders on the shape and role of the grid in future with distributed renewable energy generation and smart grid options.

In recent times, there has been much debate on how to integrate wind energy with the grid. Wind power, as a variable energy resource, is not dispatchable in the strict technical sense, though the output can be forecast to a fair degree of accuracy. There is also a question of economics, smart grid options, need to maintain adequate spinning reserve and fast response units in the system.

The integration and management of wind variability eventually calls new approaches to the management of the grid, involving investments in new forecasting techniques, spinning reserves and smart grid options. There are many who question true investments in the emerging scenario. The economics of wind power or renewable energy integration itself is perhaps a discussion that goes beyond the scope of this work but one needs to keep in mind that much work has been done on these aspects and that the economics are not only determined by market conditions (fossil prices etc.) but also the global and national policy and regulatory frameworks that should also be factored in the environmental cost in the pricing, tariff or market mechanisms.

The conventional power systems, that have evolved traditionally, have been built on the basis of evacuating electricity from a few centralized and actively controlled thermal power generation facilities serv-

ing a relatively large number of distributed, passive electrical loads[18,19].

The dominant operating principle of these operators and utilities has always been to serve the consumer demanded load with maximum reliability[20]. However, when viewed over wide range of systems from the ones in highly developed countries to underdeveloped countries the operating principles and priorities can also change. While in advanced countries, reliability in supply could be more important, in developing countries or under-developed countries, the principle may be to reach out to a wide consumer base under restricted supply conditions while maintaining grid stability. Over the years, system operators and utilities have improved their methods to achieve this task[21,22]. Generation dispatch, reserve management and automatic control have matured. Load forecasting techniques have advanced significantly to bring forecast errors to as

low as a few percent and system securities and their associated standards have evolved equally. However, many of these aspects may further change as the grid undergoes transformation.

Across, the world, multiple mega-drivers are set to dramatically change ground realities and the basic assumptions that govern power system design and operation[23,24]. These drivers are 1) Environment or Decarbonization, 2) Reliability, 3) Distributed Generation with Renewable Energy 4) Transportation electrification, 5) Consumer participation and 6) Deregulation. Again, these changes have to be viewed in the context of the country or region. For example, looking at Africa, which today happens to be the Dark Continent devoid of a significant network serving it, interconnected mini-grids with distributed renewable energy and hybrid power plants can be a major distinguishing feature from that of the conventional power systems in developed countries.

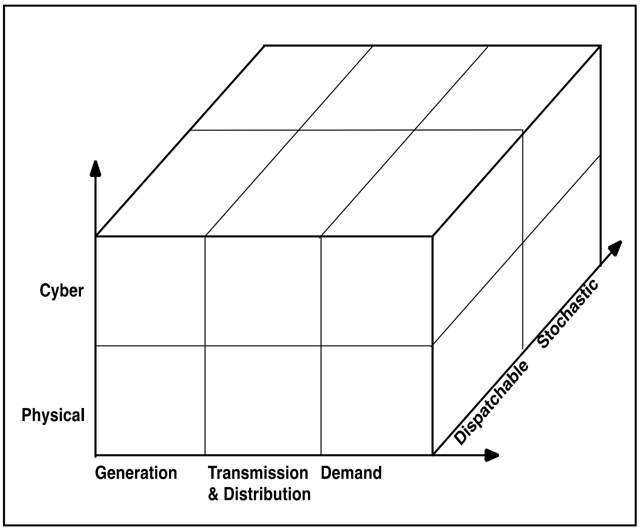
Whatever, the manner of transition, we will see steady diversification of energy to include solar, wind, storage systems and demand side resources. And these, in turn, require the grid as a whole to evolve its control capabilities to host the new found and tremendous diversity of loads and generators. Therefore, the question becomes not of wind variability, but rather how to evolve with high penetration of wind and to assess the control capabilities of the electricity grid as whole.

