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Evaluation of International Curtailment Practices for High Wind and PV Penetration

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SUMMARY

With reduction in costs of wind and solar power, as well as various policy and other factors, utilities and other organizations around the world are faced with the challenge of integrating increasing penetrations of variable renewable resources. Flexibility of power systems will be a key attribute to integrate variability and uncertainty associated with wind and solar output. As well as traditional dispatchable generation, this flexibility can come from energy storage, demand response and increased transmission buildout, as well as operational and market mechanisms, and coordination between regions. One of the flexibility options to help integrate renewables more smoothly is curtailment (dispatch down) of the resource at appropriate times.

In order to understand this issue, and inform decisions being taken in Japan and elsewhere, the Electric Power Research Institute (EPRI) and Tokyo Electric Power Company (TEPCO) recently surveyed the current state of the art in this area. This paper describes the outcome of surveys of current research and literature, compilation of key or unique elements of international standards, and analysis of fundamental themes, challenges, or potential concerns, related to curtailment of renewable resources in systems with high renewable penetration. It is not an exhaustive summary, but a discussion of the most relevant issues related to this topic.

We show that there has been significant experience in control of large, transmission-connected wind and, to a lesser extent, solar power plants. Distributed resources have not been typically controlled or curtailed to the same extent, though in countries such as Germany and Ireland that is beginning to happen. Many systems now regularly dispatch renewables, for either reliability or economic reasons; most of the US ISO/RTO regions include wind in their dispatch process. We find that automatic curtailment, such as automatic generation control or economic dispatch of renewables, has the potential to improve efficiency of system operations significantly over the manual curtailment that was traditionally used, as it can be targeted to the more opportune time periods. While applying these methods to PV generation is still in its infancy, similar

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approaches that are used for wind are expected to provide the most benefits. Curtailment as a percentage of energy is still relatively small, but some allowance for curtailment can have a significant benefit in integration of renewable resources in a reliable and efficient manner.

This paper includes the description of the need for flexibility resources to put curtailment of wind and solar PV in proper context with other options. Motivation for curtailment and different applications is then discussed. Curtailment practices are described for several system operators in the US and Europe. Finally, conclusions are drawn as to how curtailment and the ability to control active power output can be used to improve integration of wind and PV.

KEYWORDS

Curtailment, variable generation, flexibility, protocols

1.0 Introduction

One of the key findings in integration of Variable Generation (VG) over the past decade has been the need for flexibility [1-3]. There are many sources that can contribute to meeting the increased need for operational flexibility. These include conventional generation, demand side response, energy storage, and increased available transfer capability among regions, which allows for sharing of flexibility needs and resources. Most pertinent to this study, flexibility can also be obtained by active power control of wind and solar power. In the past decade, significant work has been done on the provision of active power control from wind, and more recently studies have been done for solar power [4-6].

There are multiple reasons why VG curtailment is used in system operations. Until recently, these were mainly focused on avoiding potential reliability issues, however recently there has also been more consideration of economics and the ability of a small amount of curtailment to improve economic efficiency, even while spilling zero marginal cost energy resources. In order to better understand the context of curtailment of renewables, and help guide policy in other regions, current practices were thus surveyed and are described here.

The rest of the paper is structured as follows. First, the need for flexibility is described, and different flexibility resources discussed, to put curtailment of wind and solar PV – referred to collectively as VG - in proper context with other options. Motivation for curtailment and different applications is then described. Curtailment practices are described for several US system operators, followed by experience from other regions. Finally, conclusions are drawn as to how curtailment and the ability to control active power output can be used to improve integration of wind and PV.

2.0 Flexibility to Integrate Variable Generation

For the purposes of this paper, flexibility is defined in an operational context as the ability of the system to ramp and cycle resources to maintain a balance of supply and demand on timescales of minutes to hours through reliably operating the system at least cost. It has been shown that wind and solar can be used to provide active power control, so long as inverter controls are in place, and the control and communication capabilities are available. In particular, for large wind and solar plants, the capability to control output has always been present, mainly to reduce output during periods when there is a need. More recently, this capability has been included in many markets as part of the economic decisions made during scheduling and dispatch, as described later.

