Wind and Solar Energy Curtailment: Experience and Practices in the United States

Lori Bird, Jaquelin Cochran, and Xi Wang

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Technical Report
NREL/TP-6A20-60983
March 2014

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Executive Summary

Curtailment is a reduction in the output of a generator from what it could otherwise produce given available resources, typically on an involuntary basis. Curtailment of generation has been a normal occurrence since the beginning of the electric power industry. However, owners of wind and solar generation, which have no fuel costs, are concerned about the impacts of curtailment on project economics. Operator-induced curtailment typically occurs because of transmission congestion or lack of transmission access, but it can occur for a variety of other reasons, such as excess generation during low load periods, voltage, or interconnection issues. Market-based protocols that dispatch generation based on economics can also result in wind and solar energy plants generating less than what they could potentially produce.

This report examines U.S. curtailment practices regarding wind and solar generation, with a particular emphasis on utilities in the western states. The information presented here is based on a series of interviews conducted with utilities, system operators, wind energy developers, and other stakeholders. The report provides case studies of curtailment experience and examines the reasons for curtailment, procedures, compensation, and practices that can minimize curtailment.

Key findings include:

- *In the largest markets for wind power, the amount of curtailment appears to be declining even as the amount of wind power on the system increases.* Curtailment levels have generally been 4% or less of wind generation in regions where curtailment has occurred. Many utilities in the western states report negligible levels of curtailment. The most common reasons for curtailment are insufficient transmission and local congestion and excessive supply during low load periods.

- *Definitions of curtailment and data availability vary.* Understanding curtailment levels can be complicated by relatively new market-based protocols or programs that dispatch wind down or limit wind generation to schedules and the lack of uniformity in data collection.

- *Compensation and contract terms are changing as curtailment becomes of greater concern to solar and wind plant owners.* Increasingly there are negotiated contract provisions addressing use of curtailment hours and there is greater explicit sharing of risk between the generator and off-taker.

- *Automation can reduce curtailment levels.* Manual curtailment processes can extend curtailment periods because of the time needed for implementation and hesitancy to release units from curtailment orders.

- *Market solutions that base dispatch levels on economics offer the advantages of creating transparency and automation in curtailment procedures, which apply equally to all generators.*

- *Curtailed wind and solar resources may provide ancillary services to aid in system operations.*

- *A variety of solutions is being used to reduce curtailments: transmission expansion and interconnection upgrades; operational changes such as forecasting and increased automation of signaling; and better management of reserves and generation.*

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1 Introduction

Curtailment of variable renewable generation, particularly wind and solar energy, is becoming more widespread as wind and solar energy development expands across the country and penetrations increase. Curtailment can affect the revenue of wind and solar energy projects. These impacts are specific to each balancing area due to differences in grid characteristics, operating practices, and other factors such as weather.

In this paper, we define curtailment as a reduction in the output of a generator from what it could otherwise produce given available resources (e.g., wind or sunlight), typically on an involuntary basis. Curtailments can result when operators or utilities command wind and solar generators to reduce output to minimize transmission congestion or otherwise manage the system or achieve the optimal mix of resources. Curtailment of wind and solar resources typically occurs because of transmission congestion or lack of transmission access, but it can also occur for reasons such as excess generation during low load periods that could cause baseload generators to reach minimum generation thresholds, because of voltage or interconnection issues, or to maintain frequency requirements, particularly for small, isolated grids. Curtailment is one among many tools to maintain system energy balance, which can also include grid capacity, hydropower and thermal generation, demand response, storage, and institutional changes. Deciding which method to use is primarily a matter of economics and operational practice.

"Curtailment" today does not necessarily mean what it did in the early 2000s. Two sea changes in the electric sector have shaped curtailment practices since that time: the utility-scale deployment of wind power, which has no fuel cost, and the evolution of wholesale power markets. These simultaneous changes have led to new operational challenges but have also expanded the array of market-based tools for addressing them.

