IMPACTS OF INTERMITTENT RENEWABLES ON ELECTRICITY GENERATION SYSTEM OPERATION¹

I. J. Pérez-Arriaga* & C. Batlle*

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, see e.g. European Commission (2011). Wind, photovoltaic (PV) solar and concentrated solar power (CSP) with no storage have non-controllable variability, partial unpredictability and locational dependency. These attributes make an analysis of their impacts on electricity generation system operation and design particularly interesting.

This paper reviews 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. This paper identifies open issues that deserve further analysis from a technical, economic and regulatory perspective.

1 INTRODUCTION

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. 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 regulation². Those countries with substantial volumes of these technologies are already experiencing noticeable impacts on the operation and economics of their power systems.

These issues have been examined from different perspectives and there is already a significant amount of literature on this topic. 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 electricity generation 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.

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


² When talking about “intermittent” 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 authors are with the Institute for Research in Technology, Comillas Pontifical University, Sta. Cruz de Marcenado 26, 28015 Madrid. Ph.: (+34) 91 542 28 00. <{Ignacio,Carlos.Batlle}@iit.upcomillas.es>. Also with the Center for Energy and Environmental Policy Research (CEEPR), MIT, Boston, US and with the Florence School of Regulation, European University Institute.
and further. The drivers for this change could be varied, but they will not be disputed here. Instead, the paper examines the implications on operation and control of power systems and outlines the technical and regulatory measures that will be needed to successfully integrate these new technologies in an efficient and secure manner.

1.1 Intermittency characteristics of wind and solar generation

Wind and solar generation are both intermittent. Intermittency comprises two separate elements: non-controllable variability and partial unpredictability. Note that the output of a plant could conceptually exhibit much variability, while being 100% predictable. 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”. Non-controllable variability implies a likelihood that an individual plant could be unavailable when needed that is significantly higher than in conventional plants.

Wind generation is variable over time, due to the fluctuations of wind speed. Although figures are very much system-dependent, some illustrative statistics can be found in EURELECTRIC (2010): for instance, 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 expected in conventional power plants. The variability of wind generation also decreases with spatial aggregation. Wind energy output over larger geographic areas has less variability than the output of a single wind power plant.

Although forecast techniques are significantly improving over the years, predicting wind’s output is much more difficult than predicting the output of conventional generators or load. 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).

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, so it is quite well correlated with the hours of high demand of many electric power systems. On the other hand, due to the lack of thermal or mechanical inertia in PV systems, and the impact of clouds, rapid changes have been observed in the output of PV plants. Spatial diversity, as with wind, can mitigate some of this variability by significantly reducing the magnitude of extreme changes in aggregated 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.

1.2 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 (such as the hydrothermal coordination or the economic dispatch). In power systems open to

---

3 For example, at the end of 2010 the installed capacity of wind in the Spanish system amounted to 20 GW, with a wind production record of 14962 MW on November 9th, 14:46, meaning at that time 54.2% of total production. Conversely, an annual minimum of 250 MW was recorded just three months before, on August 17th, 7:11.

4 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).
competition 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.

From a reliability perspective, see NERC (2009), different timeframes are also considered. 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 effects of penetration of intermittent generation will affect decisions made at all timescales and across geographic regions, since a variable and only partly predictable source of power generation, with zero variable costs, will be brought about 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.

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 paper focuses on several salient issues related to power system operation, reviewed from the seconds-to-minutes to one-week timeframes. The review of topics in this paper is organized into three major blocks. We shall start examining the impact on the unit commitment of the generation plants, then we will deal with the way intermittent generation will affect the reserves scheduling and finally we will review how power system stability procedures will have to be modified, leaving in all cases the network aside.

2 UNIT COMMITMENT COSTS AND MARKET PRICES

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 technologies have been displaced by the wind or solar production. However, it remains the complex task of evaluating the several side effects.

In mostly thermal systems (in which storage capabilities, as for instance hydro resources, are scarce), renewable generation implies a very significant change in the scheduling regime of the rest of the generating facilities. From the operation cost and market prices perspective, the presence of wind and solar results in both a price decrease due to a reduction of variable operation costs (i.e. fuel costs) and an increase due to the extra costs derived from more frequent cycling in the operation of the thermal units. Both impacts are examined next.

Storage, at scale, represents the most straightforward way to deal with these issues. Solar thermal systems intrinsically offer some degree of storage and more can be explicitly added, and direct solar-to-fuels conversion could eventually be the game-changing solution. 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.
2.1 The “merit order” effect

Wind and solar generation directly reduce the overall supply costs, since a zero variable cost energy contribution replaces expensive fossil-fuel electricity production, see for instance Sensfuß et al. (2007) or Morthorst and Awerbuch (2009).

