Wind and Solar Curtailment

Preprint

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To be presented at the International Workshop on Large-Scale Integration of Wind Power Into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants
London, England
October 22 – 24, 2013

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Office of Energy Efficiency & Renewable Energy
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Conference Paper
NREL/CP-5500-60245
September 2013

Contract No. DE-AC36-08GO28308

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Abstract—**High penetrations of wind and solar generation on power systems are resulting in increasing curtailment. Wind and solar integration studies predict increased curtailment as penetration levels grow. This paper examines experiences with curtailment on bulk power systems internationally. It discusses how much curtailment is occurring, how it is occurring, why it is occurring, and what is being done to reduce curtailment. This summary is produced as part of the International Energy Agency Wind Task 25 on Design and Operation of Power Systems with Large Amounts of Wind Power.**

Keywords-wind; solar; curtailment; transmission congestion

I. Introduction

In many regions, wind and solar generation are preferred instead of conventional generation because of their emissions benefits; policy, legislation, and/or incentives may be established to encourage the use of wind and solar instead of conventional generation. Additionally, wind and solar have zero or very low marginal costs, which means that as long as a system operates within transmission and operating constraints, wind and solar tend to displace conventional generation. However, increasing wind and solar penetration levels may drive a system to encounter transmission or operational constraints, forcing the system operator to accept less wind or solar than is available. High levels of wind and solar power can be challenging to integrate into power systems because of their variability and limits in predictability. When high levels are planned, infrastructural, operational, or institutional changes to the grid may be necessary. During this transition phase, curtailment may be higher than after the changes are made. We use the term *curtailment* broadly to refer to the use of less wind or solar power than is potentially available at that time.

There are many reasons for curtailment, and system operators may distinguish between these reasons for compensation and accounting purposes. The main reasons for wind and solar curtailment are listed below.

Transmission congestion, or local network constraints, is a common reason for system operators to utilize higher marginal-priced resources instead of less expensive resources. Related to congestion is insufficient transmission availability. Because of the mismatch in construction times, wind power plants may be built somewhat in advance of the necessary transmission to transport those energy resources to load centers. These new wind power plants may be curtailed until transmission infrastructure is commissioned.

Minimum operating levels on thermal generators are another driver for curtailment. Wind, in particular, is often stronger at night, when loads are low and thermal units are pushed down against their minimum operating constraints. A related issue is the requirement for downward reserves. If wind and solar are unable to provide downward reserves, then sufficient downward capability may need to be held on thermal units, raising their operating levels.

Hydro plants may also have minimum operating levels because of environmental, recreational, or irrigation constraints. For example, to comply with limits on dissolved gases to protect fish, operators may be required to run water through their turbines rather than spill water over a dam.

Curtailment can also occur in the distribution system to avoid high penetrations or back-feeding, in which a feeder produces more energy than it consumes, of distributed generation on feeders, which can lead to voltage control issues as a result of variability of the wind or solar resource. Back-feeding can be problematic if protection devices and other infrastructure were not designed or are not yet adapted for this type of operation.

Finally, limits may be placed on nonsynchronous generation levels to maintain frequency requirements and stability issues,

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especially on small, isolated grids. Modern wind and solar power plants interconnect to the grid through power electronics. Because they displace conventional synchronous generation, which provides inertia and may provide governor response, system frequency response might suffer if a contingency event occurs when there is a high penetration of nonsynchronous generation.

II. Experiences with Curtailment

A. Canada

Hydro Quebec (HQ) currently has 1,500 MW of installed wind power capacity (5% energy penetration) and expects to have 3,000 MW of installed capacity (10% energy penetration) by 2016. TransÉnergie, the transmission system operator (TSO), assumes responsibility for system security. The distributor purchases power from wind developers, estimates the cost of lost energy using wind resource data, and compensates the wind plant operator.

To date, curtailments have been caused by technical faults, and neither voluntary nor mandatory losses have occurred. However, additional installed wind capacity is planned for the Gaspésie Peninsula and will likely result in curtailment caused by congestion. It may also result in increased voluntary curtailment to ensure system stability.