This ability to curtail should be included as one tool in an operator's toolkit for efficient and reliable integration of VG. It should be considered with many other options, including both physical and institutional sources of flexibility. Institutional sources of flexibility include the use of wind and solar forecasting, improved operating practices such as shorter scheduling intervals or the use of forecasting, and increased coordination among neighboring regions. In particular, institutional approaches can be seen as the first steps ('low hanging fruit') for integration of VG, and should be explored before other sources of flexibility, including curtailment. NREL have developed a conceptual curve for flexibility sources, as adopted with small alterations by EPRI in **Error! Reference source not found.** This shows that, conceptually at least, using variable renewable sources to provide flexibility can be a relatively low cost means to provide reserves and flexibility to system operators. As such, it is important to understand when and how one would curtail, and describe experiences of numerous systems across the world.

Clearly, the fact that these resources have zero marginal costs implies that one would want to reduce the amount of curtailment or downwards dispatch from these resources. However, occasionally the fact that these can be curtailed can help improve system operations, from reliability or economics perspectives, and thus the capability should be considered appropriately.

3.0 Curtailment Mechanisms and Methods

Based on surveying numerous systems in the US and Europe, there are multiple reasons why curtailment is used in system operations. Reasons for curtailment can be summarized as follows:

Congestion-based curtailment: Here, curtailment is used in a particular location as there is insufficient transmission capacity to allow power to flow from a given location without overloading lines. In such cases, wind or solar power is reduced to an amount that can be managed. These types of situations may occur due to lack of transmission capacity to a given region, or may be due to line outages for maintenance or after faults. Examples of this type of curtailment are found in most cases; in some situations, the curtailment may be signaled economically through LMPs where they exist; otherwise the curtailment is done manually to avoid reliability issues.