This ultimately imposes fundamental changes to the grid structure and behavior. As a result, the already existing suite of control technologies and strategies are set to dramatically expand in both number and type. While existing regulatory codes and standards on grid safety, security and operation will continue to apply to a large extent[25,26,27], there will be a greater deployment of control, automation, and information technology. Together, these form the smart grid initiatives that will not only engage with generators but also with consumers and other ancillary units in the grid.

A depiction of future electricity grid with a high penetration of wind power, demand side management technologies and control technologies can be as follows:

As shown in Figure 5.1, on one axis, the electrical power grid is viewed as a *cyber-physical* system. Here, assessment of the physical integration of wind

Figure 5.1: Guiding Structure of Argument



energy and demand side resources must be in the context of the control, automation, and information technologies. On another axis, it is an energy value chain spanning generation and demand. On the third axis are the dispatchable as well as stochastic energy resources. This graph defines the scope of the grid system that must address complex technological, system and societal objectives.

The power grid is taken as a cyber- physical system composed of an energy value-chain with despatchable and stochastic elements that must fulfill certain technical and control objectives as well as environmental and economic objectives.

6. Evolution of the Physical Power Grid

(This chapter is based mainly on the work of Amro M. Farid Dartmouth/MIT)

It is within the context of the six drivers described in the previous section that wind integration must find its place. Far reaching and fundamental changes in electricity generation and consumption patterns are already taking place. As a result the overall structure and dynamics of the system is set to evolve; potentially invalidating several traditional assumptions about power grid behavior. This section characterizes wind power resources and investigates the likely evolution of the physical power grid's structure and dynamics. An expanded version of this discussion can be found elsewhere[22].

6.1 Characteristics of Variable Energy Resources

The evolution of the physical power grid is understood from the starting point of conventional practice. Table 6.1 shows that a traditional power network consists of relatively few, centralized and

Table 6.1: Traditional Grid Generation and Demand Portfolio[22]

Past	Generation Supply	Load Demand
Well-Controlled & Dispatchable	Thermal Units: Few, Well-Controlled, Dispatchable	
Stochastic/ Forecasted		Conventional Loads: Slow Moving, Highly Predictable

dispatchable generation units with many and highly predictable loads[16]. Variations span a wide range of frequencies with slow variations having larger magnitude that correspond to the daily periodicity of the demand. These multiple time scales excite and affect the different behavioral phenomena in the power grid shown in Figure 6.1. Over time, load became highly predictable with the state-of the-art forecast error being approximately 3%[28,29,30]. Consequently, different types of generation fulfilled different parts of the load: large coal/nuclear power plants supply the base load, combined cycle gas plants follow the changing load, and internal combustion engines and gas turbines come online during the peak load[19].

As the drivers described in the introduction take hold, the power grid evolves as shown in Table 6.2 so that generation and supply are on a much more equal footing. From the perspective of dispatch ability, wind power resources like other VERs are non-dispatchable in the traditional sense but have a Capacity Credit associated with them. According to IEA[31]:

Figure 6.1: Time scales of physical power grid dynamics[28]