Practices vary significantly by region and market design. In places with centrally-organized wholesale power markets and experience with wind power, manual wind energy curtailment processes are increasingly being replaced by transparent offer-based market mechanisms that base dispatch on economics. Market protocols that dispatch generation based on economics can also result in renewable energy plants generating less than what they could potentially produce with available wind or sunlight. This is often referred to by grid operators by other terms, such as "downward dispatch." In places served primarily by vertically integrated utilities, power purchase agreements (PPAs) between the utility and the wind developer increasingly contain financial provisions for curtailment contingencies.

This report delineates several types of practices under the broad rubric of curtailment done for wind or solar generation. Some reductions in output are determined by how a wind operator values dispatch versus non-dispatch. Other curtailments of wind are determined by the grid operator in response to potential reliability events. Still other curtailments result from overdevelopment of wind power in transmission-constrained areas. Responses to all types of curtailment largely reflect the operating context, including whether the wind power is part of an centrally-organized wholesale market, or whether it is in a balancing authority area operated by a vertically integrated utility.

Dispatch below maximum output (curtailment) can be more of an issue for wind and solar generators than it is for fossil generation units because of differences in their cost structures. The economics of wind and solar generation depend on the ability to generate electricity whenever there is sufficient sunlight or wind to power their facilities. Because wind and solar generators have substantial capital costs but no fuel costs (i.e., minimal variable costs), maximizing output improves their ability to recover capital costs. In contrast, fossil generators have higher variable costs, such as fuel costs. Avoiding these costs can, depending on the economics of a specific generator, to some degree reduce the financial impact of curtailment, especially if the generator's capital costs are included in a utility's rate base.

Ascertaining the level of curtailment of wind and solar generation and its impacts is challenging. Often system operators or utilities do not track it or make data publicly available, and there are differences in terminology as well. Manual curtailment processes for wind have been replaced by economic dispatch protocols in a number of regions, and under the new protocols, dispatch below maximum output is typically not referred to as curtailment. In addition, energy lost due to line outages, and limits placed on deviations from schedule can all reduce wind generator's production; some operators call these actions curtailment while others do not.

This report examines curtailment practices for wind and solar energy in the United States, with a particular emphasis on utilities in the western states. Much of the experience documented in this report pertains to curtailment of wind power, which has reached higher penetrations of bulk system power, although solar curtailment is included where information is available.[1] This report builds on earlier reviews of domestic curtailment experience by Rogers et al. (2010) and Fink et al. (2009) and a recent review of international practices by Lew et al. (2013). The information presented here is based on a series of interviews conducted with utilities, system operators, wind energy developers and owners, and non-governmental organizations as well as other available data sources. This review was conducted to better understand the diversity of practices in place and the magnitude of curtailment that has been occurring. The report provides case studies of curtailment experience and examines the reasons for curtailment, curtailment procedures, compensation, and practices that can minimize curtailment of wind and solar.

[1] This report only looks at bulk power solar generation, not solar generation that occurs on a distributed generation level.

2 Overview: Levels of Curtailment in the United States

Curtailment levels, where curtailment has occurred, are often in the range of 1% to 4% of wind generation, but higher levels have been reported by the Electric Reliability Council of Texas (ERCOT) in past years, as can be seen in **Figure 1**.[2] However, the levels of wind curtailment experienced to date in the United States differ substantially by region and utility service territory, as discussed in Section 3. In many regions, curtailment is very low and not even tracked.

Table 1 provides a summary of curtailment levels and causes for all of the utilities and grid operators interviewed for this study. Further discussion of the reason for curtailments is included in Section 3. **Table A-1** in Appendix A summarizes experiences with wind and solar energy curtailment from all of the utilities and grid operators interviewed, including utilities that reported relatively low levels of curtailment.

