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Framework paper

Managing large scale penetration of intermittent renewables

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Abstract

All power generation technologies leave their particular imprint on the power system that they belong to. Wind and solar power have only recently reached significant levels of penetration in some countries, but they are expected to grow much during the next few decades, and contribute substantially to meeting future electricity demand. Wind, photovoltaic (PV) solar and concentrated solar power (CSP) with no storage have limited-controllable variability, partial unpredictability and locational dependency. These attributes make an analysis of their impacts on power system operation and design particularly interesting.

This paper examines how a strong presence of intermittent renewable generation will change how future power systems are planned, operated and controlled. The change is already noticeable in countries that currently have a large penetration of wind and solar production. The mix of generation technologies, and potentially market rules, will have to adapt to accommodate this presence. Regulatory adjustments might be needed to attract investment in "well adapted" technologies. Distribution and transmission networks will be also profoundly influenced. This paper identifies open issues that deserve further analysis from a technical, economic and regulatory perspective.

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1. Introduction

Several factors –climate change and other environmental considerations, energy security, anticipated limits in the availability of fossil fuels and a greater emphasis on the utilization of local resources– indicate a shift toward a much stronger presence of renewable sources in the mix of technologies for electricity production, both in the United States and elsewhere. While estimates vary widely amongst competent organizations that have analyzed this topic, published results from these groups all suggest that renewables will play an increasingly significant role in the future[2].

At the end of 2009, wind and solar power accounted for slightly less than 2% of total electricity production in the US, and about 2% (0.02% solar) worldwide. However, the penetration of these technologies could increase significantly in the next decades. World wind production has doubled in the last three years. In the US, almost 10 GW of new wind capacity came online in 2009, making the US the world leader in absolute terms[3]. As shown in Table 1, the level of wind power penetration is already significant in countries like Denmark, Spain and Portugal, Germany and the Republic of Ireland. In the case of solar, countries like Germany, Spain and Japan are taking the lead in the installation of new PV capacity.

Country	Wind capacity (MW)	% demand	PV capacity (MW)
Denmark	3,480	19.3%	4
Portugal	3,616	15.0%	102
Spain	19,149	14.4%	3,523
Ireland	1,264	10.5%	NA
Germany	25,777	6.5%	9,845
Italy	4,850	2.1%	1,181
US	35,086	1.9%	1,641
Japan	2,056	0.4%	2,627

Table 1: Worldwide installed capacity of renewable intermittent generation by 2009. Sources: (IEA Wind, 2010) & (IEA-PVPS, 2010).

Recent studies have examined penetration levels as large as 20% by 2030 in the US. Meanwhile, the European Union has set a 20% target for primary energy consumption to come from renewable resources. This level of penetration is projected to represent about 35% of the total European electricity supply, where wind will play a major role and contribute more than one third to the total renewable electricity supply (IEA Wind, 2010). The IEA estimates that nearly 50% of global electricity supplies will have to come from renewable energy sources in order to achieve a 50% reduction of global CO_2 emissions by 2050 (this is the CO_2 target discussed by G8 leaders in Heiligendamm, and endorsed at the recent Hokkaido Summit).

[2] For an international perspective, see IEA 2010 World Energy Outlook. In the US, the Department of Energy, NERC and other organizations, motivated by existing or anticipated policy measures, have also commissioned several reports exploring the potential impacts of high levels of renewable penetration in the electricity generation mix.

[3] At the national scale, the US has had far less development when compared to other countries. However, on a regional scale, wind development has been important in California, Texas (about 10GW), and some Midwestern states, like Iowa (about 3.6GW).

Wind, and to a lesser scale solar –both photovoltaic (PV) and concentrated solar power (CSP)– will likely play a significant role for electricity production within the next two decades. Those countries with substantial volumes of wind or solar penetration are already experiencing noticeable impacts on the operation and economics of their power systems. It is within this context that this paper will evaluate the potential effects of large volumes of wind and solar generation on the utilization of natural gas for electricity.

Large scale penetration of intermittent renewables is expected to have profound implications on many aspects of power systems planning, operation and control, as well as on the corresponding regulation. These issues have been examined from different perspectives and there is already a significant amount of literature on this topic. Most of it is about the statement of the challenges and the enumeration of open issues, but also on the description of a diversity of experiences in dealing with intermittent generation, and some detailed analyses on specific issues. A sample of relevant documents includes (Holttinen H. , et al., 2009), (EWEA, 2005), (EWEA, 2009), (EURELECTRIC, 2010), (TradeWind, 2009), (IEA Wind, 2010), (IEA-PVPS, 2010), (ESB International, 2008), (DOE EERE , 2008), (NERC, 2009), (Charles River Associates, 2010), (EnerNex, 2010), (GE Energy, 2010), (GE Energy, EnerNex, AWS Truepower, 2010), (NYISO, 2010), (Xcel Energy, 2008), and (GE Energy, 2010). The final report (Holttinen H. , et al., 2009) of the International Energy Agency Task 25 on "Design and operation of power systems with large amounts of wind power" contains a summary of selected, recently concluded studies of wind integration impacts from participating countries.

This paper will refer frequently to the existing literature, but it is not meant to be a review paper in the strict sense. The objective of the paper is to present the major open issues that have been identified along with the major power system functions, and to classify them in a logic fashion to facilitate an orderly discussion. Some new ideas –or at least some new perspectives on well-known topics– will be introduced. The emphasis will be more on the regulatory than on the technical side.

This paper will not question the basic premise that a large penetration of intermittent renewable sources of electricity generation will take place in existing power systems over the next two decades and further. The drivers for this change could be varied, but they will not be disputed here[4]. Instead, the paper will examine the implications on capacity expansion, operation and control of power systems and the technical and (mostly) regulatory measures that will be needed to successfully integrate these new technologies in an efficient and secure manner.

When talking about "intermittent"[5] renewable generation, the paper will mean "wind" much more often that "solar," and more specifically, solar PV or concentrated solar power (CSP) with no storage. This is a consequence of the much higher present level of knowledge on wind, because of its much higher level of deployment.

The paper starts with section 2 that describes intermittency characteristics for both wind and solar. It also provides a general overview of the expected effects of penetration of intermittent generation on power systems. Section 3 specifically reviews the most relevant issues on the

[4] However, we shall discuss whether the claimed environmental benefits do materialize when detailed implementation is examined in a variety of contexts.

[5] Intermittent is admittedly an inadequate term, since the outputs of wind and solar generators do not oscillate between on and off states. Because of lack of a better name, "intermittent" is used here to comprise both non-controllable variability and partial unpredictability.

operation of power systems and the needed requirements to accommodate a large volume of intermittent renewable generation in a relatively short period of time. Section 4 explores the impacts on a longer timescale where, depending on the regulatory framework, a high penetration of intermittent generation will impact the future generation technology mix. Section 5 examines the implications on transmission network expansion and bulk power system operation. Similarly, Section 6 reviews the impacts on distribution network expansion and distribution system operation. Finally, Section 7 finishes with a list of open issues that require further consideration and research regarding how to best manage the penetration of intermittent generation in future power systems at large scale.

2. Overview of expected impacts of intermittent generation

This section examines in detail what intermittency means for both wind and solar PV generators. Next, a classification is presented of the different power system functions that are substantially impacted by high levels of intermittent generation.

2.1. Intermittency characteristics of wind and solar electricity generation

Wind and solar generation are both intermittent. Intermittency comprises two separate elements: limited-controllable variability and partial unpredictability. Note that the output of a plant could conceptually exhibit much variability, while being 100% predictable. Conversely, it could also be very steady, but unpredictable. Although the output of any actual power plant is variable and unpredictable to a certain point, wind and solar generation have these characteristics in a degree that justifies the qualification of "intermittent". Without storage, limited-controllable variability implies a likelihood that an individual plant could be unavailable when needed that is significantly higher than in conventional plants. This adverse feature is reduced when multiple plants are considered over a widespread region with sufficient transmission interconnection. Solar power has the obvious advantage of being mostly coincidental with the periods of high electricity demand, while wind production may happen at any time and, as reported in some systems, predominantly at night, when demand is lowest. Both wind and solar generation have virtually no variable operating costs.

Variability and uncertainty are familiar to the electric power industry. Demand levels, hydro inflows and failures of generation units and network facilities are uncertain. System operators have developed approaches to cope with prediction errors such as these, while still meeting the load reliably. Intermittent generation also adds new challenges to system operation and capacity expansion of power systems (these issues are discussed later in the paper).

Wind generation is variable over time, due to the fluctuations of wind speed. However, the output variability of a single wind plant is different from the variability of many wind plants dispersed over a geographic area. As noted in (Holttinen H. , et al., 2009) and (NERC, 2009), the variability of wind decreases as the number of turbines and wind power plants distributed over the area increase. Figure 1 shows an example of the variability of wind for a single wind turbine, several wind turbines and all wind turbines in a country. The variability of wind generation also decreases with spatial aggregation[6]. Wind energy output over larger geographic areas has less variability than the output of a single wind power plant.

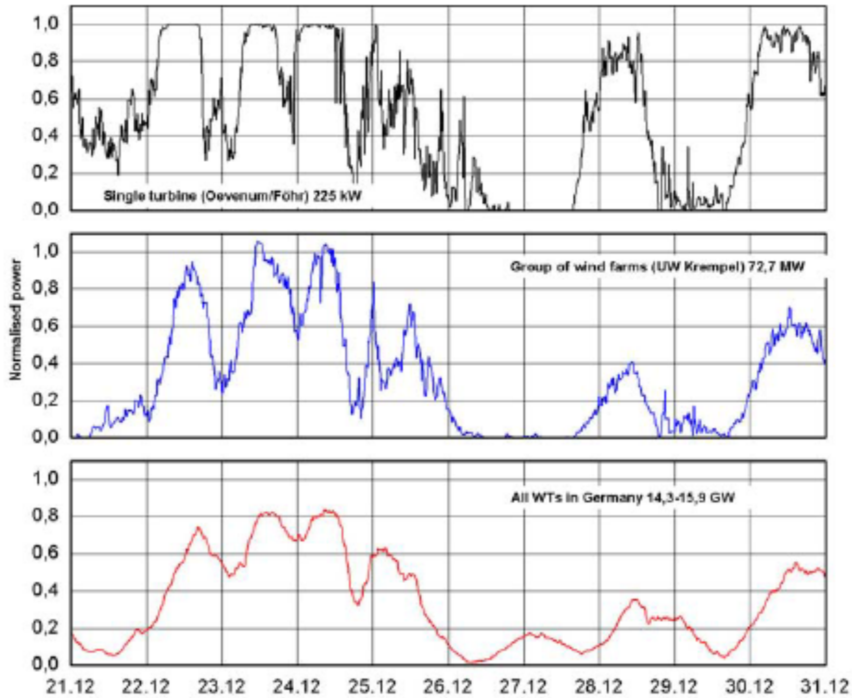

Figure 1: Sample of wind power output for a single wind turbine, and for a group of wind plants in Germany. Source: (Holttinen H. , et al., 2009).

Some illustrative statistics can be found in (EURELECTRIC, 2010): on average, only 4% (2.5% in Spain, 5.5% in Germany) of the total wind installed capacity has a probability of 95% of being present at all times, which is a similar level of availability in conventional power plants. On average, the expected working rate of wind capacity has a 90% probability of oscillating between 4% and 55%, with an average load factor (again in Germany and Spain) of 22%. These figures are very much system dependent.

In addition to wind's highly variable output, predicting this output is difficult—much more so than predicting the output of conventional generators or load. Experience shows that deviations in predictions of wind output decrease with proximity to real time and spatial aggregation. Load predictions made 24-36 hours ahead are fairly accurate. This is not true for wind predictions. Generally, only very near-term wind predictions are highly accurate (Xie, et al., 2011). In particular, the error for 1- to 2-hour ahead single plant forecasts can be about 5-7%; for day-ahead forecasts, the error increases up to 20% (Milligan, et al., 2009). This trend can be seen in Figure 2 (from REE, the Spanish transmission system operator), where clearly wind forecast error decreases as predictions approach to real time (EURELECTRIC, 2010). The picture also shows the improvement of forecast techniques over the years.

[6] This effect is explained because normally, the correlation between wind speeds at two different locations decreases with their distance. As wind speeds with varied correlations feed wind farms, their overall wind output generation will have much less variability. Thus, the geographical dispersion of wind farms has a beneficial smoothing effect on wind power variations.

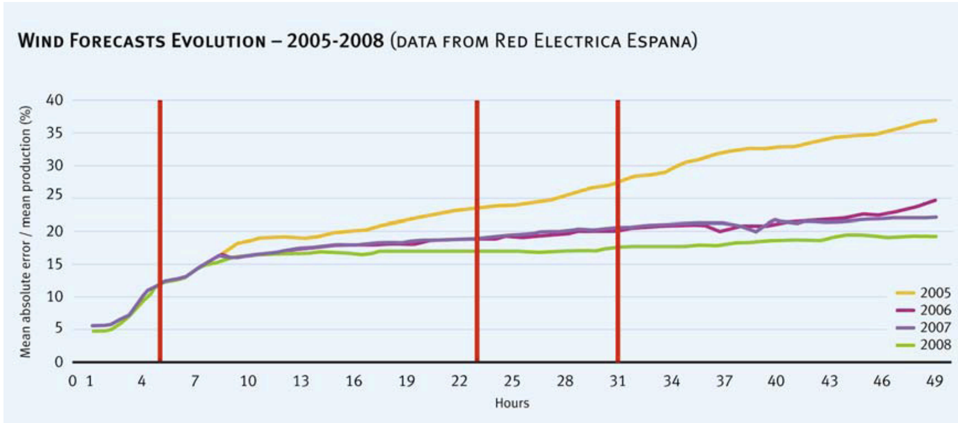

Figure 2: Evolution of the wind forecast error, as a percentage of wind production, as a function to the distance to real time. Source: (EURELECTRIC, 2010).

