GRID INTEGRATION OF WIND POWER

BEST PRACTICES FOR EMERGING WIND MARKETS

Pramod Jain and Priyantha Wijayatunga

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ABBREVIATIONS

ADB	–	Asian Development Bank
FiT	–	feed-in tariff
GW	–	gigawatts
MW	–	megawatts
MWh	–	megawatt-hour
POI	–	point of interconnection
VRE	–	variable renewable energy
WPP	–	wind power plants
WTG	–	wind turbine generators

EXECUTIVE SUMMARY

Utility-scale wind energy is the most inexpensive form of renewable energy in countries with good wind resources. Globally, wind power has experienced rapid growth of 25% annually, from 17.4 gigawatts (GW) in 2000 to 370 GW in 2014. Growth in Asia has been limited to the People's Republic of China and India. As of end of 2014, the former had 114.8 GW, which is 31% of the global installed wind capacity, while India had 22.5 GW, for a 6.1% share. Other Asian countries like Pakistan, the Philippines, and Thailand have seen a growth spurt in 2013 and 2014.

The Quantum Leap in Wind Power Development for Asia and the Pacific program of the Asian Development Bank (ADB) has been providing technical assistance for close to 5 years to three emerging wind energy countries—Mongolia, the Philippines, and Sri Lanka. This study reports observations and experiences in these and other emerging wind energy markets.

In emerging wind energy markets, issues related to grid integration of wind energy are not at the forefront. Grid integration is approached on an ad hoc, project-by-project basis. Project-specific grid integration components like transmission, substation, and physical connection are built in order to transport wind energy from a wind power plant (WPP) to load centers. Beyond this obvious component, all other grid integration components are ignored until after the WPP is online and issues start to emerge like power quality (harmonics), voltage fluctuations, congestion, and curtailment.

There is also a pervasive notion among grid operators that their specific grid is unique and there is not much that can be learned from other grid operators, especially from developed wind energy markets.

Features of Wind Energy

Wind energy (and other forms of variable renewable energy like solar photovoltaic cells) has the following unique characteristics, and consequently, implications when connected to the grid:

(i) *Wind energy is variable and uncertain.* The first implication is that other generators on the grid must react not only to load variability, but also to wind energy variability. This requires conventional generators to support higher ramp rates in both directions. The second implication is that for cost-efficient operations, accurate wind energy forecasts and responsive systems operations are necessary.

(ii) *Wind generator is asynchronous in contrast to synchronous conventional generators.* The implication is that wind energy provides no inertial response, so when wind energy penetration is high, grid inertia can be low. As a consequence, the grid may become unstable—unable to provide a stable subsecond-to-second frequency response in reaction to fault on the grid.

(iii) *Wind energy is on priority dispatch.* The first implication is that it displaces conventional generation, leading to lower minimum operating levels, and longer and more frequent shutdowns of conventional generators. The second implication is that wind energy may be curtailed during periods of off-peak load, high wind production, and generators operating at minimum capacity.

(iv) *Wind energy is usually not proximate to load centers.* The implications are new transmission or upgrade to existing transmission may be required; losses may be high; and voltage level may fluctuate beyond acceptable levels at interconnection point, thereby necessitating reactive power compensation.

Best Practices for Emerging Wind Energy Markets

Against this backdrop, the ad hoc project specific approach to grid integration is grossly inadequate to support sustainable wind power development. The following best practices are derived from grid integration failures and successes in the pioneering and mature markets.

(i) *Transmission from resource-rich areas to load centers.* Since transmission projects have a longer lead time than wind projects, transmission projects, whether new or upgrade, must be planned ahead of time. A policy of defining wind energy corridors and focusing transmission investment in a corridor is preferable to a project-specific approach.

(ii) *Responsive systems operations.* Upgrading the scheduling and dispatching process for all generators to sub-hour dispatching intervals, incorporating sub-hour lead time for wind energy forecasts, and expanding the balancing areas are process-related improvements that offer the cheapest form of grid flexibility.

(iii) *Flexible generation.* Variability in a grid is not new; it is managed by flexible generation. Wind energy introduces additional variability that must be served by generators with higher ramp rates and deeper cycles. If low grid inertia is an issue, then to support high wind penetration, wind turbines should be required to provide inertia and governor-like response.

(iv) *Flexible demand.* Wind curtailments occur during periods when wind production is higher than the difference between the load and sum of minimum operating levels of all dispatched generators. Load shifting to such periods from periods of peak load can enhance the ability of the grid to absorb a higher amount of variable energy.

(v) *Comprehensive planning process.* There is no one-size-fits-all solution that applies to all grids. A network-wide grid integration impact assessment that examines the impact on the grid of various percentages of wind energy penetration as a function of time is required to determine the grid integration issues and solutions.

(vi) *Grid code for wind integration.* A grid code for connecting wind plants is essential because it specifies the minimum technical criteria that all wind farms seeking connection to the grid shall satisfy at the point of interconnection (POI), and the operating conditions that all wind farms must comply with for safe and reliable operations of the grid.

Country Experiences with Integrated Wind Energy

Experiences from other countries are exemplified in the following observations in a 2015 Wind Vision report (US Department of Energy 2015, chapter 2.7):

(i) The electric power network operated reliably with high wind contributions (10% or higher) in 2013 with minimal impacts on network operating costs.

(ii) In regions with wind power contributions up to 20% of annual electrical demand in 2013, electric power systems operated reliably without added storage and with little or no increase in generation reserves.

(iii) Wind has been proven to increase system reliability during some severe weather events.

(iv) Studies prior to 2008 had estimated integration costs up to $5 per megawatt-hour (MWh). By 2013, the Electric Reliability Council of Texas, which has the highest penetration of wind, was reporting integration cost of $0.5/MWh.

Although costs of wind integration are grid-specific, large numbers of studies have indicated that the cost of integration for low levels of wind energy penetration (less than 5%) is negligible, and a higher level of wind penetration (20% or higher) is less than 10% of the cost of wind energy. The question is no longer “can wind energy be integrated?” but “how should wind energy be integrated?”

I. INTRODUCTION

Wind energy is widely recognized as one of the cheapest forms of clean and renewable energy. In fact, in several countries, wind energy has achieved cost parity with fossil-fuel-based sources of electricity generation for new electricity generation plants (McCrone et al. 2014). The focus of this publication is on grid integration issues in emerging wind energy markets. Although the content of this publication is applicable to all variable renewable energy sources like wind, solar, tidal and hydro, the focus will be on wind energy.[1]

The input raw material (feedstock) for a wind power plant (WPP) is wind; therefore, there is no pollution or environmental degradation due to mining and/or transporting of raw materials like coal, crude oil, or natural gas. The output is clean electricity with absolutely no pollutants—no carbon dioxide, sulfur oxides, or nitrogen oxides—and the WPPs do not use water. All these favorable characteristics of WPPs provide significant tangible benefits in terms of improved health and conservation of natural resources.

Wind energy is a proverbial three-legged stool. There is no wind project without these three legs:

(i) *Wind resources.* Without good wind resources, there is no fuel, hence no project.

(ii) *Power purchase agreement with a tariff.* Without a reasonable tariff and a signed contract to purchase all, a wind project is not economically feasible and there will be no investment.

(iii) *Grid integration.* Without interconnection of a WPP to the grid, there is no method to deliver electricity to the buyers.

Through wind resource assessment, private wind developers choose locations with good wind resources. In most emerging wind energy markets, the feed-in tariff (FiT) policy is prevalent, which guarantees a standard power purchase agreement, published tariff, guaranteed interconnection to the grid, and priority dispatch. A well-designed FiT policy therefore takes care of the other two legs.

Just because an interconnection is guaranteed, it does not mean the interconnection process will be smooth, prompt, or inexpensive. In most emerging wind markets, grid integration is an afterthought. This has sometimes led to delayed interconnection (wind plants stay idle for months after commissioning) and/or significant amount of wind energy curtailment. Table 1 lists some common myths of wind energy related to grid integration. Figure 1 illustrates the impact of wind on variability of net load.

[1] Several individuals assisted in seeding the idea, approving the work on the report, reviewing the report, and above all providing constructive criticism. Bo An, public management specialist in the East Asia Department of the Asian Development Bank (ADB) proposed the idea of undertaking a study on grid integration of wind power with a focus on developing wind power markets. Aiming Zhou, energy specialist in the South Asia Department (SARD) reviewed an early draft of the report and provided guidance on its structure. Priyantha Wijayatunga, principal energy specialist, Sustainable Development and Climate Change Department, ADB; and Kazuhiro Enomoto, energy specialist, SARD, provided valuable insights and led the effort of preparing the study for publication.