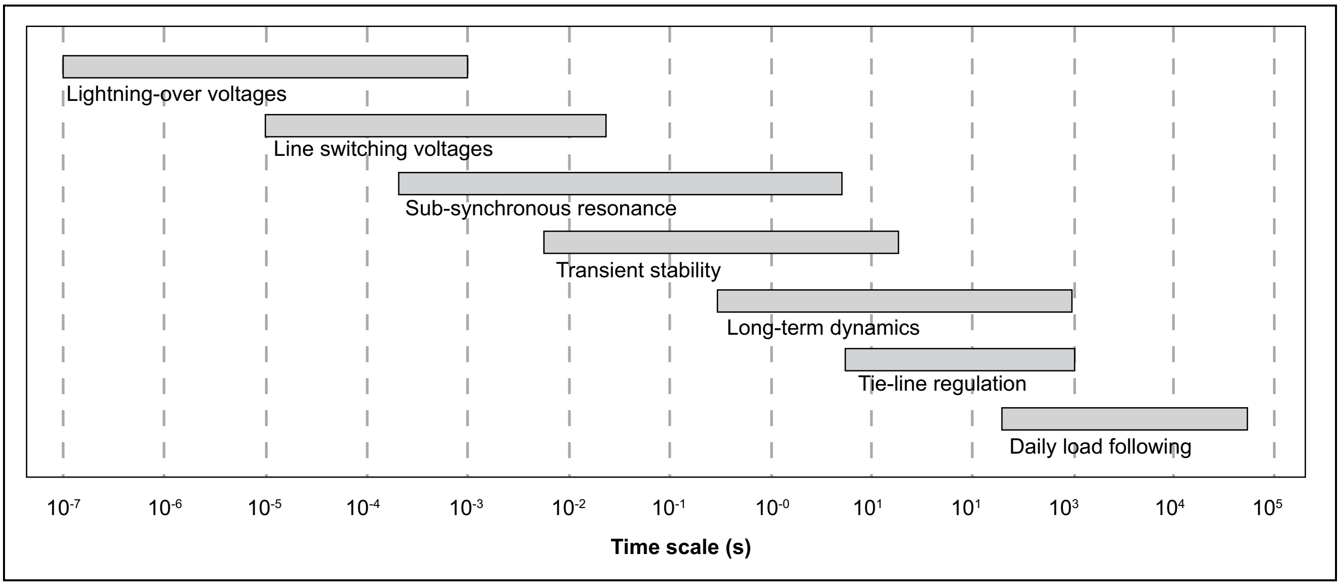


Table 6.2: Future Grid Generation and Demand Portfolio[22]

Past	Generation Supply	Load Demand
Well-Controlled & Dispatchable	**Thermal Units:** Environmentally unsustainable	**Demand Side Management** (Needs Control & market design)
Stochastic/ Forecasted	**Renewable Energy Sources** Disributed & Variable	**Conventional Loads:** Growing and need curtailment

The capacity credit is the peak demand less the peak residual demand, expressed as a percentage of the variable renewables installed. For example, if 10 GW of wind power plants are installed in a region, and their capacity credit is 10%, then the there will be a reduction of 1 GW in the amount of other plants required, compared to a situation with no wind capacity.

: the output depends on external conditions and is not fully controllable by the grid operator[32]. On the other hand, the introduction of demand-side resources allows the flexible scheduling of consumption, which raises dispatch ability of demand, which essentially means that there can be certain consumption demands that need not be stochastic but can be scheduled within certain constraints. Some of the examples are industrial loads, which can be operated under off-peak conditions. Similarly irrigation loads, which can either be at a fixed time of the day or as and when required by the system, however, within the constraint of irrigation season. These result in competing changes to the power grid's overall dispatch ability and forecast ability. Consequently, power system assessment techniques should correspondingly evolve to allow for both control as well as disturbance to originate from either generation or demand.