Given the current projection for 2016 wind penetration levels, HQ does not anticipate significant curtailments in the near future. For similar reasons, HQ has not yet considered valuing curtailed generation as a source of system operating reserve or strategized how to reduce future losses.

B. Denmark

At the end of 2012, 4,443 MW of wind power was installed in Denmark (3,280 MW onshore, 1,163 MW offshore), mostly in the Western Danish system. These installations produced 10.3 TWh electricity (6.8 TWh onshore, 3.5 TWh offshore), which is a 30.1 % share of Danish electricity consumption (peak load in 2012 was 6,106 MW). According to Danish Energy Policy, wind capacity is expected to increase by 44% by the year 2022, leading to 20.5 TWh annual production. Policy targets include a 30% renewables share of Danish energy consumption in 2020 (heat and electricity), corresponding to 52% of 2020 electricity consumption sourced from wind.

Wind integration on this scale is supported by strong interconnections to neighboring systems and functioning international electricity markets, including negative price signals to incentivize wind to dispatch down. All wind power is traded in the markets (day-ahead and intraday power markets), either by production balancing actors or by the Danish TSO. Wind owners are compensated at slightly more than the market price. Compensation for large offshore wind plants is negotiated during the tendering procedure.

In 2012, there were 405 hours during which wind production exceeded consumption in the Western Danish system and none in the Eastern Danish system. During these hours, the high-voltage direct current (HVDC) connections between the Danish systems and the hydro-based systems in Norway and Sweden are valuable because wind power can be sent to where it can be used.

An unusual situation occurred on December 25, 2012: spot prices in Denmark and Germany were negative because of surplus energy in both systems. (See Fig. 1.) However, German prices were below Danish ones, causing an import to Denmark while Danish producers’ bids had been curtailed to balance demand and supply at the minimum price floor of -200 €/MWh. (See Fig. 1.) During these hours, consumption was very low, market actors with heating boilers were not paying enough attention to the market and hence did not activate their boilers, and interconnection capacity to Sweden was reduced to limited export possibilities. Most importantly, wind in both Denmark and Germany was high, and total Danish central thermal production was at a low level of 630 MWh/h to 900 MWh/h during the critical hours, but electricity was imported from Germany despite negative prices. Among the bids, which were curtailed pro rata, may have been those from wind.

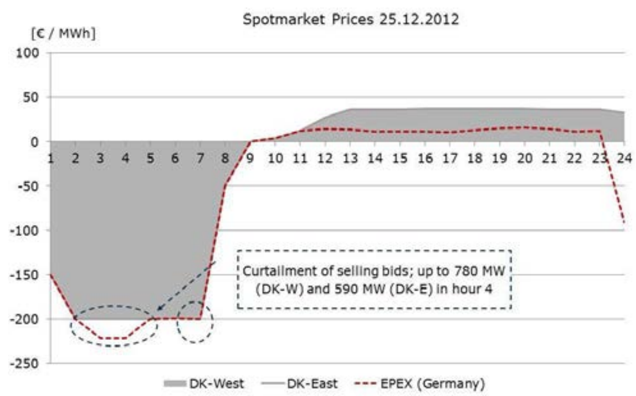

Figure 1. Spot prices in Denmark and Germany on December 25, 2012.

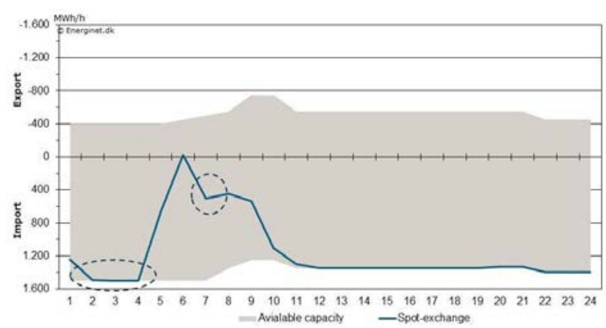

Figure 2. Exchange between Denmark and Germany on December 25, 2012.