Table 1: Common Myths about Grid Integration of Wind Energy

Wind Energy Myths Related to Grid Integration	Reality
Variability and uncertainty of wind cannot be managed by a grid; it is too disruptive	Electricity grids are designed to manage both variability and uncertainty of loads, including occasional failures of one or more generation units, transmission, and substation (N-1 scenario). To explain why variable renewable energy (VRE) generation, which includes wind and solar, is not much more disruptive than normal load variation, consider the following. Often for modeling purposes VRE generation is considered as negative load. That is, VRE generation is subtracted from load to compute net load. The net load may have slightly higher variability and slightly higher uncertainty compared to load from consumer demand. This should be analyzed specifically for the grid under analysis. As an example, consider the case of Texas with 15,000 megawatts (MW) of wind. The variability added by wind energy for different time periods was negligible: (i) 6.5MW (0.04%) for 1 minute; (ii) 30MW (0.2%) for 5 minutes; and (iii) 328MW (2.2%) for 1 hour, where 1 minute, 5 minutes, and 1 hour are averaging periods (American Wind Energy Association). As a second example, consider the case of Western Denmark, where the maximum hourly wind power swing was 18% of installed capacity, and for 50% of the time it was below 2% of installed capacity (International Energy Agency. 2005). Managing this additional variability and uncertainty is not radically different compared to capabilities of current grids. More than 30 years of experience in the People's Republic of China, the European Union, India, the United States, and other areas has shown that VRE can be managed and can be done at modest cost.
Wind generation can drop to zero in seconds Small disturbances in grid can cause wind plants to trip, causing cascading failure and total collapse of the grid	WPPs do not cause grid collapse and cascading failure. Wind speed does not suddenly drop and multiple wind turbines all do not see the same wind speed. When the generation output of multiple turbines is aggregated, it is observed that wind generation output falls smoothly. This is unlike solar plants where the output can fall quickly as clouds arrive. Most grid codes for interconnection of WPP require low-voltage ride through capability, which prevents the wind farm from disconnecting due to a transient fault (short disturbance). In fact studies have shown that modern wind power plants are grid-friendly (Ela et al. 2014). For example, GE wind turbines provide no trip during transient faults or disturbances, regulate plant voltage and reactive power, react to changes in grid frequency, provide inertial response to large under-frequency events, and limit the ramp rate (Millet et al. 2013).
Wind energy causes excessive cycling of thermal plants, which significantly increases the cost of thermal generation	Studies have shown that the increase in cost of thermal generation is minimal. NREL's Western Wind and Solar Integration Study found that with 33% wind and solar energy (25% wind, 8% solar), the additional cost of operation and maintenance of thermal plants is $0.47 to $1.28 per megawatt-hour (MWh), (Jordan and Venkataraman 2012) while the overall reduction in system operating costs of thermal plants (fuel savings and others) is $85/MWh. Although WPP do cause additional cycling of conventional generators, the additional cost is minimal.
Wind energy causes excessive cycling of thermal plants, which increases GHG emissions	Studies have shown that the GHG emissions increase due to cycling of thermal plants is minimal. With 33% VRE (National Renewable Energy Laboratory 2013), carbon dioxide emissions are reduced by 29%–34% due to VRE, while cycling has a negligible impact on this reduction. Sulfur dioxide emissions are reduced by 14%–24% due to VRE with cycling, reducing the benefit by 2%–5%. Nitrous oxide emissions are reduced by 16%–22% due to VRE, with cycling increasing the benefit by 1%–2%. GHG emissions reductions due to WPPs are marginally impacted by cycling of conventional power plants.

continued on next page

Table 1 *continued*

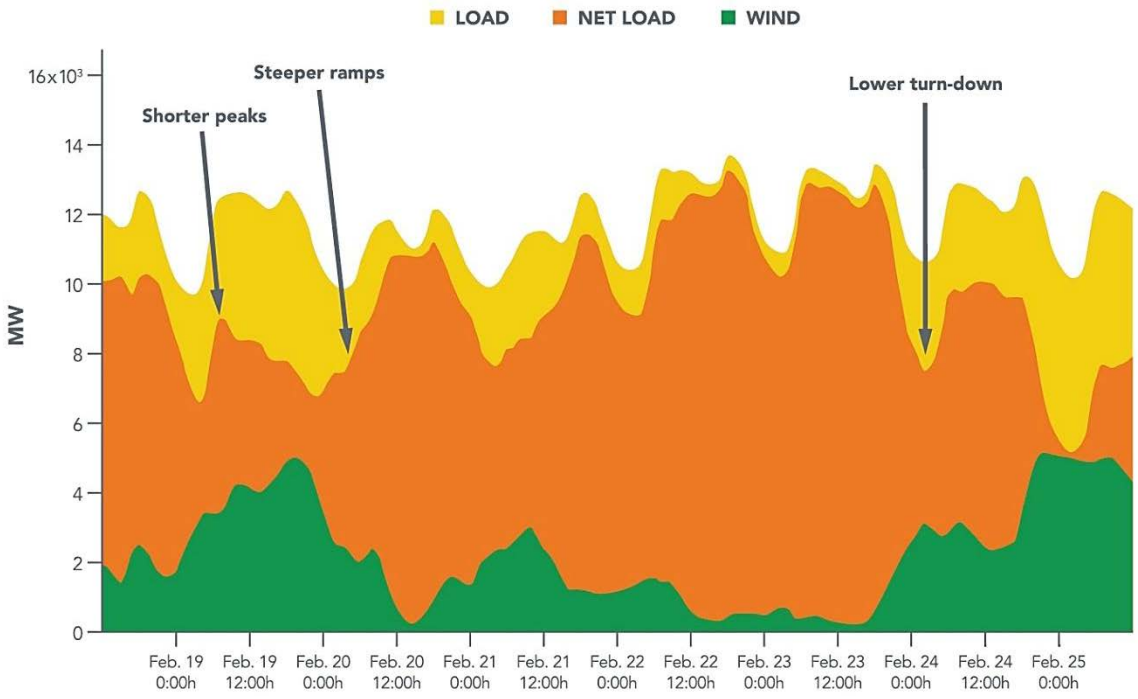
Wind Energy Myths Related to Grid Integration	Reality
Wind energy imposes high cost in terms of reserves and storage	Reserves are always managed at the system level and not at the level of individual generation or type of generation. So 1 MW of reserve for 1 MW of wind is a myth. Furthermore, studies have shown that for most grids in the United States, storage is not needed for up to 30% of wind penetration (Cochran et al. 2014); even beyond that, storage is one of many options, and others are lower-cost options. However, for inflexible grids,[a] reserves and storage may be required at lower levels of penetration. Large integration grid studies have indicated that even with 33% penetration of wind energy, the increase in cost is relatively low ($5/MWh). Small isolated systems have higher costs, while for large, diverse, and agile systems there may be little increase in cost. According to the American Wind Energy Association, on average adding 3 MW of wind energy to the US grid would result in a modest 0–0.01 MW of additional spinning reserves, and 0–0.07 MW of nonspinning reserves.

[a] Flexible grids are described in Section V. For more details see Cochran et al. 2014.

Note: The research presented here is specific to the studied grid. Although the results should translate to other grids, a grid-specific study should be performed.

Source: Asian Development Bank.

Figure 1: Plot of Net Load for 1 Week



Net load = load – wind.

Note: Net load illustrates the impact of wind on variability. Variability is measured in terms of megawatts per unit time, where time may be one minute, 10 minutes, or one hour. Steeper ramps and lower turn-down are examples of higher variability of net load. Since the conventional generation responds to net load, it sees higher variability, which is reflected in requirements for higher ramp and turn-down rates.

Source: Cochran et al. 2014.

The sections of this report are organized to answer specific questions. The second section answers the question, What is unique about wind energy with respect to grid integration? The third section answers the question, What are the components of grid integration of a WPP? The fourth section answers what is the impact of wind energy on a grid. The fifth section addresses what are the best practices for grid integration of wind energy. The sixth section answers the question what is the cost of wind integration. Section VII concludes.

II. WHAT IS UNIQUE ABOUT INTEGRATING WIND ENERGY?

This section describes the unique characteristics of wind resource, wind energy policies, and wind turbine generators.

A. Variable Power

The energy output of WPPs is variable because the wind speed is variable. Variability is in all time scales—hour-to-hour, day-to-day, month-to-month, and year-to-year variability. Variability and uncertainty are very different concepts and are often misunderstood. Variability in wind speed is caused by the earth's rotation (day–night cycle), tilt axis of the earth (seasons), and other natural phenomenon. Examples of variability are higher wind speeds occurring in early morning hours and late evening, and higher wind speeds happening in spring and autumn. Hour-to-hour, day-to-day, and month-to-month changes in wind speed cause variability in wind energy production. A conventional base-load thermal power plant may be considered to have minimal variability as long as sufficient fuel is delivered to it; any variability is due to planned activities like scheduled maintenance. Among variable renewable energy sources, solar dominates intraday variability because of sunrise and sunset. When diurnal variability is removed, then solar and wind have similar variability (Lew et al. 2013).