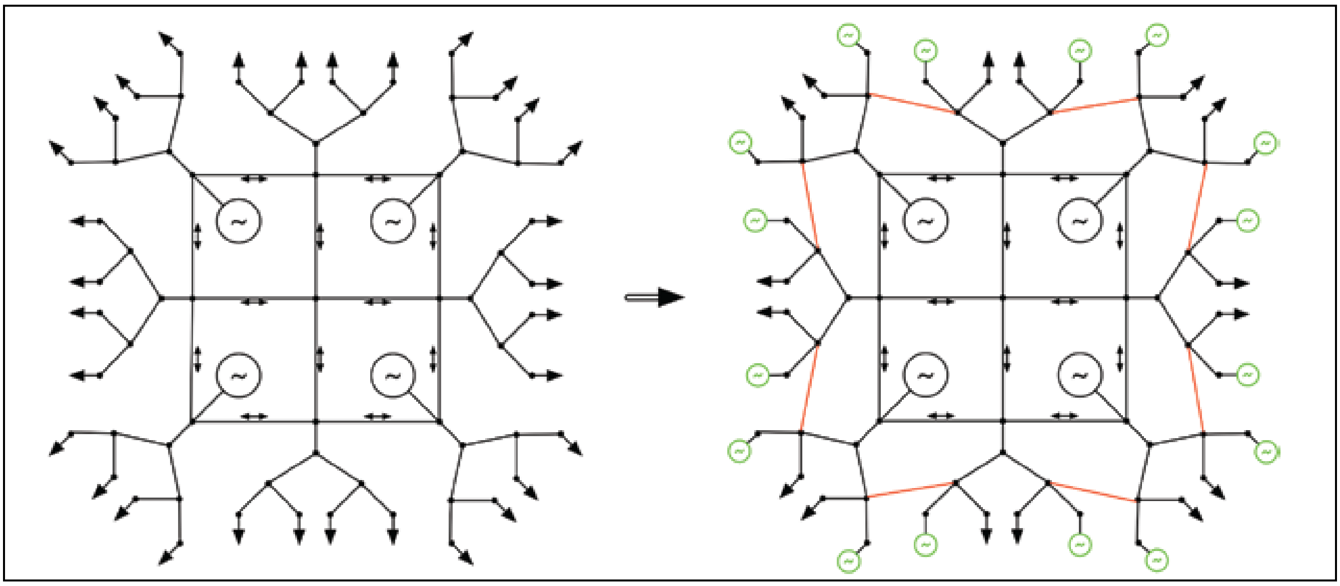
a. Changes in power grid structure

In addition to their dispatch ability and stochasticity, wind power resources like other VERs bring about a change in the spatial distribution of generation. Figure 6.2 shows that traditionally, the power network consists of meshed transmission network, connecting centralized generation units on a wide area, and radial distribution networks, delivering power to the final consumer. However, because wind power resources can vary from hundreds of MW to only several kW, they break the assumption of centralized generation and allow generation in the distribution system.

The change in power grid structure has implications on its operation. Distributed generation creates the potential for upstream flow in the distribution system, where it was not generally permitted before[33, 34, 35].

The protection system has to be redesigned accordingly[32, 36, 37, 38]. Another challenge is the potential for over-voltages. The mitigation of these challenges may require new stabilizing connection lines within the distribution system; thus turning it into a mesh network of multiple microgrids and potentially effacing the clear separation between trans-

Figure 6.2: Graphical Representation of the Evolving Power Grid Structure[28]



mission and distribution[39, 40, 41, 42]. Such structural changes create the need for joint study of transmission and distribution networks and suggest that assessment methods be developed accordingly.

b. Changes in power grid dynamics

Although the many physical power grid phenomena shown in Figure 5.1 do overlap[28], traditionally, power systems literature has treated them strictly separately. The integration of wind power resources challenges this assumption and further blurs the distinction between control technique timescale. Recent reviews summarize the impact of wind integration[43,44,45,46].

6.2 Enhanced power grid enterprise control: Strategy, Dynamic Properties and Technology Integration

Returning to the guiding structure provided by Figure 4.1, the previous section demonstrated a number of evolving trends that will change the nature of the physical power grid. These require a "re-think" of holistic power system control and assessment. This section now addresses the "cyber-layer" found in Figure 5.1. Rather than adhere to the traditional dichotomy of technical and economic control objectives, this work instead raises the concept of integrated enterprise control[47, 48, 49] as a strategy for enabling holistic dynamic properties that support wind integration. It then briefly mentions the emerging technologies set to bring about such a strategy.

a. Power grid enterprise control: strategy

The ongoing evolution of the power grid can be viewed through the lens of enterprise control. Originally, the concept of enterprise control[48,49] was developed to not just manage the fast dynamics of manufacturing processes but also to integrate[50] control with business objectives. Over time, a number of integrated enterprise system architectures[51,52] were developed coalescing in the current ISA-S95 standard[49,50]. Analogously, recent work on power grids has been proposed to update operation control center architectures[53] and integrate the associated communication architectures[54].