To avoid this situation in the future, the following improvements have been recommended. Market actors should increase their focus on risk for extreme prices and be prepared to act accordingly. Offshore wind power plants should not be compensated by fixed feed-in tariffs during periods of negative prices. Import capacity to Germany should either be reduced during these situations, or the negative prices should be harmonized at both sides of the border. The process toward harmonization of prices will probably include a reduction of the current minimum price floor in DK from -200 €/MWh to -500 €/MWh, because this will increase the probability of the market being balanced by price rather than by curtailment in surplus supply situations. The spot market should be reopened for a second auction in case prices appear to be out of a predefined interval. (This is treated differently at both power exchanges.)

C. *Ireland*

In 2012, Ireland, with an installed wind capacity of 2.1 GW, dispatched down 110 GWh (2.1% of available wind energy). Approximately 80% of this was caused by systemwide reasons, whereas the remainder was a result of local network constraints. (See Fig. 3.)

Typically, curtailment occurs during periods of low demand, most often from 23:00 at night to 09:00 in the morning, when the minimum generation levels of conventional plants are imposed. Five types of security limits have been defined that could necessitate curtailment, including system stability (synchronous inertia, dynamic and transient stability); operating reserve; voltage control; morning load rise; and, exceedance of the system nonsynchronous penetration (SNSP) limit. The SNSP limit, defined as the ratio of nonsynchronous generation (wind and HVDC imports) to demand plus HVDC exports, follows from the Facilitation of Renewables studies [1], which proposed an upper limit to this ratio (currently 50%) for system stability reasons.

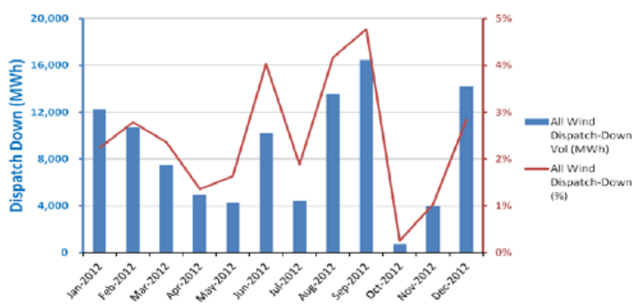

Figure 3. Dispatch-down of wind in Ireland in 2012 [2].

In contrast, local network constraints may occur throughout the day and are typically imposed because of network limitations, with the northwest and southwest part of the transmission system being most affected. Other parts of the network have also experienced constraints primarily because of maintenance outages.

A number of grid rollout programs are in place to minimize constraint levels. Similarly, the Delivering A Secure Sustainable Electricity System Program [2] proposes various plant performance monitoring and new ancillary services, including a synchronous inertial response, fast frequency response, and fast post-fault active power recovery, which will enable the SNSP limit to be raised from 50% to 75%, which is estimated to reduce the level of curtailment from more than 15% to approximately 6%. As part of grid code requirements, wind turbines have the capability to provide reserve when dispatched down; however, this capability is not currently being utilized.

D. *Italy*

In Italy at the end of 2012, the installed capacity of wind and photovoltaic (PV) was 8.1 GW and 16.6 GW, respectively, with total energy penetration at 9.8% in 2012. (In southern Italy, the energy penetration was 31%.) Most wind power plants (more than 95%) are connected to the transmission grid at the 150-kV voltage level and located in the south of Italy. Most PV plants are connected to the distribution grid at the medium- and low-voltage level (more than 95% of the PV capacity, corresponding to approximately half a million plants).

Wind curtailment occurs sometimes during low-load days when there is consistent solar and wind production. Curtailment is undertaken to relieve congestion and maintain adequate reserve margins when no other actions on conventional generators are possible (conventional power plants at minimum generation level). In fact, in these situations, the instantaneous penetration of PV and wind can exceed safe system operation levels in terms of reserve margins, voltage profiles, and dynamic stability issues.