B. Uncertain Power

Uncertainty has to do with unpredictability of wind speed. Continuing with the hypothetical case, the randomness around the variable pattern of wind speed is the uncertainty. Since wind is a weather phenomenon, uncertainty occurs in all time-scales, year-to-year, month-to-month, day-to-day, hour-to-hour, and smaller. A variety of forecasting methods are used to predict wind energy production. The following are true about accuracy of wind energy forecasts (Jain 2010): (i) day-ahead forecast is less accurate than hour-ahead forecast, which is less accurate than 15-minute-ahead forecast; (ii) forecast accuracy increases as the number of turbines increases in a WPP; and (iii) forecast accuracy increases as the number of WPPs increase and the WPPs are in geographically diverse locations. Among renewable energy sources, wind energy has higher uncertainty compared to solar.

C. Geographic Diversity, Size, and Distance from Load

Wind power plants are located where the wind resource is high. In most parts of the world, areas with high wind resources are far away from population centers. The reason is it is difficult to live in areas with sustained high wind speeds. Such areas are either not served by a central grid or served by a "weak" grid. A weak grid is characterized by a long transmission line that carries a small amount of power. An implication for wind projects in such areas is the need to build new or upgrade existing transmission lines. Long transmission lines from WPP to load center may lead to fluctuation in voltage

that is larger than the allowable limit specified in the grid code. This should be managed by using reactive power compensators on the line.

The second geographical aspect of WPPs is its density. The density of a wind farm is typically 5 MW to 8 MW per square kilometer. For example, a 50 MW WPP would be spread across 6–10 square kilometers. The output of a WPP is an aggregate over multiple turbines, and if there are multiple WPPs in the grid, then wind energy injected into the grid is an aggregate over the WPPs. Aggregation contributes to reduction in uncertainty of wind energy (because all turbines do not see the same wind speed profile) and to a lesser extent reduction in variability of wind energy.

The other implication of modularity of WPP is that scheduled or unscheduled maintenance of one turbine does not materially impact the output of the WPP. Hence, in the aggregate, a WPP can exhibit higher reliability.

D. Standardized Power Purchase Agreement with Guaranteed Interconnection and Priority Dispatch

In most emerging wind energy markets, wind energy projects avail of the following incentives:

(i) *Standardized power purchase agreement (SPPA).* Most emerging wind energy countries have a single-buyer market. SPPA is intended to simplify or in most cases eliminate the need for negotiating with the off-taker (buyer of wind energy).

(ii) *Feed-in tariff.* FiT is a cost-based tariff that is intended to ensure a reasonable return on investment for a wind power developer.

(iii) *Priority dispatch.* FiT is often accompanied with take-or-pay contract in which the wind farm owner is paid even for curtailed energy. Curtailments occur when the wind energy production is higher than the difference between the load and sum of minimum production levels of all dispatched generators. Details of take-or-pay contracts are country-specific, but except in cases of force majeure, safety of grid, or reliability of supply, the WPP owners are paid for amount of curtailed energy. Therefore, it is in the economic interest of the grid to absorb all energy produced by WPPs. In addition, since wind energy has near-zero marginal cost (because there is no fuel cost), it should be considered as a priority dispatch resource. In several competitive electricity markets this sometimes manifests as negative prices during times of high wind production and low demand.

(iv) *Guaranteed interconnection.* SPPA includes provisions for guaranteed interconnection of WPPs to the grid as long as the WPP meets provisions in the grid code. In most countries, the cost of building transmission from the WPP to an existing transmission line is borne by the WPP, while the costs of upgrading the substation and transmission line are subject to cost sharing with the transmission company. If transmission upgrade is planned to be exclusively used by the proposed WPP, then the WPP pays for the upgrade. If it is recognized that the upgrades have a regional benefit and it can be included in a regional transmission plan, then cost of upgrades may be shared.

(v) *Demand-side incentives.* FiT is a supply-side incentive provided to the seller of wind energy. In cases where FiT is higher than the prevailing tariff paid to the generators displaced by wind power (marginal tariff), then the buyer is compensated for the difference between FiT and the marginal tariff. Typically, renewable energy funds (REF) are created to compensate the buyer.

These incentives give the incumbent generation companies and the transmission company a mistaken perception that wind energy generation is getting preferential treatment. What is forgotten is that all technologies in a nascent phase get preferential treatment, and as a society, clean technologies should get preferential treatment.

E. Wind Turbine Generators

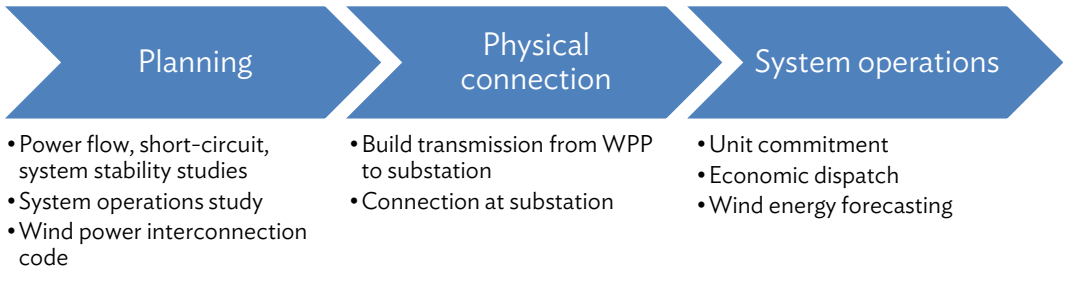
Wind turbine generators (WTG) technology has evolved from Type 1 and 2 induction-based generators to Type 3 double-fed induction generator and Type 4 full-power conversion-based generator. Type 1 and 2 generators consumed reactive power from the grid, therefore were not grid-friendly and by and large are no longer used in utility scale turbines. Type 3 and 4 WTGs are grid-friendly and can consume or produce reactive power to support grid functions. These turbines provide active and reactive power control, low-voltage ride through, high-pass filters, and other features that can increase the stability and reliability of the grid.

Wind turbine generators do not provide inertial and governor response, like conventional synchronous generators. The implication is that WPPs do not provide primary frequency response, so the grid must rely on conventional generators for it. Recently, wind turbine manufacturers have started offering advanced control systems that provide synthetic inertial and governor-like response. This is discussed in subsequent sections.

III. WHAT IS GRID INTEGRATION OF WIND ENERGY?

Grid integration of wind energy is simply a collection of all activities related to connecting WPPs to the grid. Activities are split into three categories based on when the activities occur. The first stage, planning, includes activities that occur before a WPP is integrated. Physical connection encompasses activities that occur during the physical connection of the wind farm to the grid. The final stage is system operations, which are the activities that occur after the WPP is connected to the grid (Figure 2).

Figure 2: High-Level Activities of Grid Integration



WPP= wind power plant.

Source: Asian Development Bank.

A. Planning

There are two distinct types of planning activities related to grid integration: network-wide and project-specific. Network-wide activities set the stage for all future WPPs; these include grid code development, network-wide system integration studies with scenarios for different levels of wind penetration, and system operations studies. Project-specific planning activities include system impact studies done for a specific wind project. The methodologies for both types of studies are the same, except for input data related to wind power installations. In a network-wide study, the input is wind energy targets by region; while for a project-specific study, the input is WPP of the project.

1. System impact studies

System impact studies for integrating wind energy are similar to studies performed when integrating thermal power plants. Three types of impact studies are performed to determine the nature and extent of impact: power flow, short-circuit, and power system stability (see Appendix I for details). In a network-wide system, impact studies scenarios are created for various levels of variable renewable energy (VRE) penetration over time; for example, 5% VRE in 5 years, 10% VRE in 8 years, and 15% VRE in 12 years. In addition to determining the required upgrades, the cost of integration is also computed. (It is the authors' opinion that in most grids, the impact of 5% to 10% penetration of wind energy is minimal.) Nevertheless it is a mistake to skip the impact study and assume that there is no impact because a general rule cannot be prescribed, as the impact will depend on the specific grid under study. An illustration of cost impact in various regional US grids is shown in Figure 4. A study in the United Kingdom (International Energy Agency. 2005) concluded that with 5.3% penetration of wind, the lower and upper estimate of cost are 1.3 to 2.1 €/MWh.

2. Power system operations assessment

Power system operations are a collection of activities performed in multiple time frames (daily, hourly, minutes-to-seconds) related to running the grid in a reliable and cost-effective manner. The total demand in the power system must be balanced with the total generation from all sources at every instant. This balance must happen for both active and reactive power. Traditionally, wind power was considered nondispatchable, meaning when wind energy is produced, all of it must be absorbed by the grid and the conventional generators must adjust around the timing and quantity of wind generation.