Similar to variability, spatial aggregation greatly reduces forecast errors. As seen in Figure 3, the level of accuracy improves when considering predictions for larger geographic areas. The aggregation over a 750-km region reduces forecasting error by about 50% (Holttinen H. , et al., 2009).

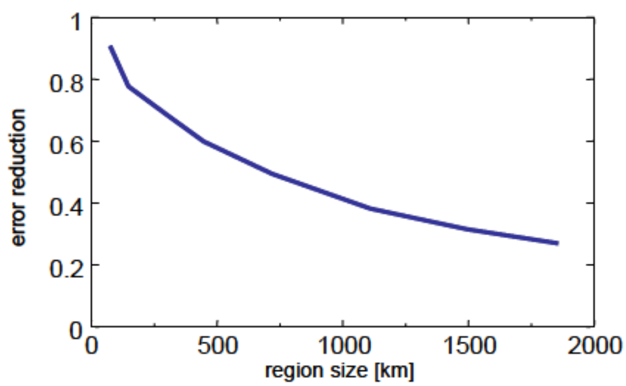

Figure 3: Decrease of the wind forecast error for aggregated wind power production due to spatial smoothing effects. Error reduction = ratio between rmse (root-mean-square error) of regional prediction and rmse of single site, based on results of measured power production of 40 wind farms in Germany. Source: (Holttinen H. , et al., 2009).

The intermittency of wind generation demands a flexible response of the power system, including making use of operating reserves, the use of advanced wind forecasting techniques and some changes in market rules to shorten the scheduling times (NERC, 2009). These issues will be discussed in detail in the following sections.

In general, solar power is characterized by a diurnal and seasonal pattern, where peak output usually occurs in the middle of the day and in the summer. This particular pattern makes solar power well correlated with the peak demand of many electric power systems (Mills, et al., 2009). Despite this beneficial characteristic, solar energy output –like wind– is still characterized as variable and uncertain. On one hand, the sun position impacts the output of PV plants due to its changing behavior throughout the day and seasons. On the other hand, clouds can rapidly change the PV power outputs.

Due to the lack of thermal or mechanical inertia in PV systems, rapid changes have been observed in the output of PV plants. For example, the output of multi-MW PV plants in the Southwest U.S.

(Nevada and Arizona) was reported to have variations of +/- 50% in a 30-to-90 second timeframe and +/- 70% in a timeframe of 5-to-10 minutes on partly-cloudy days (NERC, 2009). Figure 4 shows the output variability of PV plants located in Nevada on a sunny and partly-cloudy day, respectively.

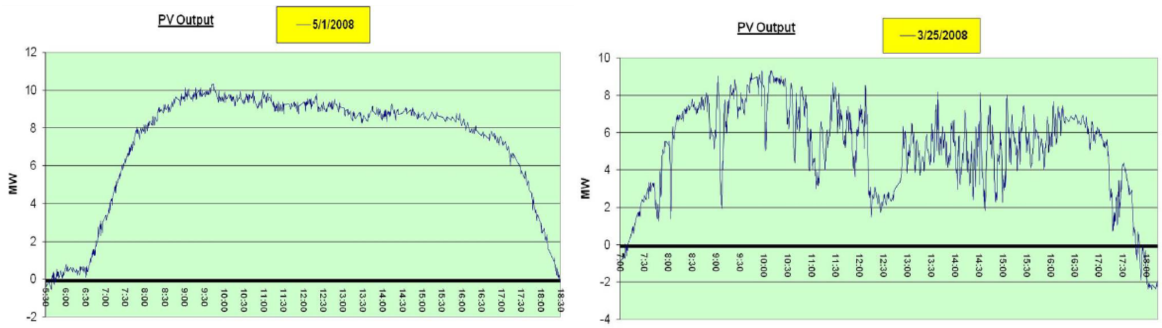

Figure 4: PV plant output located in Nevada on a sunny day (left) and on a partly-cloudy day (right) - Sampling time 10 seconds. Source: (NERC, 2009).

Although the ramping characteristics are fast for PV plants, the time it takes for a passing cloud to shade an entire PV system depends on factors such as the PV system size, cloud speed, and cloud height, among others. Therefore, for large PV systems with a rated capacity of 100 MW, the time it takes to shade the entire system will be on the order of minutes, not seconds. (Mills, et al., 2009).

Spatial diversity, as with wind, can mitigate some of this variability by significantly reducing the magnitude of extreme changes in aggregated PV output, as well as the resources and costs required to accommodate the variability. Either the aggregation of the output of separate PV panels within a plant, or the aggregation of the output of several separate PV plants at different locations helps to smooth the variability of the overall solar energy output (see Figure 5 for an illustration of this effect).

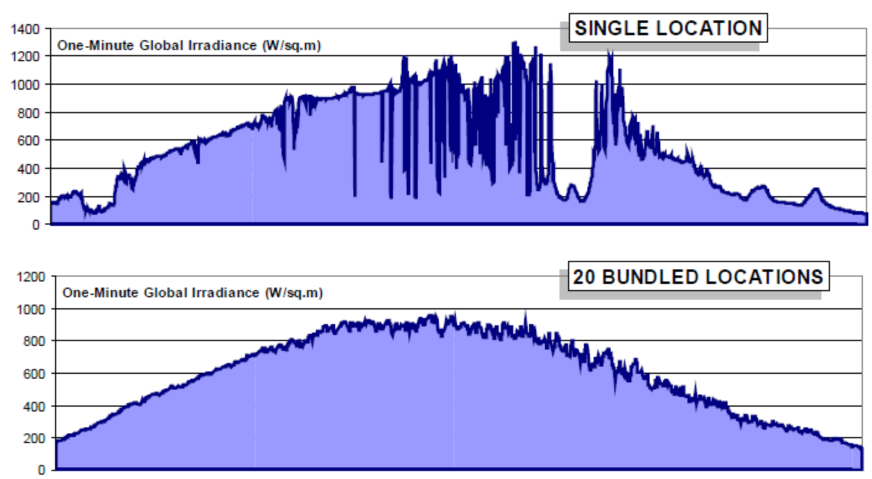

Figure 5: One-minute irradiance and variability at one single location in the network & from 20 bundled stations. Source: (Hoff, Perez, Ross, & Taylor, 2008)

Clearly, clouds are the main factor in solar forecast. Short-term PV forecasts are supported by satellite images that can predict the impact of clouds on PV output. Compared to wind energy, PV solar output is generally more predictable due to low forecast errors on clear days, and the ability to use satellite data to monitor the direction and speed of approaching clouds. For longer time scales, numerical weather models should be used to predict solar insolation out to multiple days (Mills, et al., 2009).

The system-wide smoothing effect for both wind and solar is contingent upon having enough transmission capacity in the system to pool wind and solar resources across varied geographic areas. A large body of experience with, and analysis of, wind energy demonstrates that this geographic smoothing over short time scales results in only a modest increase in the operating reserves required to manage the short-term variability of wind energy.

Finally, we need to stress the importance of accuracy in wind and solar forecast for the efficient and reliable operation of power systems. As indicated in (GE Energy, 2010), large forecast errors may compromise reliability, increase operating costs, and require greater ancillary service procurement. In particular, large wind over-forecasts can lead to under-commitment of flexible generation units resulting in contingency reserve shortfalls, while severe under-forecasts can result in wind curtailment.

2.2. Taxonomy of impacts

In a vertically integrated electric power industry, the complete decision making process is organized in a hierarchical fashion with multiple couplings. Longer-term decisions –such as capacity expansion of generation or transmission– "trickle down", providing targets and information to shorter-term decisions, see Figure 6. In power systems open to competition, as it is the case in most of the US and many countries of the world, most of these decisions are made by multiple agents in a decentralized fashion, therefore replacing centrally coordinated plans of capacity expansion or operation by the individual decisions of multiple agents driven by market forces. In general the generation activity can be open to competition, while the networks remain a regulated monopoly.

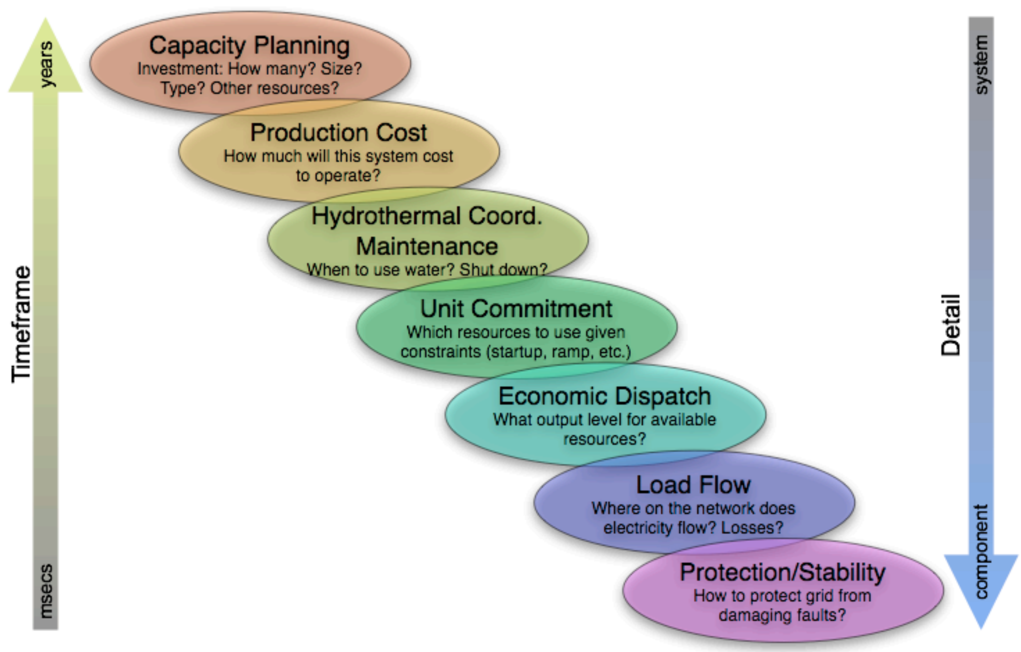

Figure 6: Hierarchical decision-making process in power systems. Source: Bryan Palmintier MIT's doctoral thesis (in preparation).

The effects of penetration of intermittent generation will affect decisions made at all timescales and across geographic regions differently. Figure 7, adapted from IEA Wind Task 25 (Holttinen H. , et al., 2009), tries to capture both of these dimensions and highlights the anticipated major areas of impact.

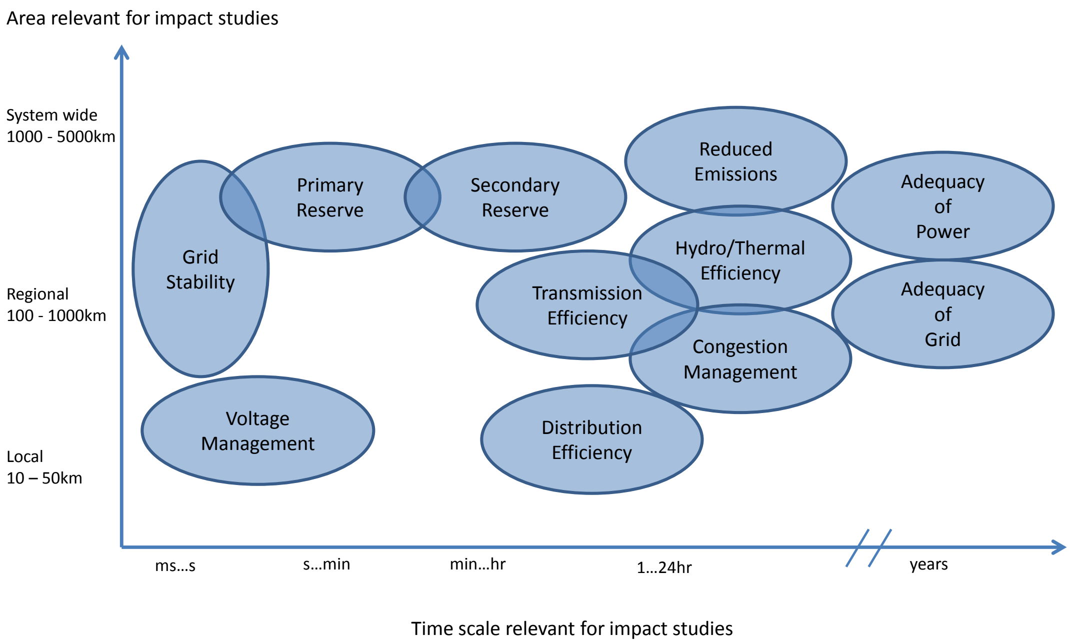

Figure 7: Impacts of wind power on power systems, divided into different time scales and size of area relevant for impact studies. Source: Adapted from (Holttinen H. , et al., 2009).

From a reliability perspective, see (NERC, 2009), different timeframes should also be considered when looking at the impacts of large-scale penetration of intermittent renewable generation on the planning and operation of power systems. From the seconds-to-minutes timeframe, system reliability is mostly controlled by automatic equipment and control systems. From the minutes through one-week timeframe, operators and operational planners need to commit and dispatch generators to maintain reliability through normal conditions, as well as contingencies and disturbances. For longer timeframes, system planners must ensure that existing transmission and generation facilities are adequate to keep a reliable operation of the system.

The addition of intermittent renewable generation will bring about a variable and only partly predictable source of power generation, with zero variable costs, to a power system that has to balance generation and varying demand at all times. At high levels of penetration, the characteristics of the bulk power system can be significantly altered. These changes need to be considered and accommodated into the current planning and operation processes, which were not designed to incorporate large volumes of intermittent generation. Multiple new issues must be addressed, ranging from increasing power system flexibility by a better utilization of transmission capacity with neighboring areas, to demand side management and optimal use of storage (e.g. pumping hydro or thermal), or changes in market rules to schedule the plants closer to real time. The future mix of generation technologies will have to accommodate the strong presence of intermittent generation and be able to cope with more cycling, fewer hours of operation and different patterns of electricity prices.

Inexpensive storage, at scale, represents the most straightforward way to deal with these issues. However, storage at the low cost and large scale needed will take some time. In the interim – which will likely be at the decadal scale– other sources of flexibility will be needed.