b. Power grid enterprise control: dynamic properties

These integrative initiatives are a fundamental step towards wind integration and power grid operation is founded upon the fusion of technical and

economic control objectives which enable holistic dynamic properties. The economic aspects are driven by global, national or regional policy and regulatory regime. The five dynamic properties to be addressed are dispachability, flexibility, forecastability, stability and resilience. Consequently, as the power grid's physical and cyber layers continue to evolve, it may become clearer how these properties improve or degrade. To that effect, these dynamic properties may be holistically enabled by the wealth of new supply and demand side resources. First, generation and demand are set to take much more equal responsibility over power grid operation. This appears in not only in the degree of forecast ability but also in the degree of dispatchability and flexibility. Furthermore, the combination of these three properties suggests a grid that is generally more dynamic in nature, and so requires specific attention to ramping capabilities and dynamic stability. Finally, the transformation of a power grid's structure from one that is topologically fixed to one that is composed of actively and readily switched microgrids suggests the need for resilience. Table 6.3 shows the balanced role of generation and demand in regard to these five dynamic control properties. An expanded version of this discussion can be found elsewhere[22].

Table 6.3: Grid Enterprise Control to Enable Holistic Dynamic Properties[22]

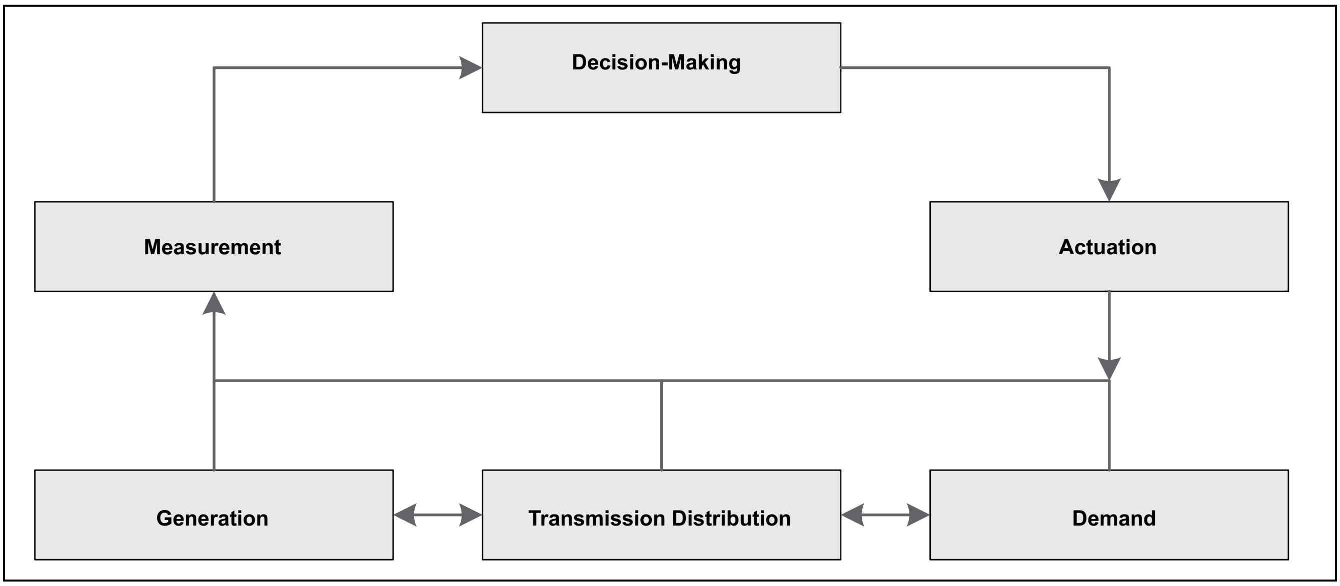
	Generation	Demand
Dispatchability	❖ Low – Wind, Solar, Run of River Hydro ❖ Medium – Hydro, Solar CSP ❖ High – Thermal Units	❖ Low – Lighting ❖ Medium – HVAC, Commercial buildings ❖ High – Industrial production
Flexibility/Ramping (Thermal Energy to Work Ratio	❖ Low – Solar PV ❖ Medium – Wind generation ❖ High – All dispatchable generation	❖ Low – N/A ❖ Medium – Lighting, Cooking, Hair Drying ❖ High – Scheduled Industrial Production
Stability	❖ Synchronous Generators w/AVR ❖ Wind induction Generators w/low voltage ride through ❖ Solar PV w/ power electronics	❖ Synchronous motors in HVAC applications ❖ Induction Motor appliances with active harmonic control ❖ EV's w/power electronic based control
Resilience	❖ Recovery from generator faults ❖ Intentional switching of generators	❖ Recovery from load shedding ❖ Intentional switching of loads
	Intentional and Unintentional Switching of Lines	