In developed wind energy markets, this traditional notion has changed, WPPs are now participants in the dispatch process. Note that wind has "limited" dispatchability—WPP output can only be reduced (not increased) from its current level of production (which is determined by current wind speed). The benefits are reliable and cost-effective grid operations. To illustrate this, consider an extreme situation in which the system operator is in a bind because of one, an imbalance in the grid—wind generation is high, demand is low, and thermal generation is at its minimum; and/or two, transmission is constrained—wind generation is high and transmission is reaching its thermal capacity. In such situations, it may be cost-effective, from a system-wide perspective, to curtail wind energy production (using for example active power control on turbines) until the constraints are resolved. The cost of curtailing wind energy may be smaller than the cost of shutting down and restarting a thermal generator in a short time period.

In emerging wind markets, it is imperative to perform an analysis to determine the impact of integrating wind into the system operation's unit commitment process and economic dispatch process. In a flexible grid with small penetration of wind, wind-integrated dispatch may not be required. However in an inflexible grid (see section V), wind-integrated dispatch may be required even for wind capacity as low as 5% of peak load. Wind-integrated dispatch would require upgrade to the power system operations process.

After assessment of systems operations, the primary upgrades are

(i) incorporation of wind energy forecast to the unit commitment process and economic dispatch process, where forecasts are required to predict the hourly variability of wind energy production;

(ii) reduction of forecast lead time and dispatch interval; and

(iii) installation of active power control on wind turbines in order to limit production to a set level.

If wind energy curtailment is substantial, then the grid can be increased flexibly using options like shifting demand to off-peak hours, adding storage, and replacing the must-run inflexible generators with flexible generators. This is discussed in more detail in Section V.

B. Physical Connection

Physically, a WPP is connected to an existing high voltage transmission line in a substation. In order to avoid the expense of building a substation, most WPPs choose to connect to an existing substation. In the substation, the WPP line is connected to the medium voltage busbar, which is connected to a transformer to step up the voltage to the high voltage transmission line. The medium voltage line from the WPP to the substation is built by the WPP. The detailed design of the interconnection depends on the conditions on the ground.

Within a WPP, a collection system is designed to connect the individual WTGs to the WPP substation. Each WTG has a transformer that steps up voltage from 0.69 kilovolts (kV) (the typical output voltage of a WTG) to medium voltage level (usually 11 kV or 33 kV) of the collection system. The medium voltage collection system is normally buried underground. The substation of the WPP aggregates feeds from the collection system and connects to the high voltage transmission line.

After the WPP is constructed and ready for commissioning, the operations engineers from the transmission operator are involved in the commissioning phase to ensure that the WPP is safe to operate and it produces energy of acceptable quality. After issues related to commissioning are resolved and supervisory control and data acquisition connectivity is established, a request for initial synchronization is made to system operations. The synchronization and subsequent testing process depends on the transmission company's processes and checklists. Primary tests performed include (Jain 2010) (i) proper functioning of start-up, shutdown, and emergency shutdown; (ii) proper functioning of switch gear in response to a variety of fault conditions; (iii) harmonics, flicker, and other quality parameters are within limit; and (iv) successful communication of data from WPP to supervisory control and data acquisition system.

C. System Operations

After the WPP is physically connected to the transmission line, the attention of grid integration turns to system operations, which integrate the production of WPPs into the grid operations. The goal of grid operations is to commit and dispatch all generation units in the system with the objective of meeting demand in a reliable and economical manner. Wind energy forecasting is an important enabler in order to meet these objectives, given the variability and uncertainty of wind resources. Day-ahead hourly wind energy forecasts are used in the unit commitment process and intraday updates to forecasts are used in the economic dispatch process. The unit commitment process and economic dispatch process are described in the next section.

IV. WHAT IS THE IMPACT OF A WIND POWER PLANT ON A GRID?

Integrating any new power plant has an impact on the existing grid and the incumbent generators. In the following, impact on multiple time scales will be described i.e., day-ahead, hour-to-hour, minute-to-minute, and seconds-to-sub-seconds.

A. Day-Ahead Unit Commitment Process

System operators create a daily unit commitment process plan based on forecasts of load and characteristics (maximum and minimum production, ramp rate and cost) of generation plants. The output of a unit commitment process is a day-ahead hourly "on/off" scheduling of generation units. It however does not commit to the level of production. The unit commitment process is therefore a "cost-effective combination of generating units to meet forecasted load and reserve requirements, while adhering to generator and transmission constraints." When a WPP is integrated to a grid, it is usually required to provide a day-ahead hourly forecast of energy production. Basically, the unit commitment process incorporates the hourly wind energy forecast by adjusting the hourly on/off status of the most expensive generators. If there is sufficient wind generation for one or more hours, then it may displace the most expensive generation on the grid.

Uncertainty of wind and demand forecasts is an issue that must be managed by a unit commitment process. It is best explained with an example. If the actual output of WPP at a specific hour is 30% less than predicted in the day-ahead forecast, then during the hour, the committed generators will have to make up the difference. If the maximum production levels of the committed generators cannot make up the 30% loss of wind, then spinning reserves, quick start units, or short-term purchases will compensate for the energy shortfall.

B. Economic Dispatch Process

System operators set the level of production of the committed generators an hour ahead of delivery. The level of production of generators is optimized to minimize the total cost of generation while meeting all the constraints of reserve requirement, generator properties, and others. This is called economic dispatch. In most grids, wind energy has the highest priority (lowest marginal cost), therefore the process dispatches all the wind energy that is forecast for the hour while optimizing the economics of the other generators. Hence when wind generators are producing energy, the level of production allotted to the most expensive generators is less.

C. Illustration of Variability and Uncertainty of Wind Energy

To illustrate how variability[2] of wind energy impacts dispatch, consider diurnal profile of wind in which wind is weak from 7 a.m. to 10 p.m., and strong from 10 p.m. to 7 a.m. Consider a demand profile in which demand is strong from 7 a.m. to 10 p.m. In this situation, as demand picks up in the morning, wind output is decreasing; which implies that other generators in the grid must ramp up faster. Similarly in the evenings, load is decreasing while wind output is picking up, which implies that the other generators in the grid must ramp down faster. So when variability of demand and wind are not synchronized, then the other generators on the grid must have the ability to ramp up or down faster. As wind penetration increases, the ramp rates may become too high for existing generators to handle, in which case additional spinning reserves may be required. With lower penetration of wind, there may be no change to the unit commitment process, while the economic dispatch process manages the ramp rates. As penetration increases, the unit commitment process would have to commit more generators to support high ramp rates.

To illustrate how uncertainty of wind impacts dispatch, consider a grid with total load of 1,000 MW and two scenarios—5% and 20% wind power penetration. In the first scenario with 5% penetration, consider a case in which the WPP output is forecasted to be 50 MW (maximum production) and actual WPP output is 30% below forecast. In this case, the committed generators must make up for 15 MW (30% of 50 MW) in shortfall of power, which is 1.58% (=15 MW/950 MW) of the committed capacity. Most grids should be able to manage this uncertainty using the cushion available in the dispatch plan—the difference between maximum and dispatched capacity of the committed generators. The reason is most grids are designed to manage 3% to 5% uncertainty in load.

Consider the second scenario in which the total load is 1,000 MW; WPP output is forecast to be 200 MW (maximum production); and actual WPP output is 30% below forecast. In this scenario the committed generators must make up for 60 MW (30% of 200MW) in shortfall of power, which is 7.5% (=60 MW/800 MW) of the committed capacity. Most grids may not be able to manage this level of uncertainty with the existing generation resources. In such scenarios, possible solutions are additional quick start units, or exchange of energy with neighboring grids.

As the level of wind energy penetration goes up, the reserve requirement goes up and the value of reducing uncertainty of wind energy forecasts in the unit commitment process and the economic dispatch process goes up. Therefore, management of wind energy uncertainty in the unit commitment process and the economic dispatch process has a prominent role. Moving from day-ahead hourly wind energy forecasts to intraday (for example, update to forecasts every 2 hours) wind energy forecasts would reduce uncertainty.

D. Implications of Wind Energy on Conventional Generators and Transmission

Besides the impact on the unit commitment process and the economic dispatch process, wind energy has other impacts on the grid.

[2] The energy output is variable because the wind speed is variable. The variability is on all time scales—second-to-second, minute-to-minute, hour-to-hour, day-to-day, month-to-month, and year-to-year variability.

1. There are three primary implications on existing thermal and hydro generation units in the grid.

   (i) *Higher ramp rates.* In the worst case scenario, the thermal generation units will have to support the sum of maximum demand ramp rate (*d* MW/minute) and maximum wind generation ramp rate (*w* MW/minute), which is *(d+w)* MW/minute. If the sum of ramp rates is high and cannot be supported by the existing generation units on the grid, then restrictions may be placed on WPP to ramp up or ramp down production of individual turbines in a staggered manner.

   (ii) *Deeper cycling.* As described earlier, output of WPPs may be treated as negative load in the grid, which results in deeper valleys in the net load profile, which then results in deeper cycling of existing generation units.