The review of topics in this paper is organized into three major blocks. We shall start examining the impact on operation of the generation plants, leaving the network aside for the moment, since this will allow understanding better the basic trade-offs that central system planners (under traditional regulation) or private investors of generation assets (under competitive market conditions) will have to deal with. Still under operation we have to distinguish the more technical security analysis of the power system –those that simulate stressful conditions for the power system, in terms of possible loss of stability, exceed voltage or transmission stability limits–, from the mostly economic functions –although limited by security constraints– that allow to make efficient utilization of the generation units to meet demand. Then we shall look into generation capacity expansion and also network issues.

Intermittent renewable generation and power system models

Suitable power system models are needed to capture the specifics of intermittent generation and evaluate its impact on planning and operation of the power system. From the generation perspective, these models should be able to represent: a) the economic merit order of the different technologies; b) how the diversity of their fixed and variable costs makes them more suitable to cover different levels and durations of demand; c) a prescribed margin of installed firm generation capacity over estimated peak demand (the investment adequacy requirement), including the contribution –the so called capacity credit– of intermittent generation; d) a specified quantity of operating reserves that will somehow depend on the volume and characteristics of intermittent generation, again including the stochastic nature of intermittent generation and any spatial and temporal correlations of production and demand; e) the chronological aspects and inter-temporal links in a realistic scheduling of the generating plants, including wind or solar curtailments and cycling –including shut downs and start-ups– of thermal plants and their associated costs and emissions. Network models are very much needed for transmission planning and to evaluate the remuneration of distribution networks with embedded distributed generation, see sections 5 and 6 of the paper.

Sound computer models that can provide a comprehensive appraisal of the economic, environmental and reliability implications of different levels of significant penetration of intermittent generation in power systems –such as the estimation of future electricity prices, levels of fuel consumption or reliability measures– should be a central piece in the design of energy policies that contemplate mandating large amounts of solar or wind generation. Dedicated efforts to expand or develop the sophisticated computation models that are needed for this task appear to be well justified.

Two relevant subjects that are transversal to all the topics covered in this paper will be mentioned next: power system models and the impact of the format of the adopted regulatory instrument to economically support intermittent renewable generation.

The influence of the adopted regulatory instrument to support renewable generation

Numerous regulatory issues are raised by the massive introduction of intermittent renewable generation in electric power systems. Foremost among them is the specific support scheme that is adopted to make wind or solar generation financially viable. Most of the discussion on the support schemes has been on their performance regarding the volume and the cost of the achieved investments in renewable generation: Some regulatory authorities prefer price mechanisms (i.e. feed-in tariffs, feed-in premiums, or tax incentives) while other consider that quantity mechanisms (i.e. renewable portfolio standards or tradable green certificates) are a better choice. However, these support instruments have also often profound implications on the behavior of the renewable plants in the operation of the power system and the electricity markets.

One example may suffice to illustrate this point. Feed-in premiums, FiPs, are paid to renewable producers as a fixed amount in $/MWh in addition to the electricity market price. FiPs are currently seen as beneficial for the efficiency of the system operation, since the premium plus market signals create incentives for the wind or solar plants to adjust their production according to the market conditions, and to improve the prediction of their output and the management of the maintenance activities. Experience has shown that exposing renewable producers to the cost of imbalances improves significantly their ability to predict their output in the short-term, leading to a significant decrease of the cost of imbalances for the entire system. But, at the same time, FiPs also create the incentive to integrate renewable generation with conventional thermal generation in the large portfolios of the incumbent utilities. They can exploit their own flexibility to solve internally any imbalances, reducing liquidity in the balancing market and thus setting an entry barrier for potential competitors in the intermittent renewable business. Wind and solar become additional inframarginal capacity within these large portfolios, thus increasing any market power that they might have. This example shows that the implications of the renewable support mechanisms have to be examined along the complete chain of capacity expansion, operation and control.

3. Impacts on power system operation

As shown in Figure 7, system operation encompasses a diversity of time spans. Common to all system operation functions is that the installed capacity is given and the decisions to be made only include how to operate the generation plants. This section focuses on several salient issues: the need for more operational flexibility in the generation resources; negative impacts on the operation of conventional thermal power plants; the need for additional operation reserves; the need for integration of balancing areas and enhancement of balancing markets; the need for support from and interaction with demand response, storage technologies and electric vehicles; the effect on operation cost and market prices; the impact of application of priority rules and the potential influence of the presence of wind and solar PV plants on power system stability.

3.1. The need for flexibility in system operation

Both the variability and uncertainty of intermittent renewable generation sources ask for more flexibility of the generation portfolio and in the operation of the power system, including the design and utilization of transmission and distribution networks.

System operators need to have generation, demand resources, or any other form of flexibility in the power system ready to respond whenever ramping and dispatchable capabilities are needed; for example, during morning demand pickup or evening demand drop-off time periods (NERC, 2009).

The power system needs more flexibility to handle the short-term effects of increasing levels of wind. The amount of flexibility will depend on how much wind power capacity is currently installed, and also on how much flexibility already exists in the considered bulk power system

(Parsons & Ela, 2008). Even with perfect forecasting, wind generation will remain variable, for instance from one hour to the next, and for this reason additional flexibility is required.

The impact of wind and solar generation on the operation of a power system can be better understood, in a first approximation and for the hourly to daily time range, by examining the changes in production levels of all technologies that take place when the output of these two intermittent technologies is modified with respect to some reference case. In principle, more wind and solar production at zero variable cost will result in less generation from other technologies. However, the share of reduction for each technology will not be the same. More wind or solar production means less production with the plants that are at the margin. Except for those non-frequent hours when peaking units are needed –typically open cycle gas turbines, OCGT– the plants at the margin for high levels of demand will be combined cycle gas turbines, CCGT, or less efficient coal plants, depending on the technology mix in the considered system, the respective prices of coal and gas and the future price of CO_2, in those systems that apply it. Obviously the impacts of wind and solar on the technologies at the margin will be different, because of the different temporal patterns of each one, within the day and also seasonally.

As an example, Figure 8 and Figure 9 show the impact of different levels of penetration of wind and solar generation (concentrated solar power, CSP, with no storage) in a 2030 projected generation portfolio. See (MIT, 2010) for details on modeling and assumptions. The three illustrations in Figure 8 give the results for varying levels of wind generation: the reference case, which is a *hypothetical representative day for ERCOT in 2030*, and other two cases with half and twice the amount of wind generation as in the reference case. Note that, in the base case, the night-time load (roughly hours 01-04) is met by nuclear and coal base load plus wind generation. There is no appreciable output from gas between hours 01-04 because it has higher variable costs than nuclear and coal, so gas gets dispatched last. Natural gas also has the flexibility to cycle. In hours 05 through 23, when overall demand increases during the early morning and decreases in the late evening, NGCC generation adjusts to match the differences in demand. In the picture, when less wind is dispatched, the natural gas combined cycle capacity is more fully employed to meet the demand, and the cycling of these plants is significantly reduced. The base load plants continue to generate at full capacity. In the case with twice as much wind as the base case, natural gas generation is reduced significantly and the gas capacity actually used is forced to cycle completely. Base load coal plants are also forced to cycle because of the relatively low night-time demand.

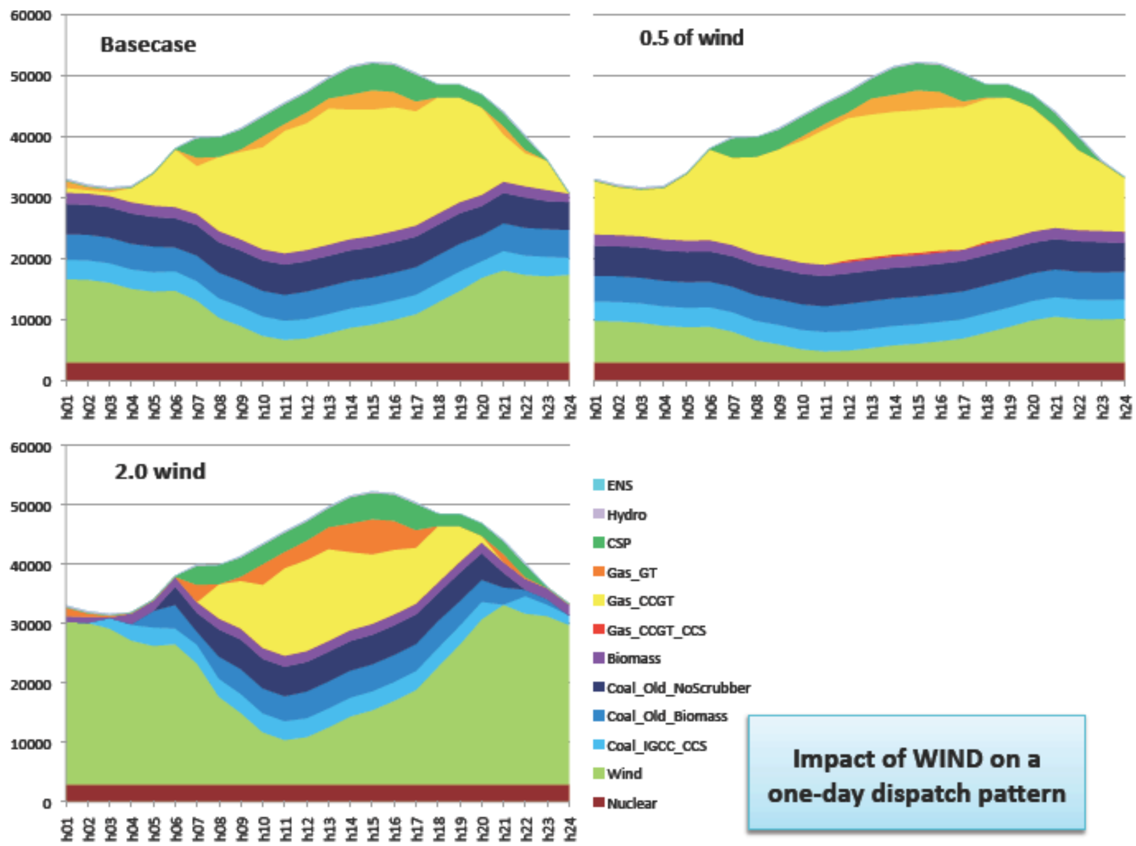

Figure 8: Impact of wind production on one-day hypothetical dispatch pattern for ERCOT in 2030. Source: (MIT, 2010).

The three cases for solar CSP with no storage in Figure 9 follow a similar pattern to Figure 8: a reference case, a case with half as much solar production, and a case with twice the level of solar production. However, there are some differences in the results. Solar generation output basically coincides with the period of high demand, roughly between hours 06 and 22, where the CCGT plants are also dispatched. The natural gas plants are used more when solar output is less. Conversely, when solar is used more, less gas is dispatched. The base load plants are largely unaffected and cycling is not a problem for them, since there is no intermittent solar-based generation during the low-demand night hours.

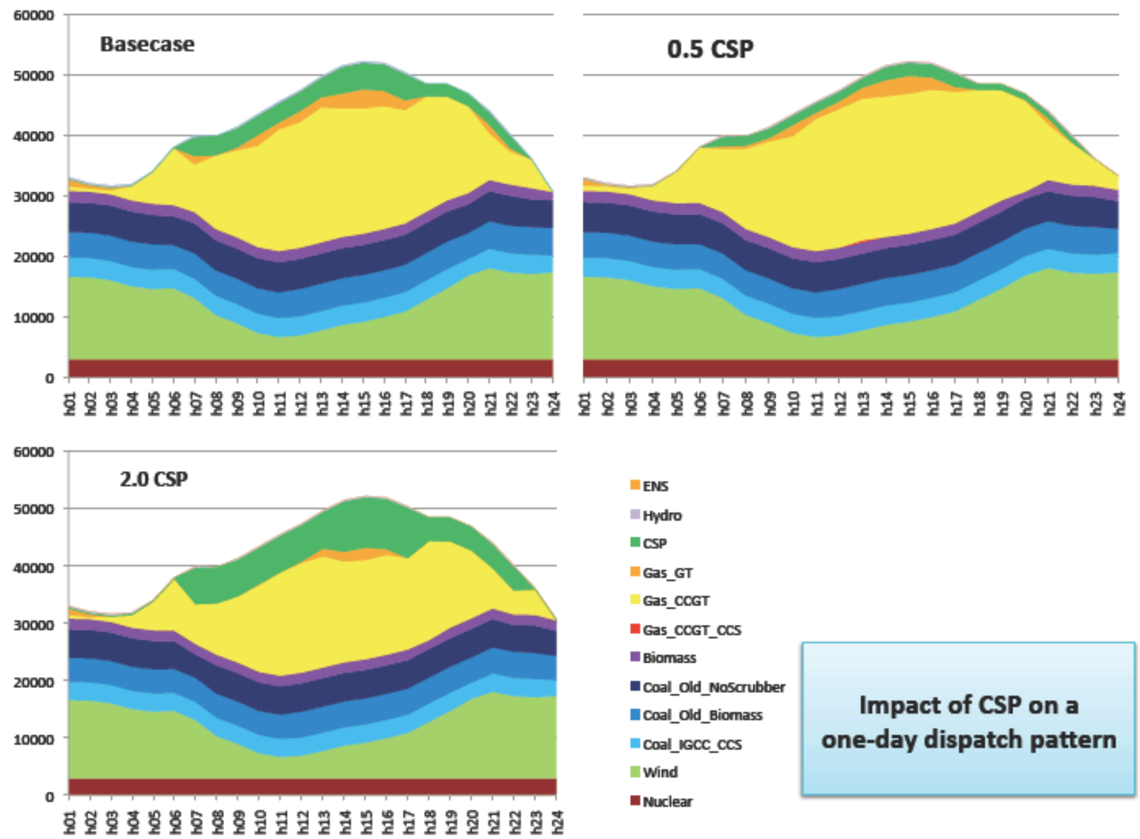

Figure 9: Impact of production of concentrated solar power (CSP) without storage on one-day hypothetical dispatch pattern for ERCOT in 2030. Source: (MIT, 2010).