c. Power grid enterprise control: technology integration

Thus, wind power resources are one of many energy resources that can enable the five holistic dynamic properties of dispatchability, flexibility, forecastability, stability and resilience. The ultimate balance of these resources takes on greater importance in the context of the vast number of emerging "smart-grid" control technologies entering the market[55]. Individually, these technologies bring their own local function. However, in reality, their value emerges in the context of the full enterprise control loop of measurement, decision-making and actuation shown in Figure 6.3[22]. While an in-depth review[56] of these emerging technology offerings is beyond the scope of this work, a cursory mention of the leading options serves to further motivate the need for holistic assessment.

These "smart-grid" control technologies are mentioned along the loop of measurement, decision-making and actuation shown in Figure 6.3. Although the transmissions system continues to introduce new control technology, perhaps the most evident upgrades appear in the distribution system; further blurring the distinction between the two systems. For example, in the measurement and communication infrastructure SCADA[56], as a well-established transmission technology that is quickly entering distribution space. In complement, smart meters[55,57,58,59], phasor measurement units[60], and dynamic line ratings[61,62] have received a great deal of attention in both academia and industry. In decision-making, transmission energy management systems functionality is being repackaged in distribution management systems[63,64]. An extension of these is facility energy management systems which can integrate with the power grid[65]. Finally, a bloom of actuation devices is set to appear all along the power value chain. Virtual and real generation aggregators are being developed for economics oriented control in both generation and demand[66,67,68]. To that effect, model predictive

Figure 6.3: Integrated Enterprise Control of the Power Grid[22]



control techniques[69] have advanced significantly to support both individual as well as groups of facilities, be they for power generation or industrial production. FACTS devices[70] such as static var compensators, once deemed cost prohibitive by many, have an active role in the integration of VERs and in the real-time control of power flows across the power grid. At the residential scale, market forces are driving towards smart energy appliances of nearly every type[55,58,71].

Driven by Environment or De-carbonization, Reliability, Distributed Generation with Renewable Energy, Transportation electrification, Consumer participation and Deregulation future grid will undergo technical, economic and regulatory changes to bring about the incorporation of renewable energy and incentivized demand side management and control. As a result, the power grid will experience fundamental changes in its system structure and behavior that will consequently require enhanced and integrated control, automation, and IT-driven management functions in what is called enterprise control.

7. Concluding Remarks

The world energy system, which is predominantly hydrocarbon based must now undergo a transition to make way for a renewable energy based system in which wind energy plays the predominant mainstream role. The planetary environmental concerns, energy access and energy security issues, the geopolitics of oil and resulting conflicts in many parts of the world, all these aspects point towards the urgent need for this transition or *Energiewende* as it is called.

WWEA in its earlier WWEA Wind Resource Report (2014) has assessed the worldwide potential to be of the order of 95 TW, which is more than adequate to meet the electricity requirements of the world in combination with other renewable energy options.

Today with wind contributing nearly 4% of overall electricity generation, 370 GW of installed generation capacity and deployment in more than 100 countries; modern wind turbines have made the transition from a fringe technology to a mainstream electricity generation option. Technology continues to evolve with greater elements of innovation, engineering complexity and technical finesse. We can say a modern wind turbine is a smart wind turbine capable of un-attended operation even in extreme climates such as offshore regions. Many new ideas and initiatives are being experimented with and this may further change the technology landscape.

Harnessing wind energy has evolved from single wind turbine concepts a few decades ago to wind farm and the integration of multiple wind farms with other available RE resources to meet the consumption requirements of a region to country-wide scale and beyond.