   (iii) *More frequent start and stop.* During the high wind season, supply-demand balance at the unit commitment process level may force displacement of the most expensive thermal power plant in favor of WPP, which will result in higher frequency of start and stop of thermal generators.

2. At high wind energy penetration levels, the inertia of the grid system decreases (Seyedi and Bollen 2013, Miller et al. 2010) because the percentage of synchronous generation is reduced. As a result, the ability of the grid to respond to loss of large production unit declines. Traditionally conventional synchronous generators (high inertia) provide frequency regulation. If frequency regulation is an issue during high wind penetration, then WPP may be required to provide synthetic inertia, which is accomplished by a control system that transfers mechanical inertia from a rotor to the electrical side in Type 3 double-fed induction generator and Type 4 full-power converter-based turbines. If the WTGs are unable to provide inertial response, then synchronous generators would have to stay online to maintain reliability, which may lead to curtailment of wind energy.

3. To manage small-signal stability, which is response to variability and uncertainty of wind in the second-to-second time frame, inertial response may be required, as described above.

4. To manage in the tenths of seconds to minute time frame, upgrades to governors and controls of current thermal and hydro units may be required.

5. To manage in the minute time frame, upgrade to automatic generation control may be required in addition to more spinning reserves.

6. The flow of electricity in the grid is impacted by introduction of wind energy. More electricity will flow through some nodes, therefore transmission line, substations, and protection systems may need to be upgraded.

V. BEST PRACTICES FOR WIND INTEGRATION IN EMERGING MARKETS

Wind integration has not been easy, especially in grids where it was an afterthought. In the East Inner Mongolia region of the People's Republic of China, 23% of wind power was curtailed in 2011 due to unavailability of transmission to transport wind energy to load centers. In the US, the Electric Reliability Council of Texas system faced 17.1% curtailment in 2009, which was brought down to 2.5% in 2012.

These two examples are extreme cases, and significant experience has been gained from these and other cases. The insights are generalized as best practices below, with a focus on emerging wind energy markets.

A. Transmission from Resource-Rich Areas to Load Center

If transmission is a bottleneck, then policies must address the "chicken-or-egg" dilemma, which is, Should transmission be built in anticipation of WPP or should WPPs be built in anticipation of transmission? The policy that has been successful in Texas is to define wind corridors or preferred zones that are earmarked for investments in transmission and other infrastructure. Wind energy corridors are regions screened for wind resources, land availability, infrastructure, and other factors with the goal of focusing the efforts of all agencies to the identified regions. Such corridors can channel limited resources to one region or a few regions, thereby leveraging transmission and other infrastructure investment in a corridor to support multiple WPPs. This would be in contrast to suboptimal, project-specific approach, which would require the utility to plan and invest in upgrades per project in the region of the project.

In emerging wind energy markets, transmission may not be a bottleneck for the first few projects because the existing lines have sufficient unutilized capacity. However this must be checked through a power flow study, which will go beyond checking adequacy of transmission line capacity to determining requirements for reactive power compensation on transmission lines greater than 100 kilometers (Matevosyan 2005) to ensure voltage and transient stability. In most cases, there is a reversal of current flow in an existing line, which requires reactive power compensation to keep the voltage at POI with limits permitted by the grid code.

B. Responsive System Operations

1. Reducing forecast lead time and dispatch interval

In most emerging wind energy markets, day-ahead hourly schedules (forecast lead time is 1 day and dispatch interval is 1 hour) are created based on load and wind energy forecasts. The daily schedule of generators is firmed up on the previous day, in the late afternoon or early evening. In the schedule, output is set for each hour for each generator based on hourly net-load. Since wind and solar are variable "nondispatchable" generators with near-zero marginal cost, the wind and solar energy forecasts are used as schedules, and all other generators are scheduled around them.

Real time imbalance between net-load and generation is cleared by redispatch and ancillary services such as regulating services. Regulating reserve is the most expensive option. Redispatch should be utilized as much as possible. However, some electric utilities perform dispatch once an hour, which makes grids inflexible (Holttinen 2013). If the dispatch interval is reduced to 15 minutes, then the dispatched generation, with the capability to adjust generation output, can respond to changes every 15 minutes, leaving regulating reserves to manage much smaller intra-15-minute variability and uncertainty. This unlocks flexibility available in dispatched generators, and enables a larger amount of variability and uncertainty to be managed in an economical manner.

One such example is from the western United States with 37 balancing areas and 160 GW of generation, and scenario of 23% variable generation (Holttinen 2013). In this example, when the balancing area is increased and dispatch intervals are reduced from 60–40 to 10–10, the average total regulation required drops from 9 GW to 1 GW. Here 60–40 means 60 minutes dispatch interval and

40 minutes forecast lead time; while 10–10 means 10 minutes dispatch interval and 10 minutes forecast lead time.

Sub-hourly forecast lead time and dispatch intervals can significantly improve flexibility (Cochran et al. 2012). In most cases, this is the cheapest form of flexibility that can be exploited. Therefore it is the most relevant for emerging wind markets. The exact forecast lead time and dispatch interval do not have to be set on day one. The system operator may choose to start with larger intervals and progressively move to shorter intervals. The intervals depend on likely amount of curtailment, forecasting accuracy of wind energy production, and flexibility of other generators. In the US, several independent system operators with high penetration of wind have adopted 15-minute scheduling and dispatch intervals.

2. Active power control

As wind penetration increases, reducing forecast lead time and dispatch interval may not be sufficient to balance supply and demand in all situations. The most challenging situations are when wind energy production is higher than the difference between the load and sum of minimum level of production of dispatched generators. Seasons play an important role in a unit commitment process and the economic dispatch process. For example, in winter, heat requirements may warrant combined heat and power plants to run at much higher capacity levels, leaving limited room for wind energy. In the rainy season, hydro power plants may be forced to run at higher capacity, leaving limited room for wind energy. In such situations active power control features of wind turbines can be useful. System operators may dispatch WPP to a set level of power production, which is below the forecasted level. That is, wind is no longer a nondispatchable resource, but is a participant in economic dispatch with limitations (wind production cannot be increased beyond the available wind resource). Note that in this situation, wind energy is being curtailed.

There are three key considerations (Ela et al. 2014) when implementing wind-integrated dispatch: (i) WPP must be adequately compensated for reduced production and additional investment in active power control; (ii) the new controls of WPP should not adversely impact the stability of the grid; and (iii) the new controls should not increase the loading of turbines, so as not to adversely impact the life of the turbines.

3. Flexible generation

Inertial response and governor response (described in the previous section), as well as reserves, provide flexibility to the grid in responding to supply–demand imbalances. Reserve generators with high ramp rates and low minimum operating capacity are flexible generators because these can be dispatched within minutes and can change production levels rapidly. Traditionally, quick response was provided by gas peaking plants, hydropower, pumped storage, and interconnection to neighboring grids. More recently, options like refurbishing of conventional power plants for flexible operations, utility-size battery storage, compressed air storage, flywheels, and others are used to enhance flexibility. Storage is a perfect flexible resource in terms of technical capabilities, but is one of the most expensive forms of flexibility. It can store and release energy (over longer periods of time), power (rapid exchange over seconds and minutes), or both. Pumped hydro storage and compressed air energy storage are examples of energy storage used for storing energy that would otherwise be curtailed. Flywheel is used for storing power, which is used for frequency regulation and ramping over short intervals. Batteries are used for both energy and power storage.

4. Flexible demand

Load or demand can provide flexibility to the grid in a variety of ways. Instead of generators responding to imbalance between supply and demand, in this case the demand responds. In emerging wind markets, very little demand flexibility is utilized. Demand flexibility can take two forms: load balancing and load shifting. Demand response (DR) is a form of load balancing, in which load is "dispatchable." Dispatchable loads are customers who possess the flexibility to postpone their operations by a few hours, or have the flexibility to reduce power consumption for a few hours. Examples are wastewater treatment plants, ice making plants, chillers, and other heating ventilation and air conditioning equipment, and others. Although this is not practiced much in the developing wind markets, it is starting to play a bigger role in grids with significant wind power penetration.

Load shifting is the other flexibility in demand that deals with the changing behavior of large consumers of electricity. This is achieved by time-of-day tariff, which provides an incentive to large consumers of electricity to shift load from times of high tariff (peak demand) to times of low tariff (off-peak demand and peak wind energy production).

5. Grid code for wind energy integration

Grid code for interconnection is a rulebook that specifies properties that generators and other equipment should satisfy in order to connect to the grid. The goal of the grid code is to ensure reliable and safe operation of the grid.

Variable generators like wind turbines and solar photovoltaic cells did not exist when the original grid codes were created, therefore a grid code refers only to synchronous generators like diesel, steam, hydro, or combined heat and power. Often in emerging renewable energy markets, the grid code is updated to explicitly account for wind and solar generation only after a few installations. In an emerging wind energy market, the existing grid code must be evaluated for compatibility with variable generation and other characteristics of WTGs like asynchronous generators and full power conversion. Appendix II contains an outline of a wind power-specific grid code.