In the past four to five years, significant grid investments have been made that have increased the transmission capacity within and between market zones, reducing wind curtailment, as shown in Table I.

TABLE I. CURTAILMENT IN ITALY

Year	*2009*	*2010*	*2011*	*2012*
Total wind generation (GWh)	6,543	9,126	9,856	13,407
Curtailment (GWh)	700	527	264	166
Curtailment/Total wind generation	10.70%	5.77%	2.67%	1.24%

The cost of curtailment is borne by the system, and the TSO has an incentive by the Italian regulator to reduce the amount of curtailments that are determined ex post by a third-party company.

Investments in battery storage (energy and power intensive) are in progress in southern Italy to increase the flexibility of the system to reduce levels of wind and solar curtailment, local congestion, and spinning reserves.

E. *Japan*

In Japan at the end of 2011, the installed capacity of wind and PV was 2.4 GW and 4.9 GW, respectively, with total energy penetration at 0.9%. Even after the Feed-in Tariff (FIT) Act (The Act on Special Measures concerning the Procurement of Renewable Electric Energy by Operators of Electric Utilities, Act No. 108 of 2011) was enforced in July 2012, utilities can curtail wind and solar for a maximum of 30 days (8% annual) without compensation. These curtailment requirements are stipulated in the Ministerial Ordinance for Enforcement of the FIT Act (No. 46 of 2012). Some utilities have required wind developers/owners to install secondary batteries onsite to mitigate wind variability in addition to the 30-day uncompensated curtailment.

Priority dispatch is not given for renewables in Japan. Description on the priority dispatch is not in either the FIT Act or the Ministerial Ordinance. According to the latest grid rule stated by the Electric Power Council of Japan, curtailment of wind and solar should be undertaken *before* other measures such as interchanges between utilities, curtailment of other power producers and suppliers (independent generators with mainly conventional combustion plants), and/or curtailment of baseload generators. Information is not available on the actual amount of curtailment that has occurred because utilities have not published this data.

F. Portugal

At the end of 2012, Portugal had 4,517 MW of wind power capacity installed (20% energy penetration). Legislation restricts curtailment of renewable energy generation except in the case of technical problems. Despite several instances of excess wind (and other nondispatchable plants) in recent years, the Portuguese TSO has yet to invoke technical problems to curtail wind. For the purpose of the current paper, excess generation in the Portuguese control area that is transmitted to Spain at zero value is called curtailment.

Excess renewable energy generation occurs in times of low loads and high wind. Generation from nondispatchable combined heat and power (CHP) industrial plants tend to further increase the supply of energy with high generation during nighttime periods of low demand.

Portugal typically manages high-penetration events by controlling production from run-of-river hydro plants, exporting excess power to the Spanish energy market, and halting the import of electricity from France through Spain. Portugal has two dispatch centers that enable the monitoring, control, and curtailment of a large fraction of wind generation during high-supply/low-demand periods [3,4].

The FIT legislation requires wind producers to be compensated only for losses that exceed 50 hours at full capacity, the value of which is calculated at the tariff payment level. Because of the economic burden introduced by these situations and significant installed wind power capacity, new connections of wind power plants to the transmission system have been halted until 2020, the only exception being one 75-MW offshore installation.

The Portuguese regulator is currently analyzing the halting of electricity imports during excess electricity events and has made an initial recommendation that this procedure be substituted by countertrading.

G. Spain

As of 2012, Spain had 22.6 GW of wind installed (18.1% energy penetration). Red Eléctrica de España (REE) is the Spanish system operator that manages the distribution and transmission system. In Spain, wind curtailment typically occurs when demand is low and wind production is high. Through most of 2009, curtailments were primarily because of inadequate transmission and distribution system capacity. However, since the end of 2009, REE has also curtailed wind to give priority to scheduled energy and to improve system stability. The need for curtailment is somewhat reduced during high wind speeds because many wind power plants are stopped to protect the turbines from damage or are operating at lower production with speed regulation controls in place.