There are several dimensions in achieving flexibility: a) better use of the flexibility that the existing system has or may have, for instance by changing market rules or by integrating current small balancing areas into larger ones; b) adding new flexible plants to the existing portfolio; c) utilizing flexibility contributions of the intermittent units.

There are different flexibility capabilities that are needed from all the power plants in a system with a strong presence of intermittent generation, corresponding to the different functions in power system operation, and ranging from fast response to frequency disturbances to the capability of shutting down and starting up again frequently. According to (NERC, 2009) these capabilities include: a) ramping of the variable generation (modern wind plants can limit up- and down-ramps), 2) regulating and contingency reserves, 3) reactive power reserves, 4) quick start capability, 5) low minimum generating levels and 6) the ability to frequently cycle the resources' output. Additional sources of system flexibility include the operation of structured markets, shorter market scheduling intervals, demand-side management, reservoir hydro systems and energy storage. System planners and electricity market regulators must ensure that suitable system flexibility is included in future bulk power system designs, as this system flexibility is needed to deal with intermittency on all time scales. It therefore can be said that, as penetration of intermittent resources increase, system planners need to ensure that the added capacity has adequate flexibility to meet the total new flexibility requirements of the system. This is a new design requirement for future systems, and it can be met with local generation, interconnections with other systems or demand resources.

Note that the lack of flexibility of some base-load technologies also imposes a cost to the power system and a burden on the remaining plants, since they are left with the entire responsibility of meeting the always changing demand. For instance, adding more inflexible nuclear capacity in Figures 8 and 9 would also result in increased cycling of coal and CCGT plants.

3.2. Negative unintended consequences

Wind and, especially, solar PV plants can be installed much faster than other generation technologies. When a quick deployment of intermittent generation takes place in an existing system without enough time for the technology mix to adapt to the new situation –power systems require massive capital investments and take decades to adjust to the new technologies and economic conditions– existing plants that were not designed for this amount of cycling and steeper ramps will have to function under quite different operating conditions. This will result in increments in start-ups, operation at sub-optimal levels with losses of efficiency in electricity production, increased ramping duty, additional maintenance costs and a premature deterioration of components of the power plants, shortening their lifetimes and, in general, increasing environmental impact and cost per unit of output. These findings are supported by multiple studies; see, for instance, (Troy, Denny, & O'Malley, 2010) and (Milligan, et al., 2009).

In particular, the operation of base-load CCGT units could be severely impacted. (Troy, Denny, & O'Malley, 2010) shows that wind displaces CCGT units into mid-merit operation, resulting in a much lower capacity factor and more start-ups (see Figure 10). In the case of coal units, it is noted that higher levels of wind also increase start-ups. However, this increment is not as drastic as for CCGTs, because coal plants are higher in the merit order, as the discussion for Figure 8 noted. Similar results are found for the Ireland's electric system under penetration scenarios ranging from 5% up to 30% of total energy requirements (ESB National Grid, 2004) and also in Spain (Alonso, de la Torre, Prieto, Martínez, & Rodríguez, 2008).

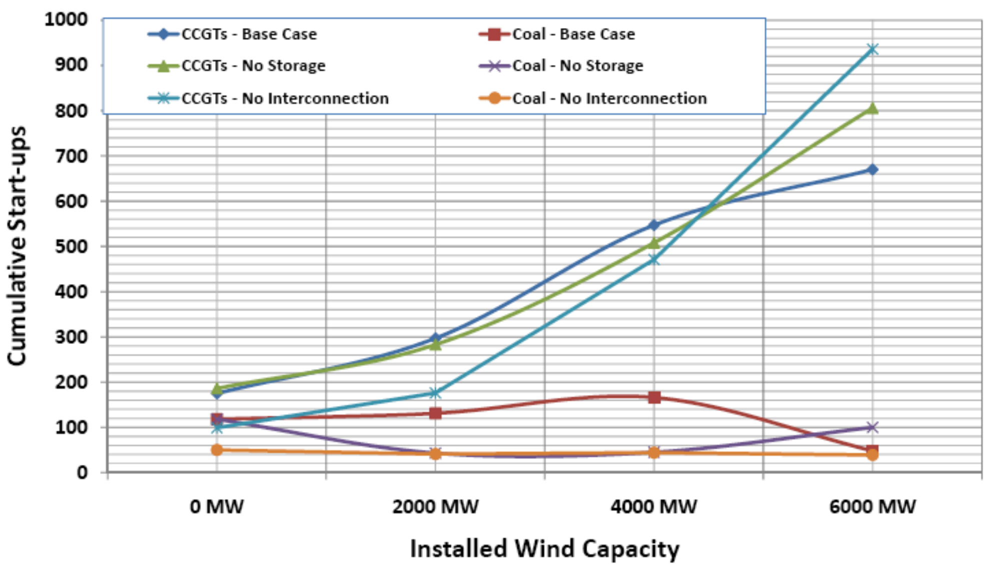

Figure 10: Impact of wind penetration on base-load and mid-range start-ups. Source: (Troy, Denny, & O'Malley, 2010).

A particularly interesting case has been reported in (Bentek Energy, 2010) for the power system of the US state of Colorado, involving also the impact of wind penetration on the emissions of SO_2 and NO_x produced by the conventional plants that are subject to cycling. The study contemplates four years of Public Service Company of Colorado (PSCO) operational history. A simulation analysis has been done for the ERCOT system, with similar results. The study shows that the installed capacity of flexible gas fuelled plants is insufficient to offset all of the amount of wind energy produced in PSCO and, therefore, coal units must be cycled to counterbalance the amount of wind that cannot be offset by natural gas. Since coal plants were not built for cycling, they operate less efficiently, substantially increasing emissions. All coal power plants show more emissions of SO_2 and NO_x, and some also of CO_2. However, this does not necessarily translate into more CO_2 emissions from an overall system perspective, since the amount of energy, and fossil fuel, displaced by wind is quite important, offsetting the increments of fuel because of efficiency loss and additional operating reserves (ESB National Grid, 2004). The study rightly indicates that these undesirable effects should be eliminated by the introduction of more gas capacity, a reduction in coal capacity or a combination of the two, which involves replacing less expensive coal generation by cleaner and more flexible gas production from spare gas capacity in the region. As indicated above, these problems should be minimized once the mix of generation technologies has had time to adapt to the new conditions with a high level of wind penetration. However, this indicates that there is a compelling need to better understand the implications of regulatory measures on the existing power systems, so that undesirable consequences can be avoided.

Reading this report also brings the question of what unintended impacts might result from adding more new base-loaded power plants to the portfolio of PSCO; for instance, a new nuclear plant or an efficient coal unit. These hypothetical new plants would augment the cycling of the less efficient coal units, with the corresponding loss of efficiency and rise of emissions.

3.3. Additional requirements of operating reserves

A critical issue in power system operation with a large volume of intermittent production is the amount of operating reserves that will be needed to keep the power system functioning securely and efficiently. The practical implications are: a) more expensive operation, as a number of plants have to be maintained in a state of readiness and kept from being used normally to generate electricity, regardless of the regulatory framework; b) a long-term impact on the generation mix, as appropriate investments have to be done to have these plants installed and ready when the level of penetration of intermittent generation makes these quick response plants necessary. A comprehensive review of the new requirements that intermittent generation may impose on power systems can be found in (Holttinen H. , et al., 2011).

Following (Milligan, et al., 2010), operating reserves are defined as the real power capability that can be given or taken in the operating timeframe to assist in generation and load balance, and frequency control. There is also need for reactive power reserve, but it will not be discussed here. The types of operating reserves can be differentiated by: a) the type of event they respond to, such as contingencies, like the sudden loss of a generator or a line, or longer timescale events such as net load ramps and forecast errors that develop over a longer time span; b) the timescale of the response; c) the type of required response, such as readiness to start quickly a plant or fast response to instantaneous frequency deviations; d) the direction (upward or downward) of the response.

Based on the characteristics listed above, a thorough international review (Milligan, et al., 2010) classifies all types of reserves used anywhere into five categories, in decreasing order of quickness of reaction: i) *frequency response reserve* (to provide initial frequency response to major disturbances; also called primary control or governor response, acting in seconds); ii) *regulating reserve* (to maintain area control error within limits in response to random movements in a timeframe faster than energy markets can clear; also termed frequency control or secondary reserve, acting in seconds); iii) *ramping reserve* (to respond to failures and events that occur over long timeframes, such as wind forecast errors or ramps; also termed deviation reserve, balancing reserve or forecast error reserve, acting in minutes to hours); iv) *load following reserve* (to maintain within limits area control error and frequency due to non-random movements on a slower time scale than regulating reserves; also named tertiary reserve, acting in several minutes); and v) *supplemental reserve* (to replace faster reserve to restore pre-event level reserve; also called tertiary reserve and replacement reserve, acting from minutes to hours). Regulating and load following reserves are used during normal system operation. Frequency response and supplemental reserves are used during contingencies. A mix of spinning and non-spinning reserves can be used for the slower reserves (ramping, load following and supplemental) while the faster reserves (frequency and regulating reserves) require strictly spinning reserves.

A review of the numerous studies that have been made on the subject of the impact of intermittent generation on the need for additional reserves appears to lead to the following findings, which have to be adapted to the diverse characteristics of each individual power system:

- Observations and analysis of actual wind plant operating data have shown that wind does not change its output fast enough to be considered as a contingency event. Therefore the largest contingency to be considered in the determination of reserves is not affected by wind penetration.
- Both the uncertainty and the variability of wind generation may affect the required amount of regulating (secondary) reserves, but not significantly in most cases. Fast response reserves – frequency response and regulating reserves– should be ready to respond to quick fluctuations in solar or wind production. However, since power systems already need these kinds of reserves to cope with load fluctuations and unexpected emergencies, the practical relevance on production levels or costs of the presence of intermittent generation on the demand for these reserves is not deemed to be of much relevance.
- More important is the impact of errors in the prediction of the output of wind and solar on the day-ahead schedule of plants, since this requires having ready a significant capacity of flexible generating plants with relatively short start-up times and/or fast ramping capabilities, such as OCGT and CCGTs plants, to provide load following and supplemental (tertiary) reserves. These reserves are typically established in the day-ahead timeframe, where the error in wind forecast is large. In a well-designed power system, a sufficient volume of these flexible peaking units must exist to cope with the not infrequent case of sustained very low output of wind and solar plants. Note, however, that the requirement for operating reserves does not necessarily mean that these flexible plants will be actually used for production. The need is more for readiness than actual production.
- These additional requirements imply an increasing amount of mandatory dispatching of thermal units. It reduces the capability of generators to manage their portfolio (trading with these units is limited), and consequently reduces the offers on the commodity market and may increase market prices.
- Results from several worldwide case studies show that reserve requirements increase with higher penetrations of wind, see (Parsons & Ela, 2008), (Holttinen H. , et al., 2011) or (EURELECTRIC, 2010). Figure 11 shows some results for Ireland: the impact of wind penetration on the requirement of reserves is strongly related to the growth of the error in the wind forecast with the distance to the real time. A sample of international experiences is displayed in Figure 12.

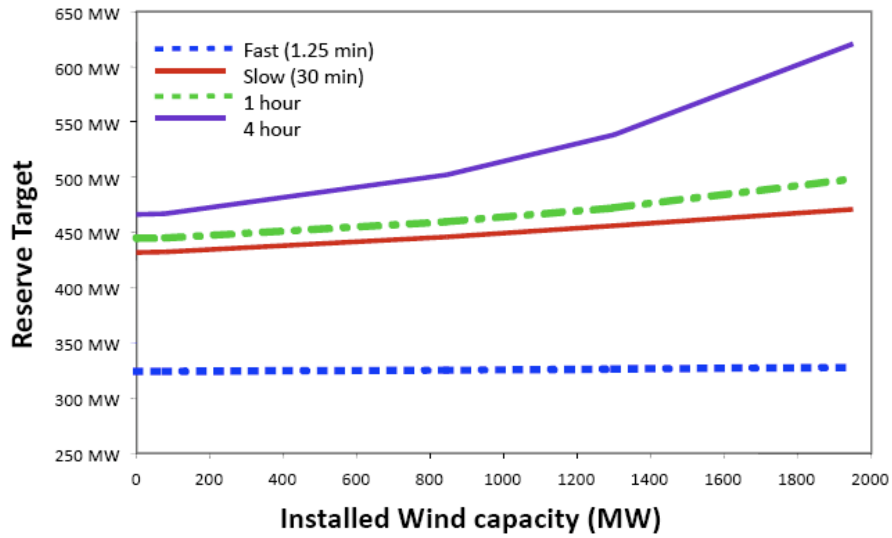

Figure 11: Operating reserve requirements as a function of wind power penetration. Source: MIT 2011 Wind Week. Presentation by Mark O'Malley. Available at http://web.mit.edu/windenergy/windweek/Workshop2011.html.

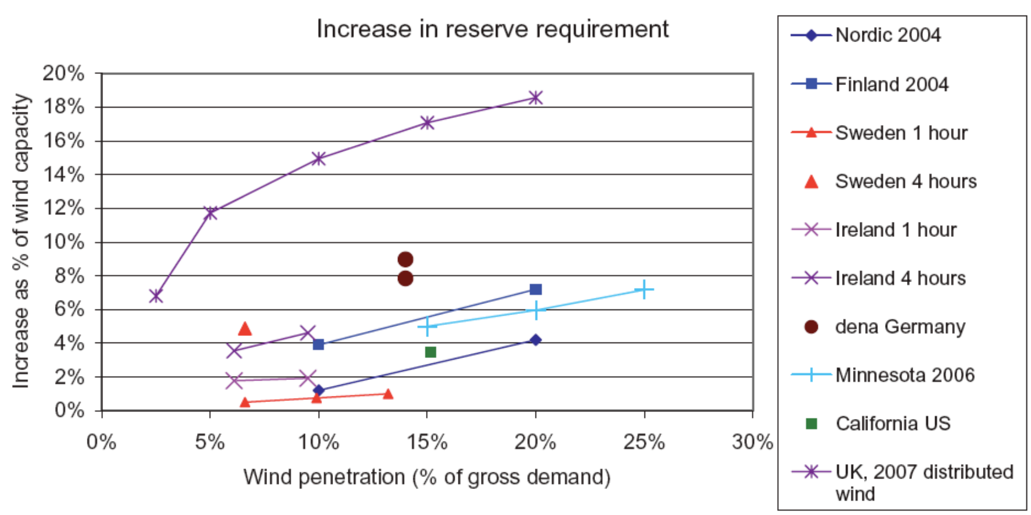

Figure 12: Results for the increase in reserve requirement due to wind power. Source: (Holttinen H. , et al., 2011).