From a planning perspective, the grid code for interconnection of wind power plant should be a top priority. Without a grid code specific to WPP, a wind developer is not obligated to provide "high quality" power output or appropriate fault ride through response.

Sometimes, in the zeal to create a rigorous grid code, the regulators and grid operators create a grid code that is too stringent and does not reflect the realities of the grid. For instance, if the grid code specifies voltage and frequency bands that are too narrow, then the WPP may be forced to trip very often; or if the grid code has conditions that are too onerous, then the cost of WPP may be too high for a feasible project. A balance must therefore be reached between specifications that are too loose and too stringent. It should also be noted that grid code is not a static document; it must be updated routinely in response to changes in the grid and new technologies.

6. Comprehensive planning process

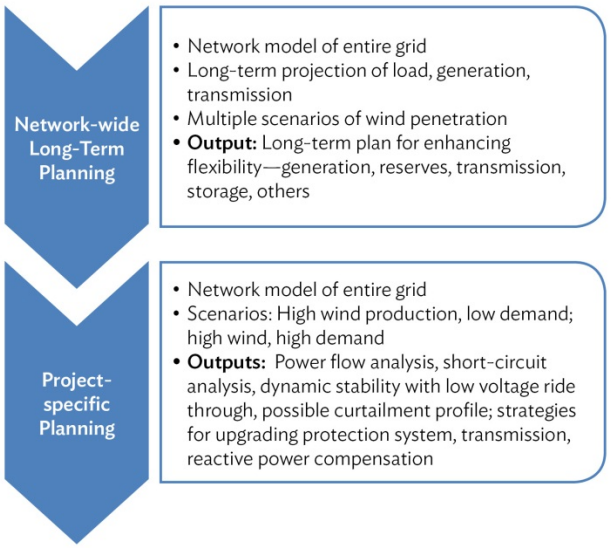
The next best practice relates to planning—long-term and project-specific short term. The previous five best practices highlight the enormity of the task and the need for long-term sustained effort. Institutionalizing a tiered planning process, which starts with an integrated energy master plan that includes wind energy and ends with wind project-specific system impact studies, can lead to faster

growth of the wind industry. Often the initial wind energy projects are considered novel and barely register a blip in planning processes. In emerging wind energy markets, grid integration occurs on an ad hoc basis. There is a general feeling that interconnection of the first few wind projects will have an insignificant impact on the grid. As a consequence, a comprehensive impact analysis, which includes system operations, is not performed.

It is however imperative that the interconnecting utility integrate wind energy annual targets into the long-term energy master plan. After the wind energy targets are modeled in network-wide power flow and dynamic stability models, then impact of wind energy on the network can be analyzed. Subsequently, longer-term plans can be developed for enhancing the flexibility of the grid in anticipation of larger penetration of variable renewable energy.

At the other end is wind project-specific planning. As part of wind project licensing, processes must be developed that require the interconnecting utility to perform a system impact study for every wind energy interconnection request. This will force the utility to assess the impact of a WPP on the grid based on power flow, short-circuit, dynamic stability studies, and system operations studies; and consequently make necessary changes to the grid prior to integration.

Figure 3: Tiered Planning for Grid Integration



Source: Asian Development Bank.

VI. HOW MUCH DOES GRID INTEGRATION COST?

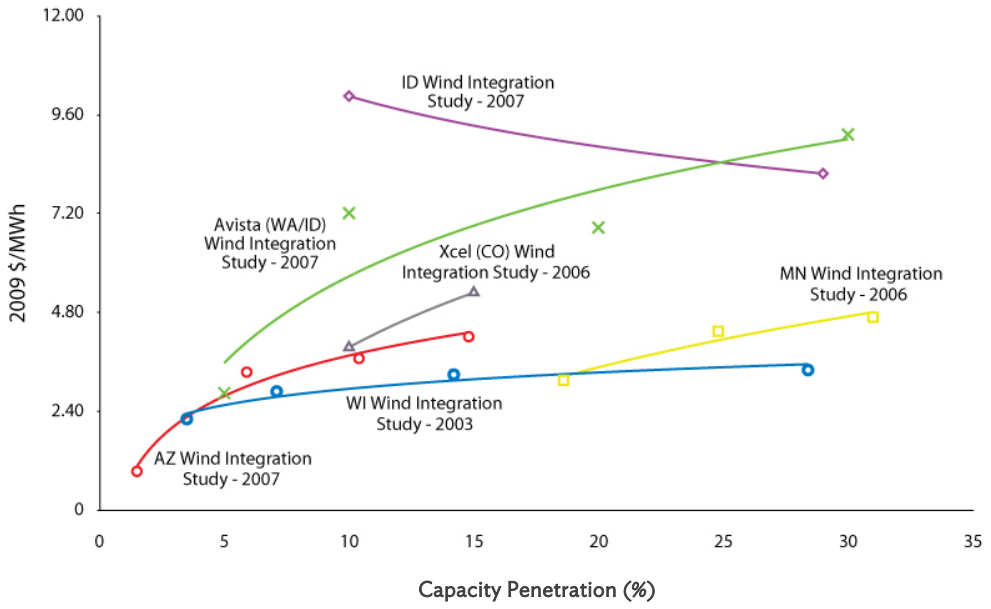
Integration costs may be divided into three categories: (i) transmission extension and related reinforcement, (ii) balancing of increased volatility in the grid, and (iii) maintaining the adequacy (ability to cover peak load). For easier comparison, the first cost category is not included. Figure 4 summarizes the results of studies on wind integration cost (excluding cost category one) for different levels of wind power capacity in the grid for different grids. The studies in the figure present the cost of

integration in six markets.[3] Four of the six markets have wind integration costs that are below $5 per MWh for wind capacity penetration as high as 30%. Across all the studies, the cost of wind integration was 1% to 14% of the total levelized busbar cost of wind electricity in 2010.

Recent studies in the US show that the cost of grid integration is even lower. Studies prior to 2008 had estimated integration costs up to $5/MWh. By 2013, Electric Reliability Council of Texas, which has the highest penetration of wind, was reporting integration cost of $0.5/MWh, primarily due to operating reserve requirements.

In emerging wind markets with low penetration of wind energy, existing transmission lines are used. However, as congestion on transmission lines increase, new transmission lines may be required. New transmission line cost is not allocated to a wind project, because the lines are used by multiple projects and multiple types of power plants. Instead, usage-based costs (per MWh of energy transported) are paid to transmission line operators, and these costs are reflected in operation and maintenance cost of a WPP.

Figure 4: Studies on Wind Integration Costs versus Wind Capacity Penetration in Various Regions of the United States



Source: Rocky Mountain Institute.

Other estimates in the literature suggest that at a 20% share of average electricity demand, wind energy balancing costs range from $1/MWh to $7/MWh (IEA 2011).

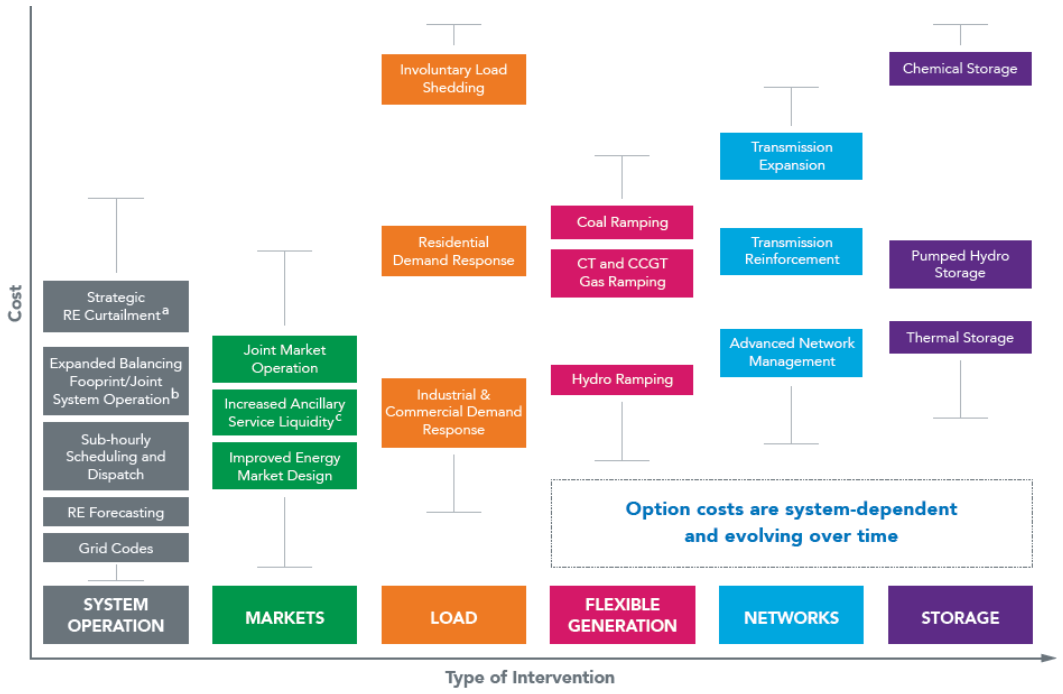
The Grid Integration of Variable Renewables project of the International Energy Agency has simulated the cost of a hypothetical case that has 45% variable renewable energy in the grid (IEA 2014a or b?). Two scenarios are analyzed: first, 45% variable renewable energy is added overnight (base-case);

[3] Please see citations contained in the summary of Rocky Mountain Institute for detailed assumptions associated with the cost estimate.

second, it is added over time in an orderly and coordinated transformation. In the first scenario, the total system costs increase by as much as $33/MWh; the total levelized cost rises from $86/MWh to $119/MWh. In the coordinated transformation scenario, a larger number of flexible power plants are deployed and the grid infrastructure is shared and managed across all of the generation.