Curtailment peaked in 2010 at 202.2 GWh of wind. Energy curtailed in January – March 2013 was 132.5 GWh. The Spanish Wind Energy Association estimated economic losses as a result of curtailments from January 2013 to April 2013 to total approximately €70 million. If the 2020 Spanish wind targets are met, curtailment is expected to reach 2.3 TWh, or 3.1% of wind energy generation, in 2020.

Future policies to mitigate renewable energy curtailment include providing wind power plant managers with production set points, which will be developed by the Control Centre of Renewable Energy. Installing new pumped hydro storage systems and establishing international transmission interconnections are additional future strategies Spain is exploring to balance significant fluctuations in wind power production. The country may also look to demand-side management, such as smart grid technologies, to improve the supply-demand balance. Valuing curtailed generation as a source of operating reserves has not yet been considered.

H. Sweden

In Sweden, the only curtailments that are currently performed are those caused by grid limitations. If grid reinforcements are needed when a wind power plant is installed, then the wind power plant owner has to pay for these. The Swedish TSO may curtail wind power plants, e.g., in a situation in which a wind power plant is interconnected before needed grid reinforcements have been completed and a line outage occurs. A signal is sent directly to the wind power plant controller to decrease the output.

In the Jönköping Energi distribution system operator (DSO), there is a wind plant with an installed capacity of 29.3 MW. But because of possible voltage problems, the wind plant owner has agreed to reduce the infeed to 26 MW. This limitation is implemented within the plant. The alternative was for the wind plant owner to pay to strengthen the grid, but analysis of how often the wind plant would produce more than 26 MW showed that this was not economically viable. This formally means that the plant is sometimes curtailed up to 3.3 MW. The agreement also stipulates that the DSO can decrease the output even farther below 26 MW if there are voltage problems in the grid. However, this has not been needed since commissioning in 2010. Again, the wind plant owner had the option to strengthen the grid at a cost that was higher than the value of expected wind curtailment [5].

I. United States

The United States has many balancing areas, each of which may have its own curtailment practices. Some key balancing areas are discussed here. The areas with the greatest amount of curtailment of wind and solar power to date include the Bonneville Power Administration (BPA) balancing area, the Southwest Power Pool (SPP), and Hawaii, which has struggled primarily with excess wind at low-load periods and minimum generation requirements. Both the Midcontinent Independent System Operator (MISO) and the Electric Reliability Council of Texas (ERCOT) have recently implemented market-based solutions and have seen reductions in curtailment levels.

BPA has approximately 4,500 MW of wind in its balancing area and a peak demand of 11,500 MW, although some wind resources have shifted out of the balancing area recently. There are two types of curtailments: curtailments caused by exhaustion of balancing reserves and those that result from seasonal hydro oversupply. Curtailments caused by the former averaged 7,000 MW in 2012, but have dropped to 1,700 MW so far in 2013. Curtailments caused by the latter reached approximately 5% to 6% of total available wind generation in spring 2011, but these levels dropped to approximately half that amount in spring 2012 [6]. Curtailments have been attributed to a lack of system flexibility and balancing challenges, which is, in part, caused by environmental constraints on hydro units. BPA has been modifying its curtailment protocols and implementing or exploring measures to help reduce the amount of curtailment, including faster scheduling, better use of forecasts, and improved methods of committing and de-committing reserves.

In the SPP, lack of transmission access has been the primary cause of curtailment. Wind has grown rapidly—essentially doubling in 2012—and has come online ahead of planned transmission. There are approximately 7,000 MW of wind in the system, which has a peak demand of 54,000 MW [7]. According to wind generators, at times approximately 40% to 50% of potential output is being curtailed. The use of manual processes to implement curtailments has exacerbated the impacts. Transmission lines scheduled for completion in 2014 or 2015 should help alleviate curtailment in the future. In the meantime, SPP is holding stakeholder processes to improve and increase transparency of its curtailment practices, and moving toward an automated, market-based approach.