As pointed out in (Holttinen H. , et al., 2011), an 'increase in reserve requirements' does not necessarily mean a need for new investments, as countries already with much wind power have learned from experience. Note that most wind-caused reserves are needed when wind output is highest and, therefore, the conventional power plants must have more spare capacity to provide reserves. Critical issues appear to be the capability to follow steep long ramps if the wind forecast errors are large enough that the slow units cannot follow.

It seems that careful attention must be given to the relationship between flexibility and reserves. It has to be realized that the need for flexibility is not the same as the need for reserves, which is smaller since a part of the variation of the net load –i.e. the original load minus intermittent generation output– can be forecasted. As it has been shown before, reserves mainly depend on forecast errors and the overall flexibility in scheduling deals also with the changes in output level for several hours and a day ahead; see ((Holttinen H. , et al., 2011), p. 182). This points out the open question of how to precisely define the flexibility requirements of a power system and how to incentivize the investment in the right kind of power plants and the provision of flexibility services.

3.4. Improving large scale integration of intermittent renewable generation: Coordination of balancing areas and reduced scheduling intervals

Large volumes of intermittent generation would be integrated much more easily in existing power systems if some institutional and organization problems could be properly addressed; see (EURELECTRIC, 2010), (Holttinen H. , et al., 2011), (NERC, 2009) and (ACER, 2011). Two approaches will be commented on here: a) geographical extension of the areas that are responsible for offsetting the variability and uncertainty of wind and solar production will smooth out the impacts and pool existing resources more efficiently and reliably; b) a proper treatment of intermittent generation requires a market organization that gets much closer to real time than the classical day ahead market, in order to reduce the negative impact of uncertainty in the operation of the system. Both approaches should be coordinated and addressed simultaneously. Other methods will be commented in the next section (3.5).

Integration and coordination of balancing areas

As described in (NERC, 2009), ancillary services are a vital part of balancing supply and demand and maintaining bulk power system reliability. Since each balancing area must compensate for the variability of its own demand and generation, larger balancing areas with sufficient transmission proportionally require relatively less system balancing through operation reserves than smaller balancing areas; see, for instance, (Parsons & Ela, 2008). With sufficient bulk power transmission, larger balancing areas or wide-area arrangements can offer reliability and economic benefits when integrating large amounts of variable generation. In addition, they can lead to increased diversity of variable generation resources and provide greater access to other generation resources, increasing the power systems ability to accommodate larger amounts of intermittent generation without the addition of new sources of system flexibility. Various kinds of coordination among different jurisdictions have taken place everywhere in the world for a long time. Now, the opportunities resulting from consolidation or participation in wider-area arrangements –either physically or virtually– have to be evaluated. Figure 13 shows a hypothetical future aggregation scenario of the current balancing areas in the US Eastern Interconnection.

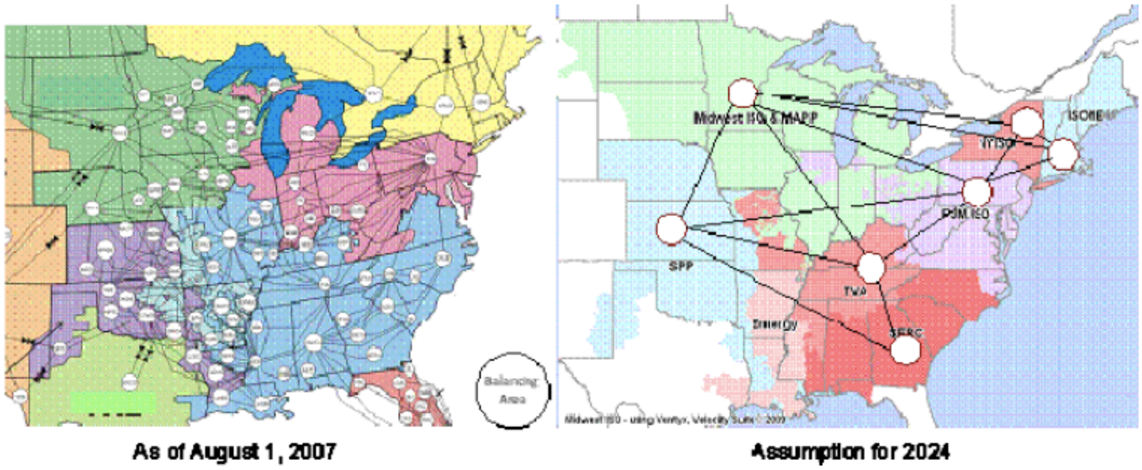

Figure 13: Assumed operational structure for the Eastern Interconnection in 2024 (the white circles represent the balancing authorities). Source: Presentation by Michael Milligan, NREL, at the MIT 2011 Wind Week.

Reduced scheduling intervals

Arrangements for the provision of the different kinds of ancillary services –and in particular operating reserves– widely depend on the individual power systems. In some cases the commitments for energy and some operating reserves are made at the day-ahead time range. In many cases, balancing energy transactions are scheduled on an hourly basis. More frequent and shorter scheduling intervals for energy transactions may assist in the large-scale integration of intermittent generation. If the scheduling intervals are reduced (for example, from one hour to 10 minutes, or providing intraday markets or even continuous trading to adjust previous positions in day-ahead markets), this will help to reduce the forecast errors of wind or solar power that affect operating reserves.

Given the strong level of presence of wind or solar generation in some power systems, there should be a level playing field for balancing responsibility, which applies to all producers, including wind and solar generator –although perhaps with some less stringent requirements– in order to stimulate all market participants to carry out thorough and proper scheduling and forecasting and thus limit system costs.

In summary, the virtuous combination of adequate available transmission capacity, larger balancing areas and more frequent scheduling –within and between areas– may significantly reduce variability of generation and demand, increase predictability and therefore reduce the need for additional flexible resources in power systems with large penetration of intermittent renewable generation. Consequently, the need for ancillary services would be less, and the costs of running the power system would be lower. As an example that this can be accomplished, a draft of mandatory Framework Guidelines has been recently issued for consultation in the European Union that contains all the necessary components: A pan-European intra-day platform to enable market participants to trade energy as close to real-time as possible to rebalance their positions, with the participation of the system operators to facilitate an efficient and reliable use of the transmission network capacity in a coordinated way, see (ACER, 2011). A similar approach is proposed in (NERC, 2009).

3.5. Other resources to improve the integration of large scale intermittent renewable generation

Some technical resources may help operators to properly respond to the patterns of intermittent generation. One should include here the additional flexibility of generation plants, energy storage, reservoir hydro systems, demand response, electric vehicles and improved wind forecast techniques.

The contribution of most power plants to the flexibility of the operation of a power system is –up to a certain point– a function of the existing economic incentives. Technical minima, ramping capabilities, start-up times and hydro reservoir management can be modified given the adequate economic conditions. It is a regulatory challenge to define these conditions and a technical challenge to respond to them. See, for instance, the debate on the regulating capabilities of nuclear generation units in (Pouret, Buttery, & Nuttall, 2009).

Wind and solar plants should also be considered in this respect. The share of wind power in relation to the strength of electricity grids and other power plants is reaching levels such that they can no longer be considered as neutral system components that do not contribute to balancing supply and demand. Now they must operate as other power plants and contribute to the needs of flexibility of the system; see next section 3.6 for details.

Storage, if available, can provide different types of reserves and also operate as a flexible plant. Inexpensive storage, at scale, represents the most straightforward way to deal with integration of intermittent generation. The benefits from this technology are more valuable when operated as a system-wide resource (rather than locally) able to provide regulation, demand following, capacity, and balancing capability (NERC, 2009), (DOE EERE , 2008). The value of storage depends on the mix of generation resources in the system, and it increases as more wind is added to the system. However, in a system with less base load units and more flexible generation, its value is not very sensitive to the penetration of wind, even at high levels (Milligan, et al., 2009). Moreover, it has been found that storage resources do not need to be developed to balance large volumes of wind (up to 20% wind energy), if enough transmission exists to allow the pooling of resources across the electric system (Ummels, Pelgrum, Kling, & Droog, 2008), (DOE EERE , 2008), (Milligan, et al., 2009) and (Denholm, Ela, Kirby, & Milligan, 2010).

Power systems with a very large percentage of hydro production, like those of Brazil or Norway, have no integration difficulties. Pumped-storage hydro plants, wherever possible, can provide an economically viable support to intermittent generation. Sites for new hydro plants are very difficult to find in industrialized countries, at least. Compressed-air in caverns, flywheels and batteries are already showing promising results. Solar thermal systems intrinsically offer some degree of storage, and direct solar-to-fuels conversion could eventually be the game-changing solution. However, technologies that could contribute very large additional amounts to what already exists do not appear to be available in competitive economic terms in the short-term, (Eyer & Corey, 2010). The same applies to electric vehicles, for the time being.

Demand response is another potential source of flexibility; see (NERC, 2009). Demand responsiveness by means of time-variant retail electricity rates, such as real-time pricing (RTP) or interruptible load agreements, could potentially reduce wind integration and forecast error costs. Through a price signal in the form of RTP, consumer demand could be made to follow the supply of wind generation, where if wind generation is high, for example, electricity demand will increase as a result of low electricity prices. Conversely, if wind generation is low, electricity demand will decrease as a result of high electricity prices (Sioshansi, 2010). Actual deployment of demand response schemes and an evaluation of its potential in the US can be found in (FERC, 2011).

The largest impact of intermittent generation on system operation costs appears to be in the unit-commitment time frame (Holttinen H. , et al., 2011), and it is caused by the potential error in the forecast of wind output. Therefore, improvements in day-ahead wind plant output forecasting offer a significant opportunity to reduce the cost and risk associated with this uncertainty. Current forecasting technology is far from perfect but nonetheless highly cost effective. Wind forecasting is very challenging. It depends on small pressure gradients operating over large distances, on turbulent & chaotic processes and also on the local topography. The dependence of wind plant output on wind velocity is very nonlinear and therefore errors in wind prediction may be substantially amplified. Improvements in prediction require better models and more observational data. The benefits of wind output aggregation at power system control level and the need for large investments in observational networks favor centralization of the wind forecasting activities.

3.6. Impacts on power system stability

Power systems must be able to maintain their integrity while responding to different kinds of contingencies that take place in very short time scales: short circuits in lines, sudden loss of load or generation, or special system conditions that gradually become unstable. Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact (Kundur et al., 2004).

There are several forms of instability that a power system may undergo. Transient stability refers to the capacity of the generators to maintain the synchronism in the presence of transmission line faults. Spontaneous low frequency oscillations must be damped quickly. Frequency excursions due to abrupt imbalances between generation and demand should be contained and the frequency brought swiftly to its nominal value. Voltages have to be maintained within safe boundaries at all times. The allowed response time to these contingencies typically ranges from some milliseconds to a few seconds or even minutes, therefore with some overlap with the activity of fast operation reserves. The most crucial factors for the stability of a power system are its mechanical inertia – provided by the rotating masses of all the turbines and the electricity generators– and its capability to damp any perturbation (Rouco, Zamora, Egido, & Fernandez, 2008).

The physical characteristics of wind and solar PV plants are substantially different from those of thermal plants –including concentrated solar power units– which consist of a boiler producing high-pressure steam that drives a turbine rotating in the same shaft with a synchronous generator. The ability to regulate frequency and arrest any sudden rise and decline of system frequency is primarily provided through the speed droop governors in conventional generators.

In principle, most wind turbine generators are often isolated from the grid by power electronic converters, and their inertial response to the overall power system is almost negligible. Solar PV plants have no contribution to the inertia of the power system. Therefore, an increased penetration of wind turbines and solar PV plants may result in significant changes in the dynamic performance and operational characteristics of a power system so far dominated by synchronous machines. In systems with a high penetration ratio of wind farms, the effective inertia of the system may be reduced and the system response to large disturbances could be significantly affected. As the system inertia decreases, the electric power systems are more sensitive to generation-load imbalances. This situation is more likely to happen for system conditions with a strong wind output and light demand. In particular, small standalone or weakly interconnected systems, as for example the Irish or the Hawaiian power systems, are more vulnerable to contingencies like the sudden loss of generation (Xie, et al., 2011).

An additional consideration is that long transmission lines are required by power plants that are located far from the main load centers –typically hydro, nuclear and, more recently, large wind or solar plants–. The synchronizing power capability of these lines is significantly reduced when they are heavily loaded (Gautam, Vittal, & Harbour, 2009).

Most wind generators that were deployed more than a few years ago were equipped with minimum voltage protections that can trip the unit, with the purpose of protecting both the machine and the power system. As noted in (Rouco, Fernández-Bernal, Zamora, & García-González, 2006), a large amount of wind power generation can be tripped if the voltage dip affects a large fraction of the power system with much installed wind capacity, leading to a potential system collapse. Depending on the technology being used, the dynamic response of wind power generators to voltage dips may be different. A sudden significant loss of wind production may also occur when wind velocity in a region happens to exceed the safety specifications of the plants, which then have to shut down immediately.