However, while this effect is undoubtedly significant from a cost perspective, in a wholesale generation market the price reduction may be less important. This happens when the addition of wind does not change the technology that sets the marginal price in most of the hours of the year. This is often the case in Europe with systems with a large component of combined cycle gas turbines (CCGT).

This is illustrated in the figures below. Figure 1, shows a supply function inspired in the Spanish system in 2004, plus the probability distribution functions of the annual demand and the thermal net load (resulting from subtracting from demand the hydro and wind production). On the y-axis the two resulting price distributions (with and without wind) are plotted, and a significant price decrease in the annual average price can be observed. On the contrary, Figure 2 reflects a typical supply function in 2010, significantly different due to the impact of CO2 prices and the entry of a large number of CCGT plants (resulting in a rather flat bidding curve in the price range in which marginal price is set most of the time). In this case, it can be easily checked that the average price gap between the with- and without-wind scenarios is significantly smaller.

To date, the newly installed CCGT plants worldwide are quite standard, with similar heat rates and also fuel costs within each power system. Most of the drop in electricity in electricity prices that has been observed in some of these electricity markets, as in Spain, can be better explained due to the reduction of
the CCGT load factors, and the activation of the inflexible take-or-pay clauses included in the natural gas supply contracts.

2.2 The increasing cycling needs

The second impact is due to the lack of correlation of wind production with demand. Wind output alters the shape of the net load to be satisfied with conventional thermal generation, therefore changing the traditional way to schedule the thermal portfolio. Peaks of thermal production no longer occur when demand is highest. In addition, wind production may result in such a low value of net demand (mostly at night) that will force a large number of thermal units to shut down only to have to start up a few hours later.

Figure 2 illustrates this effect for a few days in 2010 for the Spanish power system. Despite the considerable amount of hydro flexibility available in this system (controllable hydro output may contribute up to 6 GW), it can be illustrated how the large amount of wind generation in 2010 leads to significant changes in the economic dispatch that did not happen five years before. The thermal load can be significantly lower on a Tuesday than on a Sunday, and many CCGT plants (typically 400 MW in size) have to be started up daily when wind production is high at night (for instance, the CCGT output on Wednesday at 4:00 AM was limited to 2 GW while at the peak at 19:00 went over 11 GW and 0.9 GW on Sunday at 5:00 while more than 6 GW at 21:00).

Figure 3. Electricity supply in the Spanish system from Nov. 8th to 14th, 2010.

The term “cycling” refers to the changing operating modes of thermal plants that occur in response to varying dispatch requirements: on/off operation, low-load cycling operations and load following. Lefton et al. (1996) put forward a good qualitative summary of the impacts of fossil power plant cycling operation: significant increase in equivalent forced outage rate (EFOR), additional capital and

---

* For example, if a CCGT unit expected to produce 6000 hours per year and signed a contract with a pay penalty of 25% of the price for the first 5000 hours, but it happens later to expect an actual production of only 3000 hours per year (due to the large penetration of wind, or demand reduction because of the economic crisis or simply flawed investment planning) its opportunity cost (i.e. its rational bid in the market) is reduced by 25%.

7 Data taken from the System Operator's Information System (SIOS), www.esios.ree.es.
Working Paper Pérez-Arriaga & Batlle

maintenance expenditures and increase fatigue-related and creep-related wear and tear. These translates into a significant cost increase caused by operation, maintenance, and capital spending, replacement energy and capacity cost due to changed EFOR, cost of heat rate change due to low load and variable load operation, cost of start-up auxiliary power, fuel, and chemicals, cost of unit life shortening and general engineering and management cost (including planning and dispatch).

Since the increasing penetration of wind and solar is unavoidably going to lead to a significant increase of these cycling-related costs, any sound economic analysis needs to properly take these expenses into consideration, particularly due to the fact that the actual and expected costs of cycling fossil units that were originally designed for base-load operation is greater than most utilities had estimated.

In this new context, a key factor that minimizes the cost increase of the economic dispatch is the flexibility capability of the thermal plants. The cost impact of a large introduction of wind and solar will therefore be inversely proportional to the amount of existing flexible generation: the larger the inflexible capacity (older coal units and nuclear, typically), the larger the cycling costs; and the larger the flexible capability (including storage facilities and demand response services) the lower these costs.