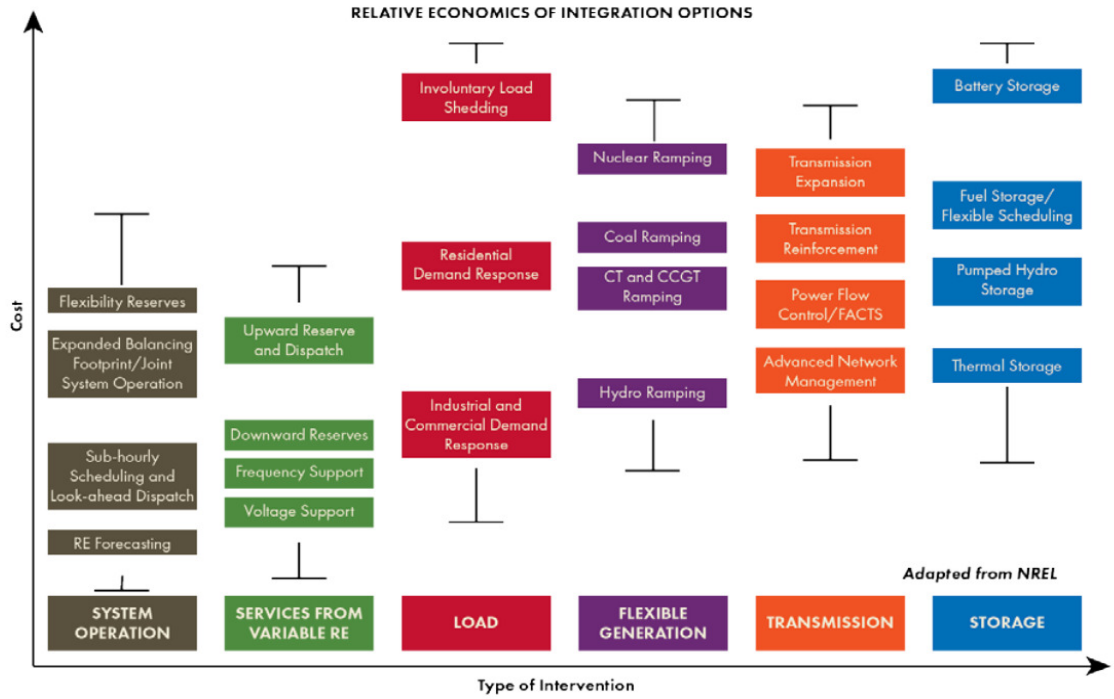

Figure 1: Conceptual figure showing relative economics of different integration options. Source: [1]

Economic/balancing: This type of curtailment refers to situations where curtailment happens to avoid the increased costs associated with cycling generation on and off to manage wind power. It may be less efficient for example to shut down a coal unit that cannot be started up again for several hours, and instead a few hours of curtailment may make more sense from a system economics perspective. In regions of Independent System Operators (ISO), this should be indicated by prices (e.g. LMPs in US, system prices in Europe) becoming negative below the price at which wind is content to keep generating. In non-ISO regions (e.g. Public Service Company of Colorado (PSCo)), this calculation is made by the system operator who determines it may be cheaper to keep certain generation online and curtail wind/solar.

Other reasons: The other reasons include the need to curtail renewables, particularly solar PV, when instantaneous penetration levels become too high for a given distribution system. One particular learning from some very high penetration cases is that there may be a need to limit the total non-synchronous penetration (typically, wind and solar) at any given time, in order to ensure that there are sufficient resources from conventional generation to provide frequency response after a fault - sometimes referred to as the System Non-Synchronous Penetration (SNSP) limit. In order not to exceed this limit, curtailment may be required.

Clearly, the above reasons for curtailment will often overlap – for example, economic curtailment due to needing to keep generation online may coincide with high SNSP, or congestion in particular areas. However, to date most curtailment has been driven by the first reason, lack of transmission.

3.1 Signals and verification

In terms of signaling curtailment, two major categories of signaling are used:

Automatic signaling: Signals are sent as part of the economic dispatch, or in some cases as part of Automatic Generation Control (e.g. in Colorado). Often, this is referred to as ‘dispatch down’ as opposed to curtailment, but it ends up with a similar outcome, i.e. the output is reduced. Many of the US ISOs use the Inter Control Center Protocol (ICCP), which provides for automatic remote control of generation facilities. The Supervisory Control and Data Acquisition system (SCADA) is the software application often used for this signaling. For example, MISO, SPP and others use this protocol when signaling to wind plants that they need to be curtailed. This would involve sending a basepoint signal every 5 minutes; if curtailment is needed, this will be below their current output level. Some ISOs, such as PJM, will follow this up with a phone call to the wind plant operator; this is less likely in regions where wind on dispatch is more common. The ability of the wind plant to follow the signal is verified, and plants must follow the signal within a certain degree of error.

Manual curtailment: Here, manual curtailment refers to the need to curtail plants outside the normal SCADA system. This is typically done by phone calls. As this is not automatically part of the dispatch process, it leads to suboptimal amounts of curtailment. It can take several minutes (up to 30 is a typical number) for these instructions to be put through, and thus curtailments typically last longer than needed, and operators will tend to be more conservative when knowing that it will take some time to happen. Thus, most regions with higher wind penetrations no longer use this method to signal to wind plants to curtail; it is expected that larger solar plants will be similar.