All these factors, plus the knowledge that large levels of penetration of wind and also solar PV are anticipated to take place in many countries, lead to two major conclusions. First, the operation of power systems with a strong presence of intermittent generation has to be profoundly reconsidered and grid codes have to be adapted to this new situation (Tsili, Patsiouras, & Papathanassiou, 2008). Second, wind and solar PV plants can no longer be regarded as passive units, shutting down when system faults occur and with local control of regulation. In this new context, they must behave as much as possible as ordinary power plants, which are able to provide reactive power, remain connected during system faults and increase the amount of control effort required to stabilize system frequency (Xie, et al., 2011). These features are considered essential for the future integration of high wind penetration in electric power systems.

The good news is that wind generation is technically able to actively participate in maintaining system reliability along with conventional generation. According to (NERC, 2009) modern wind turbine generators can meet equivalent technical performance requirements provided by conventional generation technologies with proper control strategies, system design, and implementation. In combination with advanced forecasting techniques, it is now possible to design variable generators with a full range of performance capability that is comparable, and in some cases superior, to that in conventional synchronous generators. This includes voltage and VAR control and regulation, voltage ride-through, power curtailment and ramping, primary frequency regulation and inertial response.

Regarding power management and frequency control, many modern wind turbines are capable of pitch control, which allows their output to be modified in real-time by adjusting the pitch of the turbine blades. This capability can be used to limit ramp rates and/or power output of a wind generator and it can also contribute to power system frequency control. A similar effect can be realized by shutting down some of the turbines in a wind farm. Unlike a typical thermal power plant whose output ramps downward rather slowly, wind plants can react quickly to a dispatch instruction taking seconds, rather than minutes. Operators need to understand this characteristic when requesting reductions of output. Examples of implementation of these techniques to provide frequency control can be found in (Martinez de Alegria, Villate, Andreu, Gabiola, & IBAÑEZ, 2004) or (Gautam, Vittal, & Harbour, 2009). Detailed simulations of a large penetration of wind generators equipped with doubly fed induction generators in the New York (assuming 10% wind) and WECC (assuming 20% wind) regions, have shown that wind plants can actually contribute to system stability by providing low voltage ride through capability and dynamic VAR support to reduce voltage excursions and dampen swings (GE ENERGY, 2005). From the WECC system frequency response study, results have shown benefits provided by special wind plant controls specifically contributing to system frequency performance during the first 10 seconds of a grid event by providing some form of inertia. These cases show that wind generation does not necessarily result in degraded frequency performance (Miller, N.; Clark, K.; Shao, M., 2010).

Large PV solar plants can potentially change output by +/- 70% in a time frame of two to ten minutes, many times per day. Therefore, these plants should consider incorporating the ability to manage ramp rates and/or curtail power output. It is probable that these large impacts could be smoothed out by geographical dispersion and the size of the solar plants. The use of inverters in solar PV plants makes them able to provide real-time control of voltage, supporting both real and reactive power output.

Concentrating solar thermal plants that use steam turbines typically make use of a “working fluid” such as water or oil; molten salt may be used for energy storage. The mass of working fluid in concentrating solar thermal plants results in these types of plants having stored energy and thermal inertia. Due to their energy storage capability, the electrical output ramps of a solar thermal plant can be less severe and more predictable than solar PV and wind power plants.

Voltage control can also be implemented in wind power plants, which, as well as PV plants, can control reactive power. As variable resources, such as wind power facilities, constitute a larger proportion of the total generation on a system, these resources may provide voltage regulation and reactive power control capabilities comparable to that of conventional generation. Further, wind plants may provide dynamic and static reactive power support, as well as voltage control in order to contribute to power system reliability. The most demanding requisite for wind farms, especially those equipped with doubly fed induction generators (DFIG) is the fault ride through capability. The effect of such a voltage dip in the wind turbine is different for different wind turbine system technologies. Voltage ride-through can be achieved with all modern wind turbine generators, mainly through modifications of the turbine generator controls. Older types of wind turbine-generators at weak short-circuit nodes in the transmission system must be disconnected from the grid unless additional protection systems are provided, or there may be a need for additional transmission equipment.

For the system to take advantage of the capabilities of wind and solar power plants, the operator of each balancing area must have real-time knowledge of the state of each plant regarding operating conditions, output and availability and must be also able to communicate timely instructions to the plants, regarding frequency control, voltage control or curtailment orders. Figure 14 shows the national control center and one of the 14 satellite control centers that exclusively monitor and control renewable generation in Spain.

Figure 14: National control center for renewable energies in Red Eléctrica, the Spanish system operator (left) and Iberdrola's wind control center (right), one of the 14 satellite control centers for wind in Spain.

In summary, in the near future is expected that intermittent renewable generation will actively participate in maintaining system stability through varied control capabilities such as: primary frequency regulation, power curtailment and ramping, voltage/VAR control/regulation, voltage ride-through, and inertial response. As the wind penetration increases, these features on power wind facilities will be essential for the operation of the system, in particular during post-contingency system restoration, peak generation during low demand periods, and unexpected ramp-up generation at times when demand drops (NERC, 2009) (Holttinen H. , et al., 2011).

3.7. Effect on operation cost and market prices

Much has been written about the integration costs of wind and solar generation, and also on the expected impact on electricity prices, see (Holttinen H. , et al., 2011) and (EURELECTRIC, 2010) as recent references for this topic. This interest stems from the fact that in most cases the deployment of wind and solar plants is the result of a policy decision in pursuit of some broader goal than the mere minimization of electric power supply costs in the existing system. This broader objective may include the reduction of carbon emissions, the utilization of indigenous resources, the creation of a more level playing for all generation technologies, support for the long-term technical improvement and cost reduction of these sustainable technologies or the creation of jobs and promotion of rural development[7]. As a result, some kind of regulatory support –under the format of a feed-in tariff, renewable portfolio standard or any other, see (Batlle et al., 2011)– makes economically viable the installation of these plants. It seems therefore justified to evaluate the implications of a specific energy policy favoring renewables –and wind and solar generation in particular– on costs, prices and reliability of the power system.

[7] In the preface of the European Directive 2009/28/EC it is stated that "the control of European energy consumption and the increased use of energy from renewable sources, together with energy savings and increased energy efficiency, constitute important parts of the package of measures needed to reduce greenhouse gas emissions (...). Those factors also have an important part to play in promoting the security of energy supply, promoting technological development and innovation and providing opportunities for employment and regional development, especially in rural and isolated areas".

Except for this fact –wind and solar penetration being a consequence of a regulatory decision– we might be asking the same question about other generation technologies: what for instance is the cost of integration of more base load plants –such as coal or nuclear plants– in a given power system? We would easily discover that more penetration of inflexible base load plants would result in more start-ups and cycling of other plants that are lower in the economic merit order, also with some undesirable consequences as the ones described in section 3.2 of this paper. And we cannot ignore that other technologies are also frequently supported by regulatory instruments, either at the investment or operation levels (for instance, in most electric power markets, due to alleged security concerns, nuclear plants have more priority of dispatch than renewable installations). It is also often claimed that the penetration of renewables increases the need for short-term reserves, but again, large base load plants also create a significant need for these reserves, a fact that is not usually mentioned[8].

The impact on power system costs is discussed first, and the effects on market prices will be examined later. The implications of the regulatory framework will be indicated. In power systems with a competitive wholesale market price consumers will have to pay some sort of pass-through of the wholesale market prices, in addition to some additional charge to cover the costs of subsidizing the investment in renewable energy sources. In vertically integrated power systems, under some form of traditional cost-of-service regulation, consumers typically pay average production costs instead of marginal prices, with regulated charges including an extra component to cover the higher costs of renewables.

The impact on operation costs

In the operation time frame, wind and solar are generation technologies characterized by a variable cost of production that is basically zero. Therefore, at least in a first approximation, the expected global impact on the power system should be a reduction in total production cost, since other more expensive generation technology or technologies have been displaced by the wind or solar production. However, it remains the complex task of evaluating the several side effects. These include: increase of reserve requirements and corresponding changes in the unit commitment costs, impact on the efficiency of conventional power plants, and any potential impact on the future demand and price of primary fuel for the remaining conventional plants, in particular for gas-fired based plants.

As explained earlier, until new sources of flexibility could be developed and deployed in large volumes, the additional flexibility required by the system to deal with the intermittency of wind or solar will translate into flexible generation plants operating in a frequent cycling mode, with more start-ups and fewer operating hours during the year than is presently the case (EURELECTRIC, 2010). Also, until the current technology mix has time to adapt to the new situation, mid-range and some base-load plants may have to operate at suboptimal (and hence less efficient) production levels. These effects should result in an increase of the power system operation costs.

[8] For instance, in the Spanish system, with a total of about 25 GW of installed wind and solar capacity, the System Operator asks for 600 MW of wind and solar-related regulating reserves, while the amount of regulating reserves that are needed for the event of an unexpected thermal plant failure (following the so-called n-1 criterion) is 1000 MW, the size of the largest nuclear plant in the system. In addition, 1000 MW of the very scarce interconnection capacity with France has to be left unused to allow for the sudden incoming surge of about 1000 MW into the Spanish grid in case one of the largest nuclear units trips.

The results from several studies on balancing costs –both estimated and actual numbers– for different countries and regions in Europe and the US are reported in (Holttinen H. , et al., 2011). These results normally account for the impact on operating reserves and on the efficiency of conventional power plants for day-ahead operation. The evaluation of the impacts is made by comparing the operation costs without wind and adding different amounts of wind with different historical wind patterns. The authors mention several factors that influence the estimated costs in the studies, such as the region size relevant for balancing, initial load variations, geographic distribution of wind power, and the frequency used in updating load and wind forecasts.

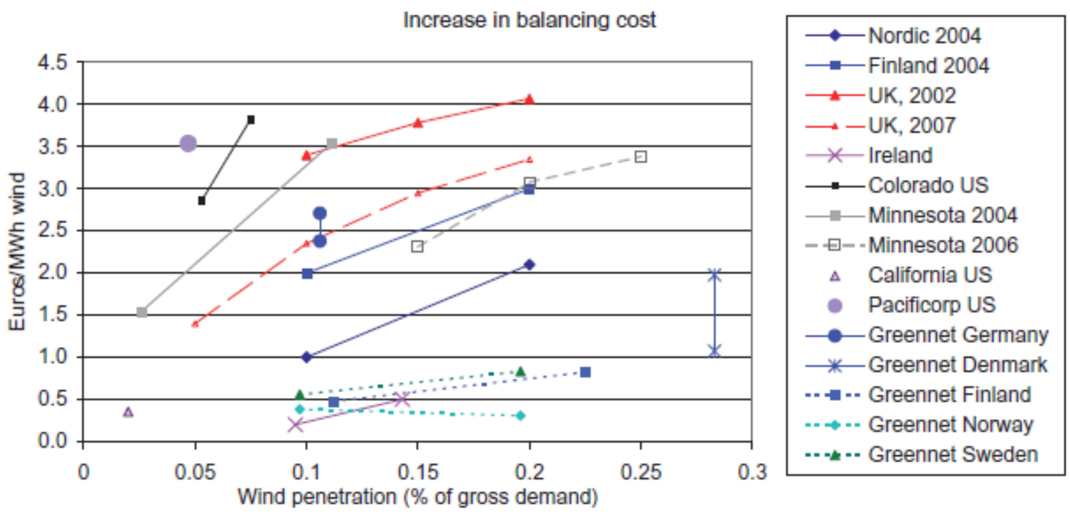

Figure 15: Results from estimates for the increase in balancing and operating costs due to wind power. The currency conversion used here is 1 € = 0.7 £ and 1 € = 1.3 US$. For the "UK, 2007" study only the average cost is presented here; note that the range in the last point for 20% penetration level is from 2.6 to 4.7 €/MWh.

Source: (Holttinen H. , et al., 2011).

From the estimated results of these studies (Figure 15), it is noted that at wind penetrations of up to 20% of gross demand the increase in system operating costs is about 1-4 €/MWh of wind power produced –equivalent to about 10% or less of the wholesale value of the wind energy–. In addition to costs estimates, (Holttinen H. , et al., 2009) also mentions actual balancing costs due to existing wind power in countries like Denmark. For West Denmark, the balancing cost from the Nordic day-ahead market has been reported to be 1.4-2.6 €/MWh for a 24% wind penetration of gross demand.

In addition, several factors have been identified to reduce operating costs due to wind power, such as the aggregation of wind plant output over large geographical regions, larger balancing areas, and utilizing gate closure times closer to real-time. The use of interconnection capacity for balancing purposes plays a major role in the estimation of costs. The studies reported lower balancing costs in those cases where the interconnection capacity was allowed to be used (Holttinen H. , et al., 2011).

It should be mentioned that distribution grids have to incur into additional costs to accommodate significant volumes of distributed generation, either intermittent renewable or not. Transmission grid reinforcements may be needed to handle larger power flows and maintaining a stable voltage, and are commonly needed if new generation is installed in weak grids far from load centers. These issues are discussed in sections 5 and 6.

The impact on marginal electricity prices

Now we focus on the impact of wind or solar PV generation on marginal –rather than average– electricity prices[9]. In principle a reduction in marginal prices should be expected, as the "residual demand" –i.e. the demand that remains after the intermittent generation output has been subtracted– is now lower and, therefore, the most expensive plants that otherwise would be needed to meet the total original demand can be avoided. Again, things are more complex that they first appear to be.

Electricity wholesale markets follow complex rules, and particularly so in the formation of market prices. These rules are noticeably different in the multiple existing markets: uniform versus locational marginal prices, simple (just quantities and prices) versus complex bids (that also include start-up costs, non-uniform heat rates, technical minima, minimum up or down times, or ramping limits), algorithms to compute the matching of supply and demand, the rules of determination of the marginal prices and, if this is the case, of make-whole payments to generators who do not recover their nonlinear operation costs with marginal prices.