The economics of adding flexibility to the grid are system-specific. Experiences across countries and across independent system operators within a country to enhance flexibility have revealed a picture of relative economics as described in Figure 5. The most inexpensive form of flexibility is obtained from system operations—grid codes that require WPP to be grid friendly; wind energy forecasting; sub-hourly scheduling and dispatch; sharing of reserves and enhanced coordination with neighboring balancing areas; and as a last resort, strategic curtailment. In competitive electricity markets, market-based solutions like nodal pricing and ancillary services pricing can increase grid flexibility because the price signals invite more investment to the ancillary service market. Enhancing load flexibility through demand response programs is the other more economical option; however, load flexibility through involuntary load shedding is expensive. Currently, flexibility is provided by conventional generators, primarily by hydropower and gas power plants; coals power plants may be refurbished to provide a higher amount of flexibility. Additional transmission and variety of network management devices and strategies can enhance flexibility by removing bottlenecks associated with power flow. Relatively, the most expensive form of flexibility is from battery-based storage, while thermal and pumped-hydro storage are more economical.

Figure 5: Relative Cost of Various Options to Increase Flexibility of the Grid with Varying Wind Percentages



CCGT = combined cycle gas turbine, CT = combustion turbine, RE = renewable energy.

Note: Six classes of interventions are examined, as labeled on the X axis.

Source: Cochran et al. 2014.

In Figure 5, as evidenced from the above description, physical flexibility (the three interventions on the right of the chart) is expensive, while operational practices and market design are relatively economical.

VII. CONCLUSIONS

Experience around the world has demonstrated that wind energy can be integrated into power systems reliably and economically.

In emerging wind energy, grid integration is an afterthought. This has resulted in a variety of issues: poor power quality, large voltage variations at POI, delayed interconnection after the wind plant is commissioned, and significant curtailment. The result is investments in wind energy projects slow down.

Grid integration has three components: technical, planning, and policy. Just because a conventional generator can operate in a more flexible manner does not mean it will operate flexibly; policies must be in place to incentivize the various parts of the grid to release locked flexibility.

Most emerging wind energy countries have a single buyer market, in which the buyer runs large fiscal deficits. In this context, if the wind power plants are perceived as adding to the deficit of the buyer, then the buyer has no incentive to solve the grid integration problems, irrespective of the environmental benefits. Therefore, incentivizing the buyer and other enabling grid integration policies plays an important role.

The following best practices for emerging wind energy markets should lead to effective and cost-efficient grid integration of wind projects.

(i) *Transmission from resource rich areas to load centers.* Since transmission projects have a longer lead time than wind projects, new transmission or upgrade to transmission must be planned ahead of time. A policy of defining wind energy corridors and focusing transmission investment in a corridor is preferable to a project-specific approach. Note that this approach requires the government to have a high level of confidence in both the wind resource and near-term uptake in wind project development. This approach has been adopted in Mannar, Sri Lanka, and through the CREZ initiative in Texas.[4]

(ii) *Responsive systems operations.* Upgrading the scheduling and dispatching process for all generators to sub-hour dispatching intervals, incorporating sub-hour forecast lead time for wind energy forecasts, and expanding the balancing areas are process-related improvements that offer the cheapest form of grid flexibility.

(iii) *Flexible generation.* Variability in a grid in not new; it is managed by flexible generation. Wind energy introduces additional variability that must be served by generators with higher ramp rates and deeper cycles. If the dispatched generators are unable to provide the ramp rate, then additional generators should be dispatched at partial load. To support high wind penetration, wind turbines should have capability to provide inertia and governor-like response.

[4] H. Smith. 2014. Texas CREZ Project Completed and Already Responsible for Expanded Wind Energy Development. 10 February. http://www.texasvox.org/texas-crez-project-wind-energy/

(iv) *Flexible demand.* Wind curtailments occur during periods when wind production is higher than the difference between load and the sum of minimum operating levels of all dispatched generators. Load shifting to such periods from periods of peak load can enhance the ability of the grid to absorb higher amount of variable energy.

(v) *Comprehensive planning process.* There is no one-size-fits-all solution that applies to all grids. A network-wide grid integration impact assessment that examines the impact on the grid of various percentages of wind energy penetration as a function of time is required to determine the grid integration issues and solutions.

(vi) *Grid code for wind integration.* A grid code for connecting wind plants is essential because it specifies the minimum technical criteria that all wind farms seeking connection to the grid shall satisfy at POI, and the operating conditions that all wind farms shall comply with for safe and reliable operations of the grid.

Wind integration can be further facilitated and integration costs further reduced by efficient grid operating procedures such as large or coordinated balancing areas, fast-interval generation scheduling and dispatch, setting wind generator schedules as close as possible to the dispatch time to minimize forecast errors, and use of wind power forecasting.

APPENDIX I: SYSTEM IMPACT STUDIES

Power Flow Study

The objective of a power flow study is to determine if the flow of electrical energy from generators to consumers meets the line loading requirements and all the grid code requirements in terms of voltage levels, and active and reactive power flow. A power flow study is performed on a power systems modeling software like PSS/E, ETAP, or MiPower. Inputs to the power flow study are (i) one-line diagram of the network; (ii) details of transmission lines, transformers, generators, reactive power compensation devices, and loads; and (iii) variety of scenarios that pertain to the nature of analysis. In network-wide wind energy integration analysis, multiple scenarios of growing wind penetration levels are created, starting with a base year and projecting into the future.

The purpose of the power flow study is to determine the following:

(i) new transmission requirements if the existing transmission line is not dimensioned to accommodate wind power potential in the area;
(ii) reactive power compensation requirements to maintain voltage levels;
(iii) operating characteristics of planned system—mix of generators, losses in the system, active and reactive power flows, transformer tap settings, protective relay settings, and others; and
(iv) system performance under emergency conditions (loss of one transmission line or generator).

In a wind integration study, the following combination of demand and wind generation scenarios is typically analyzed: maximum, minimum, and average. This leads to nine scenarios, out of which the two worst-case scenarios are minimum demand with maximum wind generation, and maximum demand with maximum wind generation. Power flow analysis provides two types of insights: impact on schedule of existing generators, and performance of grid in emergency conditions.

Power flow analysis reveals the impacts on existing generators in the grid due to injection of wind power. For example, in a minimum demand and maximum wind generation scenario, a power flow analysis determines which generators must be shut down and which generators must run at minimum capacity (while abiding by requirements of necessary reserves) in order to achieve load-generation balance.

The nine scenarios are analyzed under emergency conditions—in power systems this is done using N-1 contingency analysis, which is loss of one transmission line or generator. In wind integration study the focus is on contingencies that occur in the vicinity of the WPPs. In the analysis, loading of transmission lines near the WPPs are computed and checked against maximum capacity of the lines.

Short-Circuit Study

The objective of a short-circuit study is to determine the impact of WPP on the protection systems at the interconnection substations and existing equipment in the vicinity of the WPP. Protection systems work by detecting higher levels of current (fault current) when faults occur on the grid, and subsequently opening a circuit breaker to protect the equipment from damage. Two types of faults are modeled: three-phase symmetrical fault and single-phase ground fault.

There are two important factors in a short-circuit study: The maximum short circuit power in mega volt amperes (MVA), which determines the ratings of switch gears; and minimum short circuit MVA, which dictates the sensitivities of switch gears. In a grid integration study for a WPP, the maximum and minimum fault current available at the point of interconnection before and after the interconnection are simulated. The fault currents in "after interconnection" scenario are compared to the ratings of the switch gear to determine if it can safely operate (disconnect) in case the two types of faults occur in the grid.