The order in which curtailment happens varies across different regions. In situations where curtailment is based on economics, typically the curtailment order is automatic, similar to the way conventional generator dispatch is determined. For congestion related situations, curtailment should be, and typically is, based on curtailing the generation that is most effective to relieve congestion. For balancing or system wide regions, several factors are considered. Some regions will see different costs to curtailment, based on costs negotiated in the Power Purchase Agreement (PPA), and thus more expensive units will be dispatched down first. In some cases, offtakers have negotiated a set amount of 'free' curtailment hours, and they would be used first. Finally, some regions either curtail all equally or have a 'last-in-first-out' policy, whereby newer plants are curtailed first. Hawaii is a good example of the latter policy, where their utility scale wind and solar is curtailed in reverse installation order.

3.2 Forecasting and Curtailment

All ISOs in the United States, and most balancing authorities in non-ISO regions, now use a state-of-the-art wind forecasting system; some are also now forecasting solar. Typically, this is provided by a third-party provider (though in some utilities, in-house forecasts are also developed), who provides an output forecast at suitable time resolution for the system operators. For day-ahead, this will require a forecast being made typically the morning prior to operations, with updates throughout the day before and day of operations, at an hourly resolution. Shorter term forecasts at higher resolution (e.g. 5-minutes) may also be made, though typically, persistence forecasts are used in these time frames, where output is assumed to stay constant in the immediate future. For wind, this method typically outperforms any skilled forecast from horizons of 20-30 minutes and longer. Solar may require persistence forecasts to be modulated based on clear sky conditions, to allow for movement of the sun over the forecast horizon.

In most regions, the central forecasts are used to make dispatch decisions about wind and solar power. Wind and solar plants can provide their own forecasts in some places, but those that do not follow the central forecast tend to be exposed to penalties, and therefore need to be confident that their forecast can outperform the central forecast over time. These forecasts are then used to determine the need for curtailment. They can also be used to track the expected current output, were curtailment to be used. For example, in Ireland, PSCo and others, when wind is curtailed, operators are still aware of the likely available wind power were the curtailment to be released. One challenge associated with both wind and solar curtailment is related to understanding what the output could be if the curtailment is released. For solar, this will require being able to understand irradiance, and thus will require instrumentation; this is normally available for larger utility-scale plants but may not be available for all plants. Wind speed is required to understand potential wind output.

3.3 Compensation and payment

As described above, there are different underlying reasons for curtailment. Typically, each of the result in different compensation mechanisms. For many years, the typical method for compensation was a 'take or pay' type approach, whereby offtakers of wind and solar would pay for the energy, whether curtailed or not. In some cases, some curtailment may have been allowed (i.e. a certain number of hours per year), before compensation was required. More recently, newer contracts in areas with high penetration rates (e.g. Xcel in Colorado) have started to outline specific reasons for curtailment, and in some cases compensation is not required. For example, some areas do not compensate if curtailment is carried out due to emergency conditions, or due to transmission congestion. Bonneville Power Authority (BPA) does not compensate when wind is curtailed to its scheduled hourly output to ensure balancing reserves are maintained. In California, wind and solar plants can be curtailed without compensation up to a certain number of hours, above which the investor owned utility (IOU) that has signed the PPA needs to compensate the plant owner.

When wind is included as part of the economic dispatch, as in MISO and SPP, it is not typically compensated -instead price signals are sent based on the level of negative pricing that the wind plant is willing to be exposed to. If they are asked to deviate from their schedules beyond this for other reliability reasons, they are normally compensated. In PJM, only wind that can be curtailed automatically is compensated. For all ISOs, even if there is no curtailment through the market, offtakers may have negotiated some form of compensation to wind plant owners as part of the PPA.

4.0 Curtailment practices and experiences in selected US entities

There has been significant growth in wind and solar over the past several years in the US, and as such there has also been an increase in experience with renewable curtailment. The vast majority of this experience has happened with wind power, although solar has started to become significant enough that curtailment of solar is now also being seen, especially in places like California and Hawaii. The most common reason for curtailment in most regions is due to lack of transmission infrastructure, where curtailment is needed in order to maintain transmission lines within their limits. The below figure shows the percentage of potential wind generation that was curtailed in a few select regions (note, solar would be significantly lower). Note that ERCOT has seen a significant reduction in curtailment, attributed mainly to increased transmission being built to renewable energy zones in the Texas panhandle, and the move to a 5-minute nodal market allowing significantly more efficient pricing to ensure flexibility in the system.