Several authors have recently tried to assess the impact of intermittent generation on electricity market prices. See, for instance, (Troy, Denny, & O'Malley, 2010), (Morales, Conejo, & Perez-Ruiz, 2010), (EWEA, 2009), (Mac Cormack, Hollis, Zareipour, & Rosehart, 2010), and (Nicolosi & Fürsch, 2009). Many of these studies come to the conclusion that marginal electricity prices will be reduced, because of the reasons already mentioned. For instance, in (Mac Cormack, Hollis, Zareipour, & Rosehart, 2010) simulations show that as wind generation penetration increases, average electricity prices decrease in the short to medium term as more supply is added to the system and prices are more frequently set by the marginal cost of intermediate and base load generator units. However, as (Batlle & Rodilla, 2011) shows, for the most part these papers miss the fact that in many electricity markets, now and increasingly in the future, the system marginal price is mostly set by the same technology (CCGTs) so the supply bidding function is, and it will probably be, rather flat, so the actual market price reduction might be much less significant than what these publications expect.

Additionally, many authors have indicated that the deployment of intermittent generation will necessarily result in a larger need for operation reserves, with an upward pressure on the energy supply costs, see for instance (Holttinen H. , et al., 2009) or (Nicholson et al., 2010).

Also, until rather recently, many of these papers have missed or poorly considered the detailed impact of the operation complexities of actual power plants in the market price formation and also the long-term effects of the short-term prices on future generation investment. Some authors who claim to have taken into consideration this issue in one way or another and get to varied conclusions are (Delarue et al., 2006), (De Carolis & Keith, 2006), (Rosen et al., 2007), (Milligan & Smith, 2007), (Milligan, et al., 2009), (Poyry Energy, 2009) and (Traber & Kemfert, 2011). A rather rigorous, but merely qualitative discussion of just the expected short-term impacts is given in (EURELECTRIC, 2010), and anticipated in (Batlle & Rodilla, 2009). More recently, (Batlle & Rodilla, 2011) provide a broader assessment of the impact of wind generation on a power system with a satisfactory realistic representation of the operation of thermal plants and also the varied bidding

[9] The analysis is similar for the impact on marginal costs in power systems with no competitive wholesale markets, where marginal costs can be used as a component of real time pricing.

and pricing mechanisms currently in force in different electricity markets, as well as a discussion on the long-term implications on investment.

(Rodilla, Cerisola, & Batlle, 2011) examine in detail the effect that the modification in the operation pattern of mid-range plants like CCGTs, because of a strong presence of wind, has on the bidding behavior of these plants, as well as on the formation of prices according to actual pricing rules in different market designs. The paper distinguishes those markets with complex bids (e.g. PJM) from those with simple bids (e.g. the Iberian Market). When designing simple bids, mid-range units facing frequent cycling, with short functioning periods of uncertain duration, will have to internalize those costs in their bids in short functioning periods, resulting in higher bids and, consequently, higher marginal prices for consumers. This has been also indicated by (Troy, Denny, & O'Malley, 2010). The results that are obtained indicate that, contrary to what has been generally announced to date, a large penetration of wind does not necessarily lead to a reduction of marginal prices in wholesale electricity markets.

Short-term electricity market prices have also implications on the long-term behavior of the market agents. This effect has been analyzed in several studies for a variety of power systems, see for instance (EIRGRID, 2010) (Poyry Energy, 2009), (Mac Cormack, Hollis, Zareipour, & Rosehart, 2010), (EURELECTRIC, 2010), (Traber & Kemfert, 2011) and (Batlle & Rodilla, 2011). Here, the key point is that the future technology mix of generation will depend on the anticipated short-term marginal prices of electricity and the operating conditions that the investors expect to encounter in the market in the future. In the presence of a large wind or solar PV penetration, marginal market prices are expected to be more volatile, with larger differences between peak and off-peak values, and more uncertain. More important, the expected average level of electricity market prices will also depend much on intermittent generation penetration via the competing factors that we have just described: reduction in the net demand (price reduction) and impact on the cycling activity of mid-range plants (price increase, via internalization in bids or price formation mechanisms). In particular, (Batlle & Rodilla, 2011) highlight how, in the presence of a large volume of intermittent generation, the adopted pricing mechanism plays a key role, since it significantly affects the expectation of income in generation capacity investments. Some pricing schemes include any incurred nonlinear generation costs in the marginal price (e.g., Ireland) while others just make whole the individual generators that have incurred into these costs (e.g., PJM). The former scheme is more favorable for base loaded technologies and the latter for peaking ones. This second impact on future investment will be discussed in more detail in section 4.

Priority of dispatch, negative prices and normality of market rules

The presence of intermittent generation in power systems has frequently motivated the creation of ad hoc market rules to deal with the new patterns of behavior that have been encountered. A prominent case is the so-called "priority of dispatch" rule included in the EU legislation –the Renewables Directive 2001/776– to promote the development of renewables. This requires that "Member States shall ensure that when dispatching electricity generating installations, system operators shall give priority to generating installations using renewable energy sources in so far as the secure operation of the national electricity system permits and based on transparent and non-discriminatory criteria". The practical effect of this rule is that production with renewables can only be limited because of security reasons. Therefore, whenever the market price equals zero, even if the optimal solution of the unit commitment algorithm indicates that the most economic option is to curtail wind rather than to stop some conventional thermal plant for a short period of time, renewable production will be scheduled and receive the feed-in tariff or premium, if this is the case.

Several reasons have been given to support this drastic rule. In the first place, the rule helps meet the committed renewable production targets, as well as any carbon reduction targets, by minimizing curtailments of renewable production. The rule may also incentivize a more flexible operation –to avoid being driven out of the market– of conventional plants that, otherwise, might not try to make an effort to accommodate increasing volumes of intermittent generation.

The down side of this rule is that it may be the cause of inefficient dispatches of generation, as described above, as the rule may constrain what otherwise would be the optimal unit commitment, whether based on generators operating costs or bids. The arguments from both sides in this trade-off have value, and it seems that a reasonable compromise should be reached, attending to the specific circumstances of each case.

Note that conventional generators may be willing to bid negative prices to avoid being shut down. Wind or solar generation would be also willing to bid a negative price to retain the income from any financial support scheme that is linked to production. The link between negative prices and renewable support mechanisms has to be carefully examined. Note, however, that negative prices may already occur in the absence of intermittent generation since, at times with low demand, conventional generating plants may be forced to regulate downwards up to their technical minima or even to shut down and, in an effort to avoid incurring in the additional operational costs and tear and wear of the machines, these generators prefer to bid negative prices with the purpose of keeping their plants running (EURELECTRIC, 2010). This is normal rational economic behavior of the agents in a competitive market and should not be interfered with. The occurrence of negative prices becomes more frequent in the presence of high wind output during times of low demand. What may not be considered reasonable is that renewable generators that receive some kind of financial support linked to production –such as a feed-in tariff– can outbid the conventional power plants with negative prices up to the value of the feed-in tariff. And the higher the subsidy –e.g. solar PV would have a higher subsidy than wind– the more "competitive" a technology would be bidding negative prices while still capturing some rent. The conclusions of a careful analysis on this topic may lead to revisions of market rules, with the purpose of eliminating any undesirable market behavior or distortion.

"Normal" market rules should be used as much as possible with intermittent generation (EURELECTRIC, 2010). Making wind generators subject to the same balancing and scheduling obligations as conventional power plants does not jeopardize the development of this technology, as the experience of several European countries already shows. On the contrary, this seems to be the best way to stimulate improvements in forecasting methods, operation of reserves and frequency control by wind generators: as a result of it, system balancing requirements can be reduced and costs will be fairly allocated. Priority of dispatch and guaranteed network access for renewable generation should not exempt these generators from their scheduling and balancing obligations. This will speed full integration of wind generation in the power systems.

On the other hand, as it has been already indicated in section 3.4, market rules should facilitate this integration as much as possible by increasing trading possibilities closer to the moment of physical delivery and by augmenting the geographical scope of the balancing areas.

Allocation of the costs of support to renewables

Finally, it is worth mentioning one related issue that has received little attention to date from an academic perspective. Currently, the economic burden of supporting renewables is passed to electricity consumers in most countries, with the production tax credits in the US being one of the few exceptions to the general rule. This allocation criterion results in an inefficient energy consumption behavior. The targets of a broad renewable energy policy concern all energy supplies (explicitly in the EU case, implicitly in other instances). Therefore, charging electricity consumers only, sends the wrong signal to switch to other less efficient sources of energy, thus increasing the need for more electricity generation with renewables to offset the increment in consumption of other types of final energy (EURELECTRIC, 2010). (Batlle, 2011) reviews these efficiency incentives linked to tariff design and proposes a methodology to allocate the costs of renewable support whereby these costs are charged to final energy consumers, in proportion to their total energy consumption, regardless of the type (liquid fuels, gas, electricity or coal).

4. Impacts on the future electricity generation mix

The operation of a system with a substantial presence of intermittent generation will be very different from today's operation. The future well-adapted mix of generation technologies will also change, probably reducing the weight of less flexible base-loaded units and increasing the percentage of more flexible generation plants, always depending on the level of penetration of intermittent generation.

The impact analysis will be different depending on the existing regulatory framework in the power system under consideration, either market oriented or centrally planned. In those power systems under competitive market regulation, the generation mix will be dictated by the expected profit margin that the investors in the several technologies expect to obtain in a market with these characteristics. Note that, under competitive market conditions, a shift in the technology mix will happen in a natural way, as the investors react to the new economic opportunities to capture profit margins in systems that have a strong presence of intermittent renewable generation. The mix of generation technologies will be the outcome of a complex process, where each decision of operation and investment has a justification. If some socially acceptable system of market signals and incentives results in a technology mix with a strong percentage of intermittent generation and also with flexible plants that take advantage of the increasingly frequent situations of high market price spikes, then this is the first best mix under the circumstances, freely chosen by the investors. This also includes the response of investors to any economic incentives (such as, for instance, a capacity payment mechanism) or command-and-control mandates that have been established by the regulatory authorities.

On the other hand, in those systems with traditional cost-of-service regulation and centralized capacity expansion planning, the critical issue is how much investment is necessary and of which technology, in order to meet the expected demand at minimum cost while meeting some prescribed reliability constraints and environmental targets. The key point here is that a strong presence of intermittent generation will significantly change the existing procedures and evaluation techniques.

The assessment of the impacts on the future electricity generation mix is presented next for both regulatory approaches.

4.1. Centralized capacity expansion planning and resource adequacy

Each generation technology has different technical and economic characteristics and the challenge of capacity expansion planning is to combine them properly. Intermittent generation technologies presently have high investment costs, provide energy at basically zero variable cost, but are subject to high variability and uncertainty, and generally contribute much less to the firm capacity of the power system than conventional technologies[10], (Batlle & Barroso, 2011).

From a reliability perspective, according to (NERC, 2009), the system planner has to maintain some percentage reserve margin of capacity above its demand requirements to maintain reliability following unexpected system conditions. Reserve margins are determined by calculating the firm capacity of supply resources; this requires that some fraction of the rated capacity be discounted to reflect the potential unavailability of the resource at times when the system is in high-risk of not being able to meet all the demand.

If a large portion of the total supply resource portfolio is comprised of intermittent generation, the reliability evaluation becomes more complex. However, this does not fundamentally change existing resource adequacy planning processes in that the process must still be driven by a reliability-based set of metrics. The analytical processes used by resource planners range from relatively simple calculations of planning reserve margins to rigorous reliability simulations that calculate probabilistic measures of loss of some demand.

The capacity credit of wind

Much has been written about the "capacity credit" or "firm capacity" of intermittent generation, i.e. a measure of the contribution of wind to the reliability of the power system, see (Milligan & Porter, 2008). The capacity credit of wind or solar PV per unit of installed capacity is significantly inferior to that of conventional generation technologies, although the importance of this factor is very dependent on specific system characteristics, such as interconnection or hydro storage capacity.

The capacity contribution of conventional generating units to reserve margins is mostly based on the unit performance rating, forced outage rate, fuel availability and maintenance schedules. However, the capacity contribution of intermittent generation is not straightforward, as it will depend on its variability and uncertainty, as well as on the correlation of the availability of wind with electricity demand. It has been noted in (NERC, 2009) that current approaches based on the "Effective Load Carrying Capability (ELCC)" may need to adapt to properly include intermittent generation, see also (IEA, 2011). Thus, for ELCC, the weather-driven correlation between variable generation and demand is critical, where a large amount of time-synchronized hourly wind generation and demand data is required in order to estimate the capacity contribution of variable generation. Approximations should be avoided and more detailed approaches, such as ELCC with abundant historical data should be employed.

It has been stated that the capacity value of wind decreases as its level of penetration increases, indicating a diminishing incremental contribution to reliability with output, see (NERC, 2009) or (ESB National Grid, 2004). The results of several studies are summarized in Figure 16. According to

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[10] This statement is correct for most, but not all, power systems. In Brazil wind generation is a strong contributor to the reliability of electricity supply, and not only because of the dominance of hydro production in the Brazilian power sector, see (Batlle & Barroso, 2011).

some of these sources, the contribution can be up to 40% of installed wind power capacity in situations with low penetration and high capacity factor at peak load times, and down to 5% under higher penetration, or if regional wind power output profiles correlate negatively with the system load profile. It remains to be well understood the logic behind this result, which is probably the effect of a “common cause of failure”: a quasi-simultaneous absence of the wind resource throughout the entire system. The larger the presence of wind in a system, the stronger this negative impact is on the system reliability performance.