The role of those technologies that until now have been considered inflexible (older coal and nuclear, typically) will have to diminish radically. In the future they will probably exhibit more flexibility if the incentives exist to make proper investments in refurbishing the plants and changing the maintenance contracts. Next we briefly approach this matter.

**Nuclear plants flexibility**

According to EURELECTRIC (2011), properly designed or refurbished nuclear plants may perform in a rather flexible mode. In most power systems (with probably the only exceptions of France and Germany), nuclear plants are currently operated in a pure base-load mode, mainly based on security rather than economic reasons (e.g. in Spain, the nuclear security agency rejected the possibility of allowing nuclear units to perform in a “load following” mode during the night).

If this situation persists, the presence of nuclear capacity will increase the number of start-ups of mid-range plants. If the installed capacity of inflexible nuclear plants grows, the amount of units that can pass the off-peak (night) hours at minimum load to avoid being started-up is smaller.

**The importance of the maintenance planning**

Significant costs are incurred when shutting down and starting up coal and CCGT generation plants. A considerable amount of fuel is needed to raise the boiler to its minimum operating temperature prior to producing electricity. Moreover, the heating and cooling processes intensify the wear of plant equipment that shortens the maintenance cycles. Cycling, and starting-up in particular, accelerates component failure, resulting in an increase in the failure rate, longer maintenance and inspection periods and higher consumption of spares and replacement components. The results are higher operating and maintenance costs and lower plant availability. As extensively analyzed by Batlle and Rodilla (2011), the impact of the increase of the number of starts on the maintenance of the generating units turns to be a crucial factor in the power system operation when a significant amount of renewable generation is installed.

Maintenance procedures are reflected in the Long-Term Service Agreements (LTSA), see for example Sundheim (2001). LTSAs typically commit the original equipment manufacturer (OEM) to providing, on a relatively “fixed-priced” basis, maintenance services for the equipment that they manufacture (e.g., gas turbines, steam turbines, etc.). By transferring an agreed risk to the OEM or other provider, LTSAs

---

8 The work by Prof. O’Malley’s team is a good example, see Denny (2007) and Troy et al. (2010).
Impacts of intermittent renewables on electricity generation system operation

offer turbine owners a mechanism for controlling maintenance costs and maximizing turbine reliability while minimizing the need for internal resources to manage and perform turbine maintenance. A LTSA (and accordingly its cost) can be tailored depending on the level of risk an owner wishes to take on (depending on the expected scheduling regime), its in-house technical expertise, and the age, condition, configuration and dispatch of the affected gas turbines. Thus, LTSA are priced in various ways, including per fired hour, per start, per planned maintenance event and per calendar year, but the most common methodology to determine the recommended, maximum maintenance intervals, is firstly based on the definition of a baseline that depends on a maximum number of firing hours and start-ups.

Traditionally, particularly for the case of coal and CCGT plants, which in principle were supposed to work in a mainly base-load regime, generating plants’ owners assumed that the next maintenance event would be scheduled only after the unit had reached a firing hours limit. These baseline limits, depending on the type of turbine and manufacturer, can be set up to 24,000 hours (in most cases) and up to even 1200 starts for hot-gas-path inspections. Most generators assumed that their CCGT plants would be base-loaded, so they signed LTSA contracts involving much lower limits for starts (e.g. 150 starts per maintenance cycle of 24000 hours). Now, due to the large penetration of renewables, these plants may be operating in cyclic conditions where the load at off-prime time can be as low as 40–50% of the base load and the number of starts can double. This increases the owners’ risk and may result in costly and time-consuming LTSA contract renegotiations with the OEM.

This matter turns to be much more significant (as well as difficult to solve) for the case of traditional coal plants. In this case, the problem is not just that the variable operation and maintenance (VOM) costs skyrocket when the unit is required to start and stop. The fact is that most of the existing plants have not been designed to start in any case more than a number of times (e.g. 50) per year. According to the different electric power utilities and plant managers consulted, it would not be realistic to consider that a coal plant could be operated beyond this limit.

Therefore, a large deployment of wind and solar will result in conventional thermal units increasing their cycling needs, with a corresponding augmentation of the O&M costs. This new scheduling regime alters both the operation and planning in the short and medium term as well as the capacity expansion (the future generation mix) in the long run.

2.3 Market rules: priority of dispatch, negative prices and clearing algorithms

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 behaviour 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 or a negative value, 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.

9 In the case of gas turbines (Kiameh, 2002), the parts that require the most careful attention are the combustors and the section exposed to the hot gases that are discharged from the combustors. These are known as the hot-gas-path parts.