As can be seen, even though total wind energy has increased over the time period covered, curtailment has reduced significantly. Several different reasons have been proposed as likely candidates. The buildout of new transmission in ERCOT, as well as the ability of the system operators to include wind power in the automatic dispatch, are the most likely reasons for the reduction in total curtailment. In any case, the total curtailment likely reduces the capacity factor of these plants by approximately 1%-3%, depending on the year.

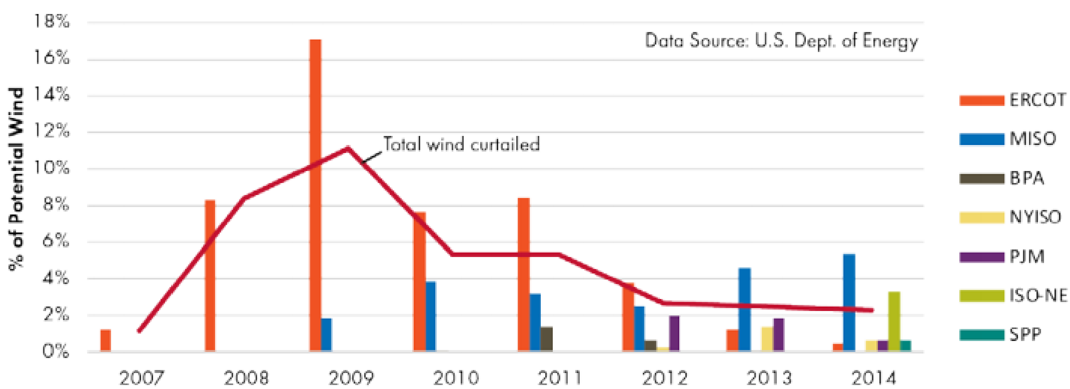

Figure 2: Curtailment in selected regions across the US in past several years. Source: [7]

5.0 Curtailment practices and experiences in non-US entities

As well as experiences in the US, as described in the previous section, there has been significant experience in other countries around the world worth examining.

Germany: Renewable penetration in Germany has grown very quickly over the past decade. Solar power has gone from approximately 1 GW to approximately 40 GW between 2004 and 2015, while wind power has increased from approximately 16.6 GW to 45 GW over the same period. Together, they provided over 18% of electrical energy needs in 2015. In some periods, over 70% of energy requirements was met by wind and solar (though exports mean that total share of generation was lower). Curtailment in Germany is used for different reasons yet it has mainly been driven by congestion and balancing issues. Different legal structures are in place depending on the reason for curtailment. German DSOs and TSOs can control any DER over 30 kW, with 100kW and larger requiring two-way communication and control. In total, just over 1% of total energy from wind and solar was curtailed in 2014; this is still a relatively small amount, but is over twice that in 2013 [8]. The estimated cost of this is 82.7 million Euros. Most of this curtailment was due to the fact that wind in the north could not reach demand centers in the south, due to lack of transmission. As such, Germany is planning to build large HVAC and HVDC links from the north of the country to the south to reduce curtailment and better integrate renewables.

Ireland: As an island with a very good wind resource, Ireland has installed a significant amount of wind capacity in recent years. Total installed generation capacity on Ireland is approximately 10.3 GW (7.6GW in the Republic of Ireland and 2.7 GW in Northern Ireland), of which, in mid-2016, approximately 3.1 GW is wind power. Approximately half of the wind is on the distribution system, so TSO/DSO coordination is crucial; this is an area of ongoing effort, and has been closely coordinated and studied, with larger distribution connected wind farms providing reactive support. The vast majority of the installed wind is onshore. Eirgrid use a metric called System Non-Synchronous Penetration (SNSP) to manage the maximum amount of non-synchronous generation. This is calculated as a percentage of total generation (not load), and is based on detailed planning studies that examine frequency response, voltage stability, short circuit strength, etc., to identify potential operating limits that are then used in operations. Wind is curtailed if this amount is reached; currently the limit is set at approximately 55%. Total curtailment in 2014 was about 4.4% of energy, with over half due to system balancing issues [9].