Wind power plants provide limited short circuit power to the grid, so in general the maximum short circuit MVA due to addition of WPP rarely poses a problem. Nevertheless, this scenario must be simulated to ensure that all the existing protection systems will work as planned. Regarding minimum level of short circuit MVA, there may be problems. In cases in which the WPP is located far away from load centers, the grid in proximity of the WPP is weak, which means that the minimum short circuit MVA is low—that is, a fault on the grid that is far away from the WPP interconnection point does not appreciably increase the short circuit current at the WPP interconnection point. Since the short circuit current is not appreciably higher during the fault, the switch gear keeps the WPP connected to the grid, which is a safety hazard.

The results of a short-circuit study are used to verify if the existing protection system is adequate when a WPP is connected to the grid, and need for strengthening of the grid at WPP point of interconnection.

Power Systems Stability Study

The objective of a stability study is to determine the response of the system to a variety of disturbances. There are two types of studies. The transient stability study examines rotor angle swing in response to large disturbances, while the dynamic stability study examines responses to small disturbances.

In the power systems world, stability is a complex concept that involves variability of load, and responsiveness of generators and the protection system. All elements (loads, generators, transformers, transmission lines, and compensation devices) of a grid are protected with switch gears. The purpose of switch gears is to disconnect the element it is protecting from the grid in case the state variables (voltage, frequency, current) in the grid are out of the safe operating range of the element. After a disturbance on the grid, various scenarios may play out. The generators in the grid may respond in ways that enable the grid to reach a stable end state without disconnecting any element, or the protection system disconnects elements and enables the grid to reach an end state that is stable. The grid is considered stable only in the first scenario. In the second, the grid topology is changed, that is, one or more elements of the grid (loads or generators) are disconnected in order to reach a stable end state. It is important to note that the end state is always stable, even if a disturbance causes large oscillations in the system. The reason is large oscillations will trigger protection elements to disconnect a variety of element until stability is reached and in the worst case the entire system will collapse (which is a stable end state). In short, only the pre-disturbance state is labeled "stable" or "unstable."

It is important to note that power system stability refers to the starting state of the grid before the disturbance, and not the end state (which is always stable). A power system is considered stable if all the loads and generators stay connected after the disturbance. The implication is that the state variables must stay in an acceptable range such that protective relays are not triggered and loads and generators stay connected. A grid configuration is considered unstable if a disturbance leads to tripping

of protective relays and therefore disconnection of load or generator in order to reach a stable state. So although the end state is stable, the grid started in an unstable state (Slootweg and King 2005) [15].

Transient Stability

Large disturbances in power systems are caused by variety of events, for example sudden loss of a generator or load, or fault on a transmission line. The impact of such disturbances is analyzed in transient stability study.

A transient stability study models all the elements of a power system, the control systems of the generators, and the relay settings of protection systems. In addition, various scenarios are simulated that are related to: (i) types of disturbance—single phase to ground fault, three phase to ground fault, loss of synchronous generator, loss of WPP, and loss of load in proximity to point of interconnection of WPP; and (ii) levels of wind generation and load—high wind and low load, high wind and high load, and others.

The wind integration transient stability study determines if introduction of WPP in the grid will cause the frequency to dip below the limit set in grid code, and the length of time for the frequency to recover is longer than specified in grid code.

Disturbance events cause an imbalance in supply and demand, which must be corrected by frequency control. Frequency control is accomplished most often by adjusting the output of generators (supply) and in rare occasions by adjusting demand. There are three types of frequency control based on timeframe:

(i) *Inertial response.* This covers milliseconds to a few seconds response of synchronous generators on the grid. As the name implies, the rotating inertia of the moving mass in the turbine transfers its stored energy to the generator.
(ii) *Governor response.* This is also called the primary response and has a duration of 1 second to tenths of seconds in which the governors of generators incrementally opens or closes valves to consume more or less fuel on the turbine side and therefore generates more or less electrical energy in order to reduce the imbalance in supply and demand. It is important to note that not all generators have governors.
(iii) *Automatic generator control (AGC) response.* This is also called the secondary response. This covers tenths of seconds to several minutes in which AGC issues commands to generators based on control logic.
(iv) *Reserve deployment and reserve restoration by dispatch center.* This is also called the tertiary response. This covers a few minutes to tenths of minutes during which the system operations center sends dispatch instructions to spinning reserves.

The first three responses are automated: inertial and governor responses are autonomous actions of generators, while AGC is automated response of control logic. The fourth response is manual.

Before WPPs are introduced in a grid, transient stability study is performed to understand the response of the grid to large disturbances. At a high level, the following forces are in play:

(i) Traditionally, wind generators do not contribute to inertial response and governor response, in general. Some WTG manufacturers offer these services as add-ons, however most grid codes do not require it.
(ii) With WPPs in the grid, and low load and high wind scenarios, some of the synchronous generators are not committed in the unit commitment process. This causes a reduction in system inertia and reduction in governor response. In addition to de-committing, some synchronous generators are dispatched at lower power levels in the economic dispatch process, which provide more "headroom" for governor response.
(iii) Lower inertia causes the grid frequency to dip faster in response to a disturbance, and to reach a lower minimum. While the governor response leads to a faster recovery of the frequency because there is more headroom.
(iv) Low-voltage ride through capability of the WTGs should enable the WPPs to stay connected to the grid in response to a transient disturbance, thereby preventing cascading failure.

Dynamic Stability or Small Signal Stability

The impact of small disturbances in the grid is analyzed using dynamic stability studies. As opposed transient studies that are modeled in the time-domain, dynamic studies are modeled in the frequency domain. A power system experiences change in load moment-by-moment. With WPPs in the grid, there is an increase in the variability and uncertainty of net load (demand load – WPP production). The amount of increase is a function of the penetration of wind in the grid. These changes in net load introduce oscillations in frequency, voltage, and other variables. The grid responds to these disturbances using the same three methods described in the transient stability section—inertial response, governor response, and AGC response.

The key to a dynamic stability study is to examine the damping of oscillations caused by small changes in net load and the subsequent response of the other generators on the grid. In a WPP grid integration study, a variety of disturbances are simulated like net load variability, to determine if introduction of WPP in the grid will cause significant changes to the damping of oscillations.

APPENDIX II: CHECKLIST FOR REQUIREMENTS FOR INTERCONNECTING VARIABLE GENERATION

A grid code for connecting wind plants is the rulebook that specifies the minimum technical criteria that all wind farms seeking connection to the grid shall satisfy at the point of interconnection (POI), and the operating conditions that all wind farms shall comply with for safe and reliable operations of the grid. Some grid codes separate the code into two sections, the connection code and the operating code. Table A1 contains the topics that a grid code should cover for completeness.

Wind energy penetration is likely to increase in the future, therefore, it is imperative for the grid operators and electricity regulators to formulate a grid code that can meet future requirements. Since it is difficult to predict future technological advancements, a process should be established to review and update the grid codes on a regular basis.

Table A1: Requirements for Interconnecting Wind Power Plants to a Grid

Requirement	Features
Voltage and Frequency Ranges	Specifies the deviation in voltage and frequency that a wind plant must be able to withstand at the point of interconnection (POI). The capability to tolerate deviations is specified for both normal and abnormal operating conditions.
Active and Reactive Power Requirements	Specifies the capability of a wind power plant (WPP) to deliver active power within specified power factor range, both leading and lagging, at the POI.
Active and Reactive Power Control	This is an advanced feature applicable to grids with large variable energy penetration. It specifies the capability of WPP to limit (to a set point or to limit ramp up or down) active and reactive power production in response to signal from system operator.
Power Quality Requirements	Specifies the limits on quality parameters like voltage fluctuations, flicker, and harmonics.
Fault Ride through Requirements	Specifies the capability that WPPs should possess in order to ride through a low voltage fault on the grid.
Protection Requirements	WPP is responsible for protecting its equipment from faults in the grid. It also specifies the situations in and duration for which WPP should stay connected.
Metering; Supervisory Control and Data Acquisition Requirements	Specifies the location of installation and properties of the revenue meter.
	Specifies the data elements that must be exchanged between the WPP and system operators.
	Specifies the technical documentation of wind turbines, transformers, protection systems, and other features of the WPP.
Documentation of Facility and Inspection Requirements	Specifies the procedure for inspection and certification of the POI.
Forecasting Requirements	Specifies the frequency, duration, and resolution of wind energy forecasts.
	Specifies the frequency, duration, and resolution of wind energy forecasts.

Source: Jain. 2010.

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Grid Integration of Wind Power

Best Practices for Emerging Wind Markets

Issues with grid integration of wind energy has led to curtailment of wind power, delay in interconnection for commissioned wind projects and/or denial of generation permit. This report describes the impact of wind power on the grid, methods to analyze the impact and approaches to mitigate the impact. Countries like Denmark, Germany, Spain, and regions within the United States like Texas and Colorado have achieved high penetration of wind energy with modest changes to the grid. The key to high penetration of wind energy has been flexible grids. The report outlines the lessons learned with a focus on applicability to emerging wind energy markets.

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