10 This does not mean that coal technology may not evolve to adapt to the new situation. This paper just considers the standard technologies that are presently available.
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 it may constrain what otherwise would be the optimal unit commitment, whether based on generators operating costs or bids. Note that conventional generators may be willing to bid negative prices to avoid being shut down. This is normal rational economic behaviour of the agents in a competitive market and should not be interfered with. 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, although this could not be considered acceptable.

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. The link between negative prices and renewable support mechanisms has to be carefully examined. Note, however, that negative prices may occur in the absence of intermittent generation.

Large wind penetration amplifies the differences in the diverse pricing rules of the numerous electricity markets. As illustrated also by Batlle and Rodilla (2011), the effect of the nonlinear characteristics of power plant operation (costs of starts, ramping limits, technical minima, etc.) in the computation of the electricity market prices and thus in generators income differs significantly in those markets in which a non-linear pricing approach plus discriminatory side payments is implemented (in which marginal prices do not include the effect of non-convex costs, e.g. PJM or ISONE) from those in which a convex-hull or linear pricing approach is implemented (an hourly uplift perceived by all producers is added to the marginal price, e.g. Ireland) or just simple bids are accepted (most European markets). In these latter cases, the market operator when calculating the market price or generators when designing simple bids, must internalize the nonlinear costs in shorter functioning periods, resulting in higher bids and, consequently, higher marginal prices for consumers.

Additionally, as discussed in Batlle et al. (2011), when remuneration of RES-E installations is tied to short-term energy market prices, RES-E receive market signals that may lead to more efficient operations, but, conversely, this approach also creates incentives for incumbent generators to increase their market power by assembling a generation portfolio that includes both RES-E infra-marginal capacity and conventional units. Thus, the more suitable alternative would be to set a fixed remuneration per MWh produced from non-dispatchable RES-E, regardless of the value of spot prices. However, to encourage the improvement of the forecast of the output of these non-dispatchable plants, generators should be exposed to the balancing markets and be responsible (partly, at least) for the costs incurred by deviations from their declared schedule.

All these issues should be taken into consideration when evaluating the impact of intermittent generation on electricity prices for end consumers and on the remuneration of the existing generators.

3 REQUIREMENTS OF OPERATING RESERVES

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. See also Milligan et al. (2010) for a thorough international review of definition and use of 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 et al. (2011).

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:

- The 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. Also, 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. 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 CCGT’s plants, to provide load following and supplemental (tertiary) reserves. Therefore, improvements in wind plant output forecasting offer a significant opportunity to reduce the cost and risk associated with this uncertainty (Lew et al., 2011). 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.

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.

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.

**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. One of them is the integration and coordination of balancing areas: the 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. 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 areas⁴; see, for instance, Parsons et al. (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, and benefitting competition, removing entry barriers for new and small generation and retailing companies.

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 (e.g. the US power markets), while in others balancing energy transactions are scheduled one or two hours before real time (as it is the case in many EU power markets). 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, providing intraday markets to adjust previous positions in day-ahead markets and closer to real time balancing 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 generators (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 frequent scheduling (within and between areas) may significantly reduce the variability impact 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, mandatory Framework Guidelines has been recently adopted in the European Union with some of 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).

4 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).

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

---

⁴ For instance, in the US, New York, New England, and Texas are each tightly integrated and have one balancing authority each, while Arkansas and Arizona each have eight and Florida has eleven (MIT, 2011).
Impacts of intermittent renewables on electricity generation system operation

In principle, the inertial response of wind turbines and solar PV plants to the overall power system is almost negligible. Therefore, 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. 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).

The good news is that wind generation is technically able to actively participate in maintaining system reliability along with conventional generation. It is now possible to design wind 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.

**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 Martínez de Alegría et al. (2004) or Gautam et al. (2009).

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. 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. 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**

Voltage control can also be implemented in wind power plants, which, as well as PV plants, 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. Voltage ride-through can be achieved with all modern wind turbine generators (GE Energy, 2005), 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.

In summary, 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 et al., 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. Also, 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. These features are considered essential for the future integration of high wind penetration in electric power systems.

5 CONCLUSIONS

This review of operational impacts of intermittent generation shows the multiple challenges that most power systems will have to face in the future, as well as general guidelines to successfully address these challenges and the multiple open issues that require further research. There is overwhelming evidence that system operation practices and power sector regulation will have to adopt innovative approaches. The main message is, therefore, that system operators and regulators should act quickly to avoid that reality runs over current operation and regulatory practices, leading to inefficient and less reliable outcomes. System operation and electricity regulation must pave the way for a future power system where wind and solar will play a major role.

6 REFERENCES