Italy has the highest solar power penetration in the world, with over 8% of total generation in the country coming from solar in 2014 and over 19 GW currently installed. Typically, much of the PV is distributed, with some larger plants also present. Additionally, wind power, with a little less than 10 GW installed, provided over 5% of total demand in 2014. Curtailment has been high in the past in Italy, as much of the wind and solar power is in the south of the country. This caused transmission congestion, and meant that curtailment of total output was nearly 10% in 2009. However, network upgrades and extensions has reduced this amount significantly, and it was lower than 1% by 2012 [10]. In contrast to Germany, where the TSO has to request the DSO to control or curtail PV output, in Italy the TSO (Terna) has the ability to curtail output of PV installations. This ability to shut down plants for security reasons showed up most noticeable during the solar eclipse of 2015 [11]. While Germany had to manage the reduction and subsequent increase in solar by procuring a significant amount of balancing reserves, the Italian system could switch off all PV installations greater than 100 kW, thus significantly reducing the costs of managing this type of event. This shows how, even if only used sparingly, this ability is crucial for efficient integration of PV and wind power.

6.0 Summary and Conclusions

This paper describes experiences and lessons learned from several different regions for integration of wind and solar into system operations. Flexibility is key to the successful integration of variable energy resources. This includes the ability to ramp the system up and down over multiple hours. Flexibility can be obtained from conventional generation, energy storage, demand response and can also be obtained by increased interactions between neighboring region s.

Institutional sources of flexibility are also important. These include improved system operation methods, the use of advanced wind and solar power forecasting, and the ability to curtail wind and solar power when it is effective to do so. There has been significant experience in control of large transmission-connected variable generation, in particular wind energy. At first, this was mainly to aid in reliability and ensure thermal and voltage constraints were respected, but recently these resources have been used to improve system economics (e.g. Dispatchable Intermittent Resources in MISO).

As wind and solar have zero marginal costs, it is desirable to obtain as much energy from them as possible. However, occasionally there will be a need to reduce their output, to aid in maintaining or improving system reliability and/or economics. PPAs and other contractual and regulatory schemes need to evolve to recognize that curtailment is an option, but that it should be used effectively. Examples include agreement on how often, and under what conditions, curtailment can occur, how it can be compensated for, and how renewables can provide certain services. Market signals should be designed to complement these capabilities and recognize the limitations inherent in variable generation. For example, making decisions as close to real time as possible improves forecast accuracy.

Inverter based generation is well suited to be controlled, once the underlying weather patterns are considered. Automatic curtailment in system operations, such as economic dispatch and AGC, improves system operations substantially. Many regions are now moving to including automatic curtailment in more functions, and reducing the less efficient manual curtailments, which have typically been done by phone. In some cases, the inverter based capability for active power control, particularly for larger generation, is already being used to provide system services, such as AGC and Primary Frequency Response. This helps maintain reliability, and may result in additional revenue streams for variable generation.

Forecasting and communications are both crucial to successfully integrating curtailment mechanisms in system operations. Forecasting allows operators to understand how much wind and PV may be available, and thus determine how it can be most effectively curtailed. Distributed resources, including distributed PV, have not been curtailed to the same extent. However, some regions (e.g. Italy) do provide control over systems, typically over a certain size (e.g. 30 kW), to avoid reliability issues. It would be expected that operators would first have some level of control and visibility over these regions, while future activities could involve understanding more sophisticated functions, individually or in aggregate.

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