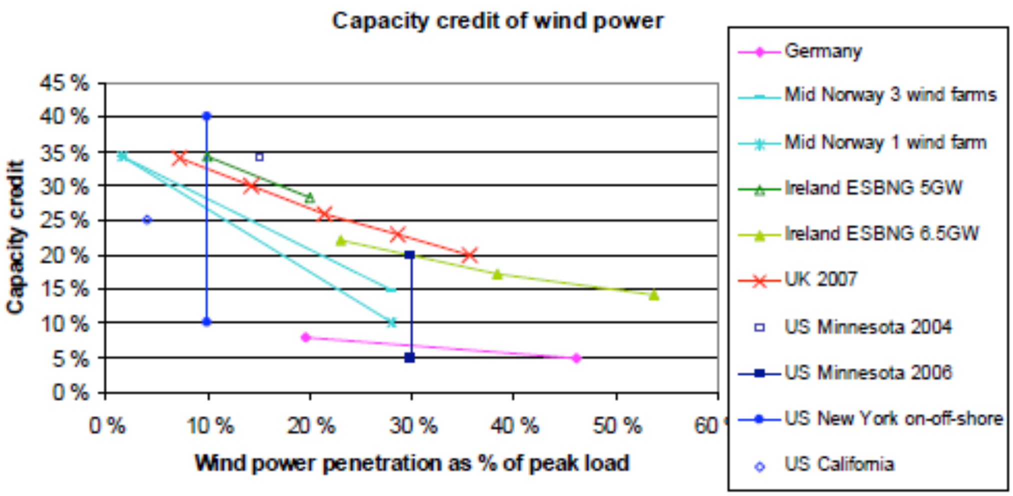

Figure 16: Capacity credit of wind power, results from eight studies. The Ireland estimates were made for two power system configurations, with 5 GW and 6.5 GW peak load. Source: (Holttinen H. , et al., 2009).

The smoothing effect due to geographical distribution of wind power has a positive impact on the wind capacity value at high penetration, subject to having enough capacity in the grid (Parsons & Ela, 2008).

Note also that a sudden loss of all wind power on a system simultaneously due to a loss of wind is not a credible event. It might happen because of automatic disconnection in case of excessive wind velocity, but this can be mitigated by adequate control measures. A sudden loss of large amounts of wind power, due to voltage dips in the grid, can also be prevented by requiring fault-ride-through from the turbines.

The worst credible scenario for wind under a reliability viewpoint consists of an extended period of time –maybe as long as a few days– with very low output, during a high demand season. It is very important to characterize the probability of occurrence and the depth and duration of these events, since the power system has to be ready to cope with them. More on this issue on section 4.4.

4.2. Competitive electricity markets and the incentives to invest

In power systems under competitive market conditions generation capacity expansion is left to the decentralized decisions of private investors[11], who will evaluate the convenience of building plants

[11] In most electricity markets the regulatory authorities have implemented some kind of mechanism to ensure generation security of supply, see (Batlle & Rodilla, 2011) for a review of this topic.

in a particular power system depending on the expected price levels and operating conditions during the lifetime of the potential facility, among other considerations.

Several studies for a diversity of power systems –see for instance (MIT, 2010), (DOE EERE , 2008), (GE Energy, 2010), (Charles River Associates, 2010), (Poyry Energy, 2009)– have analyzed, in detail, plausible future scenarios with a large presence of wind and solar generation, and shown that this also leads to an increased presence of flexible mid-range generation capacity with high cycling capability and low capital cost. The function of some of these plants –typically open cycle gas turbines, OCGT– is almost exclusively to provide reserve capacity margins. Other plants are subject to heavy cycling regimes with relatively low capacity factors (e.g., 2000 to 3000 hours per year), typically combined cycle gas turbines, CCGT. These results are obtained under the assumption of centralized planning. Ideally the same mix should also be the outcome of a competitive electricity market.

However, in deregulated wholesale markets with substantial penetration of renewables, the volatility of marginal prices is expected to increase. Also, mid-range technologies, of which CCGT is the most likely candidate, will see their output reduced, as indicated above. The uncertainty regarding the adequate technology mix, the penetration of renewables, and the economics of such a mix under the anticipated future prices and operating conditions raise concerns about attracting sufficient investment in these flexible plants under a competitive market regime.

This issue is presently being addressed by several European countries with significant penetration of wind generation, where the patterns of production of combined and single cycle gas turbines, and also of some base load technologies, have already been substantially affected, see (EURELECTRIC, 2010), (Poyry Energy, 2009) and (Batlle & Rodilla, 2011). Similar situations are already developing in some parts of the U.S. Presently there is no consensus on a suitable regulatory response to this situation, which could include enhancements of any capacity mechanisms such as those already in place in most U.S. wholesale markets, new categories of remunerated ancillary services or other instruments. This issue must be analyzed in the context of the market price implications that were discussed in section 3.7 and, if justified, appropriate regulatory measures should be developed to facilitate adequate levels of investment in flexible generation plants to ensure system reliability and efficiency.

4.3. The "back-up cost" of wind

It is frequently stated that intermittent generation needs back-up power, implying that the installation of wind capacity is necessarily associated with additional capacity of some other technology, therefore increasing the actual investment cost of the wind generation technology.

As it has been already discussed here, the meaning and implications of this statement depend on the regulatory context and the specific technology mix of the system in which wind generation is deployed.

Regarding the technology mix, it has to be realized that there is no single technology that is fully suitable, both technically and economically, to meet all the electricity demand, with its daily, weekly and seasonal patterns and associated uncertainty. Each technology presents some advantages and also shortcomings. One could ask what "the flexible back-up cost" is for inflexible base-loaded technologies, like coal or nuclear. Or the cost of reserve capacity, and spare interconnection capacity, that has to be permanently available in case the largest unit in the system –a nuclear generator, typically– suddenly trips. Or, the "economic back-up cost" of peaking plants, with high variable operating costs. An optimal generation mix with a strong presence of wind will be very different depending whether the specific power system has good storage resources (presently only hydro reservoirs, either the regular kind or pumped hydro, provide substantial capability), strong interconnection capacity and significant demand response (for instance with interruptible supply contracts with large consumers). Many systems have abundant flexible spare capacity, typically because of recent overinvestment in CCGT plants –less flexible than OCGT plants, but much more than coal or nuclear generators–, and they can accept large amounts of intermittent generation before additional flexible capacity is needed.

When the "back-up cost of wind" is mentioned, what appears to be loosely meant is the cost of the amount of firm capacity of the least expensive conventional technology that is needed to go together with 1 MW of wind capacity so that the combination has a firm capacity of 1 MW. But this does not make much sense, because the investment in wind is not meant to be a substitute of a base-load technology. More investment in wind does not require additional investment in back-up capacity. Quite the opposite, more investment in wind reduces the utilization of conventional fuels and modestly contributes to the total firm capacity of the system, therefore reducing the need of investment in conventional generation technologies.

The question about the impact of the presence of wind is very dependent on the reason why the investment in wind generation has taken place. If the amount of installed capacity of wind generation is the result of a regulatory decision, and the installed capacity of the remaining technologies is well adapted to the demand with the amount of wind, then it is a valid question to ask how much the total cost of electricity supply would be, should the installed wind capacity increase (ignoring any cost of externalities, which normally would decrease with more wind generation). The correct question would be: how much is the additional total cost for the system of the mandated level of wind production?[12] Answering this question is not a trivial exercise, since it requires including both investment and operation costs and the comparison with a counterfactual: what should have done had the wind not been installed[13].

Note, however, that if the installation of wind obeys to purely economic reasons and the existing amount of wind happens to be well adapted to the demand and the other technologies because wind happens to be competitive, the presence of wind naturally follows from the logic of the market. In this case the presence of wind is necessary to achieve the lowest cost of supply for the system and, therefore, the question of "how much is the back-up cost of wind" or how much is the cost that the presence of wind is causing to the system becomes meaningless and cannot be answered. This is, of course, an issue open to debate.

4.4. Other sources of flexibility

A power system can respond with flexibility to the variability and uncertainty of wind and solar PV generation with more resources than new investments in flexible power plants. To start with, as indicated in the previous section, a very important source of flexibility is the spare capacity of

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[12] A parallel question to this one is how many CO2 emissions are avoided by increasing wind or solar production. And, piecing all the pieces together, what is the abatement cost of CO2 that is achieved by increasing the production with renewables. Of course, this comparison does not take into account other side benefits (and also costs) that can be achieved by a higher production of renewables.

[13] If a capacity expansión optimization model is used, then the required information is provided by the dual variable of the constraint that imposes the mandated amount of wind generation.

already existing flexible power plants. For instance, the New England Wind Integration Study (NEWIS) has revealed that the ISO-NE system presently has adequate resources to accommodate up to 24% of annual energy penetration of wind generation by 2020, see (GE Energy, EnerNex, AWS Truepower, 2010).

But in a power system there are more sources of flexibility besides generation plants, see (EURELECTRIC, 2010) for instance. Reinforcement and optimal use of interconnections and integration of balancing areas is essential to accommodate large amounts of intermittent generation resources, as discussed in section 3.4. Market rules that reduce the scheduling intervals in electricity markets help wind and solar PV mitigate the uncertainty impact.

Contribution from the intermittent generators themselves will also be needed. Note that costs of operating reserves are socialized in most markets through the system tariffs, which means that presently in many systems there is no price signal to the intermittent generators to contribute to the higher flexibility requirements in the power system.

Storage other than hydro still is in need of development; however, existing regulations do not provide the right signals or the incentives needed for storage systems to mature adequately. Increased penetration of intermittent generation should result in large price differentials, providing appropriate economic signals that should not be limited by caps or floors. Storage, in sufficient amount, should allow renewable energy sources to be captured and stored for later use, reducing the waste of resources; and it can also be a valuable instrument to provide the needed flexibility.

Demand response holds a huge potential that still has to be demonstrated; see (FERC, 2011). This includes applications that have been used for a long time, such as interruptibility contracts with large industrial consumers, as well as others that still are in its infancy, like tapping the response of smart domestic appliances or of large aggregates of medium size consumers, as the company ENERNOC has already achieved. More futuristic measures, such as massive vehicle to grid coordinated control, could be commensurate with potential very large penetrations of wind and solar generation, as anticipated at least in some European countries. Creative solutions, perhaps revising the classical concept of power system reliability metrics, will have to be adopted in this case, especially when confronting the worst case scenario that was described in section 4.1.

5. Impacts on transmission network expansion and bulk power system operation

TO BE COMPLETED

6. Impacts on distribution network expansion and distribution system operation

TO BE COMPLETED

7. Some open issues

A large number of relevant issues have been identified during the review of the power system functions that can be affected by a large penetration of intermittent renewable sources of electricity production. We are left with many open questions regarding how to best manage each one of these areas of concern. A list of topics for discussion follows.

On how to facilitate the integration of large volumes of intermittent generation in electric power systems, either to mitigate any negative impacts or to make possible an even larger penetration level:

- What should be done to minimize any negative impact (or to maximize any positive impact) of wind or solar PV generation on power system stability?
- What should be done to reduce the uncertainty and the variability of intermittent resources
    - as an input to the unit commitment function?
    - in the determination of the volume and cost of operating reserves?
    - in balancing supply and demand close to real time?
- What should be done to reduce undesirable effects (frequent cycling of conventional plants with limited operational flexibility, resulting in loss of efficiency of these plants) of the strong presence of intermittent renewable generation in the dispatch of generation in existing power systems? In the short-term? In the longer-term?
- What should the regulation be for intermittent renewable generators as participants in a competitive electricity market?

  Case A) If they receive some regulated financial support to be economically viable:

    - As any other generator, subject to spot market electricity prices, cost of deviations from schedules and acquisition of operation reserves, and remuneration for contribution to firm system capacity.
    - Completely independent on market prices and other economic signals.
    - Not subject to spot market electricity prices or capacity payments, but receiving other operation-related economic signals regarding to deviations and utilization / contribution to system reserves.

  Case B) If they do not receive any financial support:

    - (Same as above)

On the short-term and the long-term consequences of a strong presence of intermittent generation on the power system *costs and environmental impacts*.

- Identification of types of costs and environmental impacts that could be modified.
- The effect of reduction of net demand.
- Other consequences of the presence of intermittent generation. Evaluation of other costs and / or benefits.
- Why evaluate the costs of integration of intermittent renewable generation only, as opposed to doing this for all technologies?
- What is really meant by “the back-up cost” of wind or solar generation? Is it related to the fact that wind and solar generation are presently given some kind of financial support, or the subject of mandated targets?

On the short-term and the long-term consequences of a strong presence of intermittent generation on *electricity prices*. The effect of the reduction of net demand. The effect of the nonlinear characteristics of power plant operation (costs of start-ups, ramping limits, technical minima, etc.) in the computation of the electricity market prices.

- Evaluation of the impact on final electricity prices for end consumers.
- Evaluation of the impact on remuneration of the existing generators. Should any "stranded costs" be allowed if some "unexpected" large penetration of wind or solar generation takes place in a short amount of time with regulatory support?
- Long-term impact of the price signals on future generation investments.
- Should negative electricity spot market prices be allowed? Should intermittent generation plants be allowed to bid negative prices?

On the future "well adapted" generation technology mix with a strong presence of intermittent renewable generation.

- What does a well-adapted technology mix look like?
- Does this mix need of any regulatory support? What kind of support (e.g. capacity remuneration mechanisms, some new type of ancillary service)? Implications on the design of electricity market rules.

On the need for additional flexibility in the response of power systems with a strong presence of intermittent generation.

- Is all the existing flexibility capability of the current power system being fully used already? Of the conventional power plants? Of the interconnectors? Of the intermittent generation itself? Are the market rules properly designed so that all the existing flexibility capability can be used?

On the possible existence of barriers to the deployment of intermittent renewable generation because of the distribution or transmission networks.

- How is the remuneration of the distribution activity linked to the level of penetration of wind or solar generation?
- Is the present regulation of transmission (planning criteria, responsible institutions for planning, cost allocation procedures, business models, siting processes) adequate to support a large deployment of intermittent renewable generation?

On the influence of the regulatory mechanisms to support the deployment of wind and solar production.

- Could they have an impact on the functioning of electricity markets? Could this be a matter of concern when the penetration of intermittent renewables reaches a substantial level?
- Could a "priority of dispatch" regulation be justified?
- Who should pay the direct extra costs of promoting renewables?

On computer models to evaluate the impact of large volumes of intermittent generation.

- Are existing computer models able to properly simulate the potential impacts of a large penetration of intermittent generation on power system stability, unit commitment, utilization of operating reserves, electricity costs and prices and the future generation technology mix? What improvements are needed?

On plausible characteristics and management approaches to electricity markets with very large penetration levels (e.g., larger than 50%) of intermittent generation.

- What happens when intermittent generation becomes the dominant production technology? What are the new challenges and opportunities? How could power systems cope with a “worst case” scenario?

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