In regions with existing infrastructure, a major barrier to large-scale wind power deployment is its integration with the conventional electricity grid, yet in less developed regions, with little or no existing grid infrastructure, the ability to design a grid that is planned in advance for RE sources, could be the clear advantage for those regions supporting implementation of RE at much higher pace.

We have looked at the entire issue of grid and its management with high penetration of wind and other renewable energy with deep insights but from a broad evolutionary perspective. We conclude that higher penetration of wind in the power systems is not an insurmountable problem and there are specific technological or management practice solutions to each of the problems, which either already exist or are clearly soluble. We feel with greater component of generation from wind, the grid has evolved and it must undergo further significant evolution to enable 100% RE scenarios. We summarize our conclusions as follows:

1. WWEA in its wind resource report has assessed that there is enough wind resource potential in the world to meet its energy requirements in combination with other renewable energy sources and an evolved electricity grid that can manage diversity of components and variability in them more effectively.
2. Climate change, energy access, energy security and serious environmental and security issues around extraction of fossil fuels from reserves and mines concentrated in only some areas of the world as well as serious risks of accidents around nuclear power plants will continue to drive renewable energy, in particular wind energy capacity additions and integration with the grid – Renewable energy with wind energy as a major component is becoming more of a necessity than choice.
3. In terms of worldwide developments, wind energy is proliferating across all nations and is poised to take on the role of one of the major contributors to electricity grid.
4. While Wind Power developments in Asia are likely to exceed developments in other parts of world, in EU and parts of US high penetration of renewable energy is getting established.
5. We note that even in the absence of wind, a power system has to deal with many dynamic parameters such as availability of plants and variability in load demand. Wind generation only adds to the level of complexity that in any case is getting addressed.
6. Grid is evolving rapidly and will change dramatically from what it is today. Some of the key elements of this change are:

   a. Distributed generation or geographically dispersed generation in the distribution system.
   b. A large number of transmission links lead-

ing to a transmission mesh in contrast to the radial systems that we have today from large centralised coal or nuclear power plants to consumption loads.

c. Greater deployment of DC and HVDC technologies with converters not only for transmission but also to improve the power quality.
d. Deployment of smart grid options. Smart grid is considered an important pillar in comprehensive RE implementation. It includes the abaility to forecast, to control loads, engage dispatchable power generation units and balancing of the network
e. More hydro capacities, pumped hydro storage, other kinds of storage systems and fast response units such as IC engines, diesel and gas based generators for fast ramp up, balancing and back-up.
f. Enhanced and more accurate load demand and wind resource forecasting will get established as more and more windfarms and other RE technologies come up and a track record of their variability is established. New scientific and analytical methods will be used for this purpose.

g. Transmission planning keeping in view areas with high wind resource, load centers and different types of loads such as agricultural, water pumping, industrial etc.

7. Transport sector will increasingly get linked to electricity grid through battery storage systems. This too will lead to enhancement of renewable energy in the grid.
8. Increasingly we foresee the need for part load operation of conventional power plants.
9. There shall be emergence and proliferation of many new technologies in the area of innovative storage systems, automated control options, sensors and power electronics that will support grid integration of renewable energy.
10. There is a need for technological modifications in wind turbines to enable better control and grid friendly operation or power factor adjustments.
11. Policy and regulatory mechanisms and grid codes will also evolve accordingly
12. Mini and micro grids will emerge in countries and regions with sparse electricity networks. Such regions have the option of setting up networks designed for RE – Integration from a conceptual and design stage. Africa is one such region.
13. Islands need to develop new and innovative approaches to harness abundant wind energy. The challenge will be the size of the network (mini and micro grids) and higher variability on account of the scale and size.
14. In a future energy mix by 2050, under a most likely scenario we expect around 9.8 TW of wind power installations generating nearly 17000 TWh/yr
15. Apart from distributed generation, we also see the possibility of large blocks or parks of windfarms of the order of 1 GW getting established on onshore and offshore regions with dedicated transmission lines and other power evacuation ancillaries fort grid connection. Such large parks and windfarms are likely to be managed by large IPPs or utilities themselves.

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