MISO, which has more than 12,000 MW of wind capacity and a peak demand of 98,000 MW, implemented the Dispatchable Intermittent Resource (DIR) protocol in mid-2011, which includes wind generators in 5-minute dispatch. As a result, manual curtailments have decreased. Of wind generators not participating in the DIR program, curtailment levels range from 1% to 3% of total wind generation [8]. Similar programs are in place at PJM and the New York Independent System Operator (NYISO).

ERCOT shifted from a zonal congestion market with 15-minute dispatch to a nodal market with 5-minute dispatch in December 2010. In addition, new transmission was added, which helped reduce curtailment levels from 17% in 2009, to 8% to 9% in 2010 to 2011, and 4% in 2012 [7].

III. How Wind Is Curtailed

There are various approaches to how wind and solar are curtailed. There is emerging interest in performing curtailment as part of the market function. The advantage to this approach is that economic signals regarding the cost-effectiveness of alternative curtailments (dispatch down) are transparent. If all market participants, including wind power plants, participate, then the solution will be economically efficient. In the United States, MISO, ERCOT, and NYISO are examples that use the market mechanism. Conversely, when no market mechanism exists or is available for curtailment, a system operator must typically make a decision in real time concerning which plant(s) to curtail. The absence of price signals in this case will likely result in an economically inefficient outcome. SPP and BPA are example U.S. regions that use manual curtailment.

For example, in 2010, wind was being increasingly curtailed in MISO via manual phone calls from operators. The DIR program allows wind to participate in the real-time market like other generation. MISO obtains a wind forecast for each plant for each 5-minute interval that sets the maximum for that plant in that time interval. Wind is part of the co-optimized 5-minute market dispatch. This allows wind to set price and to choose not to generate if prices are severely negative.

Grid-congestion events result in local curtailments, and balancing-related events can, in principle, impact either all wind and PV plants or part of them, depending also on possibilities to control the output of the plants. First experience on using curtailed plants for up or down regulation is emerging.

An example of a balancing-related event is shown for the vertically-integrated utility of Xcel/Public Service of Colorado (PSCO), which needs to balance its own load with its own generators (mostly thermal) and long-term contracts with wind power plant owners. At night, when winds are high and loads are low, PSCO runs its thermal units down to minimum generation levels and still needs to curtail wind at times to balance the load. Fig. 4 depicts an example of this. At 02:45, the system operator initiated a manual block curtailment of a wind power plant to 300 MW because of a high positive area control error (ACE). ACE decreased but began to run too low in the negative direction, so at 4 a.m., the operator put the wind power plant on automatic generation control (AGC), by which ACE signals are sent to the wind power plant every 4 seconds to 6 seconds to keep ACE within a prescribed band. This resulted in much better control of ACE, as shown in Fig. 4. In fact, PSCO has gone a step further, and when wind is curtailed, they have used wind to provide down regulating reserves.

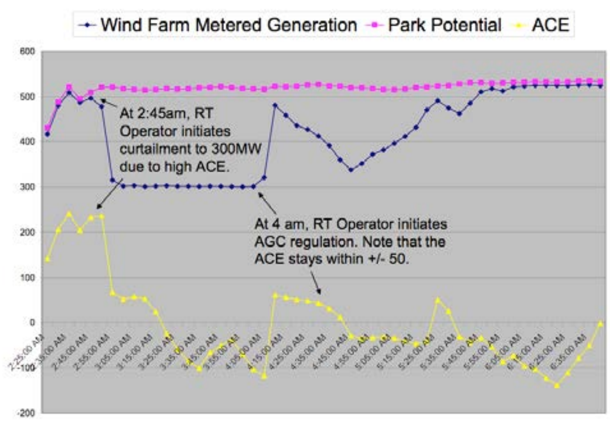

Figure 4. ACE during wind on block curtailment and wind on AGC [9].

In Ireland, given the distinction made between constraints (resolved by reducing the output of particular units) and curtailment (resolved by reducing the output of any or all units), constraints are normally applied first, followed by curtailment, if both are required simultaneously. Curtailment and constraint instructions are shared out based on the active power control set point of each unit. When a dispatch-down instruction is required, noncontrollable wind plants will be prioritized first (by opening relevant circuit breakers), then controllable wind plants, followed by wind plants that are still in a commissioning phase.

IV. Mitigation Options

Reducing curtailment typically involves finding additional sources of flexibility in the system. These can be physical additions (e.g., storage), grid capacity, institutional changes (e.g., access to a new market) or operational changes.

Portugal has a high wind penetration (20% wind energy in 2012), with limited interconnections to other regions (1,600 MW to 2,250 MWto Spain) [10]. Other constraints include run-of-river hydro and significant CHP plants. To reduce wind curtailment, the Portuguese operator uses pumped hydro and the intertie to Spain.

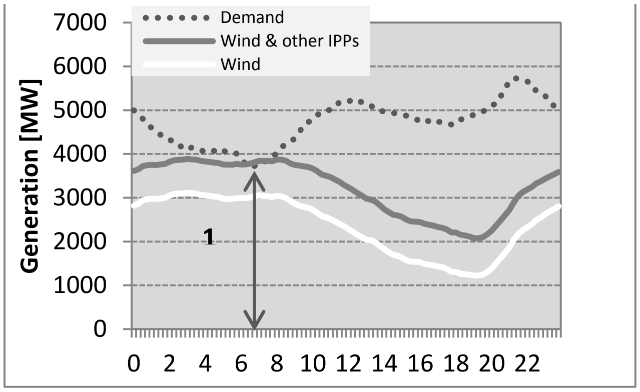

Figure 5. Portuguese load and generation profiles for May 15, 2011 [3].

For example, on May 15, 2011, at 06:45, wind penetration reached 81% of load. See Fig. 5. Most of the hydro generation was shut down, with a few plants staying online to provide balancing services. The pumped hydro storage facilities were pumping water up at full output. One thermal plant remained in operation, and its output was reduced by 25% near 04:00 and closely coordinated with the hydro units. Imports of electricity from France through Spain were replaced by exports.

In the United States, PSCO has examined in detail the trade-offs between cycling their coal units and curtailing their wind in high (2-GW to 3-GW) wind scenarios [11]. They conducted a detailed analysis of their cycling costs for their coal units to understand the costs of starts, shallow ramps (to economic minimum generation levels), and deep ramps (to emergency minimum generation levels). They determined that shutting down a coal unit during low-load periods at night was uneconomic. They then analyzed the trade-off in cycling cost for deep ramps versus shallow ramps with wind curtailment. Costs were found to be essentially the same with either mode of operation.

In Ireland, when priority dispatch generation must be dispatched down, a specific ranking order has been defined with the principle of preserving least-cost dispatch: the TSO may perform countertrades on HVDC interconnectors after gate closure, followed by set point reductions for peat plant, high-efficiency CHP, biomass and hydro generation, and finally wind generation. the output of the peat and CHP units is reduced to their minimum stable generation levels, rather than de-committed, as such units represent the major source of negative reserves for the system.

The European Union's Twenties project has studied market scenarios for 2020 and 2030 in Northern Europe including the countries with significant plans for offshore wind power development: United Kingdom, France, Germany, Belgium, Netherlands, Denmark, Norway, Sweden, Finland, and Poland. The studies are based on detailed scenarios of offshore wind power development. Large-scale offshore wind development is expected to increase wind curtailment, mainly because of increased wind generation, but also because of additional variability from geographically concentrated offshore wind plants. Market simulations show that wind curtailment is expected to increase from 0.4 TWh in 2020 to 9.3 TWh in 2030 [12].

The Twenties project studied different mitigation options. One is introduction of virtual power plants—aggregations of distributed generation and demand response that replace conventional generators—in Denmark in 2030 that will reduce wind power curtailment by 0.18 TWh [12]. This is marginal compared to the 9.3-TWh curtailment in Northern Europe, but the consumption in Denmark is only 2.2% of the consumption in this region, so the mitigating impact of virtual power plants can be significant. Anotheris a recommended scenario for feasible expansion of hydro power and transmission capacity that will reduce wind power curtailment by 1.5 TWh [13]. This result confirms that the flexibility of hydro power has a significant impact on wind power curtailment. Finally, Twenties also demonstrated the use of dynamic line rating (DLR) technology for increasing transmission capacity without building additional lines. A reported 10% to 15% increase in transmission capacity using DLR would mean a significant reduction of wind curtailment [14].

V. Implications of Curtailment

Curtailment is a growing concern in the wind and solar industry. It has implications for wind and solar developers and owners as well as utilities that purchase wind and solar power. In markets or contracts in which curtailment is not compensated, developers need to assess the risk and quantify the amount of future curtailment, which depends on many factors (future markets, future penetration levels of wind and solar, future flexibility in the balance of generation, etc.). Even when curtailment is compensated, developers need to assess the risk that these rules may change. Utilities with renewable energy targets also need to assess their risk and quantity of future curtailment, which is likely to increase with increased penetrations of wind and solar power. Utilities that are signing long-term contracts for wind and solar may want to consider who bears the curtailment risk during the lifetime of the contract. No easy answers have been identified for how the curtailment risk should be borne. Legal battles have already been fought about how wind and solar are curtailed and how much has been curtailed. This issue is ripe for future research.

Acknowledgment

D.L. thanks the U.S. Department of Energy, which supported this work under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

References

[1] EirGrid and SONI. Facilitation of Renewables studies, 2010. www.eirgrid.com/renewables/facilitationofrenewables/

[2] EirGrid and SONI. Delivering a Secure Sustainable Electricity System, 2013. www.eirgrid.com/operations/ds3/information/

[3] A. Estanqueiro, et al., "Energy storage for wind integration: Hydropower and other contributions," IEEE Power and Energy Society General Meeting, San Diego, CA, July 2012.

[4] A. Estanqueiro, C. Mateus, and R. Pestana, "Operational experience of extreme wind penetrations," in 9th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, T. Ackerman, Ed. Quebec City, Canada: Outubro, 2010, pp. 371–383.

[5] L. Soder, et al., "Experience and challenges with short-term balancing in European systems with large share of wind power," IEEE Transactions on Sustainable Energy, vol. 3, no. 4, pp. 853, October 2012. Doi 10.1109/Tste.2012.2208483.

[6] BPA. BPAT Operational Analysis, DSO216 Report, 2013. http://transmission.bpa.gov/wind/op_controls/fy2013_q1_q2_q3_dso_216_event_report.pdf. Bartlett. UWIG Forecasting Meeting, 2012.

[7] G. Moland, "Integrating wind into future markets," Presentation by Garrad Hassan to AWEA Windpower Conference, May 2013.

[8] M. McMullen, "2013 UVIG Forecasting Workshop MISO," Presentation by MISO to the UVIG Forecasting Workshop, February 27, 2013.

[9] D. Bartlett, Presentation by Xcel Energy to UVIG Forecasting Workshop, February 8, 2012.

[10] "Capacidades Indicativas de Interligação para Fins Comerciais para o ano de 2013," Relatorio REN RL ELPR-PR 04/2012, http://www.centrodeinformacao.ren.pt/.

[11] S. Connolly, K. Parks, and C. Janacek, "Wind induced coal plant cycling costs and the implications of wind curtailment for the Public Service Company of Colorado," Denver, CO, August 29, 2011.

[12] TWENTIES Deliverable 15.1. Report on the economic impact of enhanced network flexibility and new solutions for ancillary services (Indicative title) Draft June 2013.

[13] TWENTIES Deliverable 16.6. Market impact of offshore wind power and hydro power (Indicative title). Draft July 2013.

[14] TWENTIES. Final report. June 2013. Available at http://www.ewea.org/fileadmin/files/library/publications/reports/Twenties_report_short.pdf