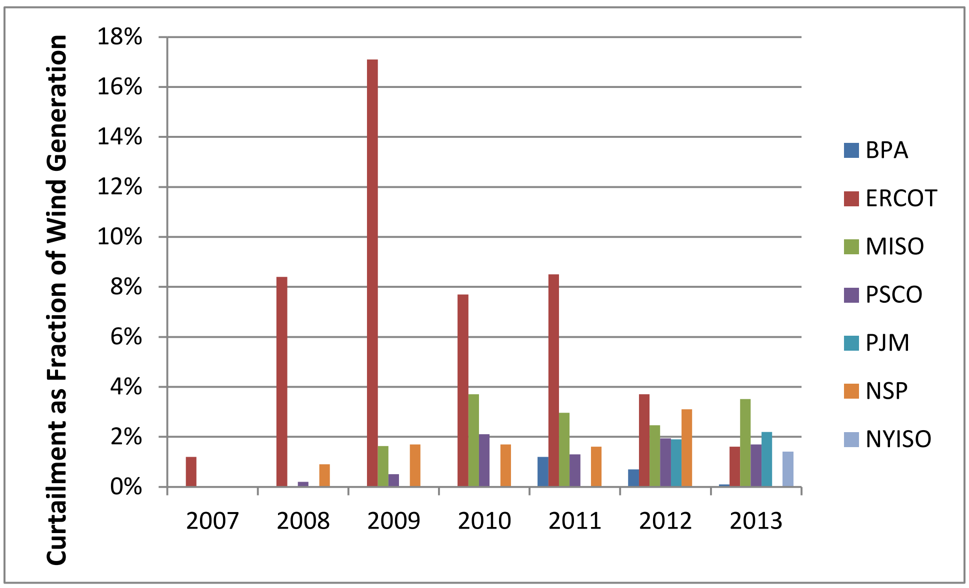

Figure 1. Curtailment levels by region, 2007–2012

Note: Data are indicative. Inconsistent definitions and reporting of curtailment make it challenging to compare curtailment levels across regions. Data for MISO includes manual curtailments and wind dispatched down. NSP is reported separately but also captured in the MISO data. BPA DSO 216 curtailments assumed to occur for one half hour per event. Sources: BPA (2013a; 2013b), ERCOT (Maggio 2014), MISO (Rudd 2013; 2014), Xcel/PSCO (Bartlett 2014), PJM (2014), NYISO (2013), and Wiser and Bolinger (2013)

[2] Higher curtailment rates have also been reported in Hawaii. For example, 40% of wind generation was curtailed in Maui in February 2013, but levels dropped to 10%–15% of wind generation in the following months after minimum generation levels were modified on fossil plants; modeling suggests that 2%–4% curtailment is achievable. Modeling of Oahu found curtailment to range from 4% to 8% of wind and solar generation, but 1% might be achievable with operational changes (Corbus 2014).

Table 1. Summary of Curtailment Levels and Reasons for Curtailment

Utility/Grid Operator	Wind and Solar Curtailment Levels Frequency	Primary Reasons for Curtailment
Alberta Electric System Operator (AESO)	Infrequent	Oversupply; transmission constraints, high wind ramps
Arizona Public Service (APS)	Infrequent	Local transmission outages or constraints
Bonneville Power Administration (BPA)	Varies by year; less than 2% of wind production	Balancing issues related to exhaustion of reserves; oversupply
California Independent System Operator (CAISO)	Infrequent; not tracked	Oversupply; transmission constraints, congestion
Electric Reliability Council of Texas (ERCOT)	Varies by year; 2% to 4% in 2012–2013, but higher in previous years	Transmission constraints; oversupply, new transmission lagged wind capacity
Hawaiian Electric Co. (HECO), Hawaii Electric Light Co., (HELCO) and Maui Electric Co. (MECO)	Substantial curtailment on Maui and the island of Hawaii	Oversupply in low load periods and balancing challenges
ISO New England (ISO-NE)	Infrequent, but some plants experienced substantial curtailment	Local transmission constraints; oversupply; voltage control; other (wildlife protection, ice formations)
Midcontinent ISO (MISO)	1%–4% of wind generation	Transmission congestion; oversupply handled by downward dispatch
NV Energy	Infrequent; 6–7 occasions per year	Oversupply; local transmission outages
PacifiCorp	Much less than 1% of total wind production	Transmission congestion; avoid area control error (ACE) violations
PJM Interconnection	Not tracked	Local transmission constraints,
Puget Sound Energy	Infrequent in PSE balancing area and not tracked	PSE wind subject to BPA's curtailment protocols related to balancing and oversupply
Salt River Project	Very infrequent	Transmission issues and maintenance
Sacramento Municipal Utility District (SMUD)	Not tracked	SMUD not affected by curtailments
Southwest Power Pool (SPP)	Some wind generators report high levels	Local transmission constraints, expansion of wind outpaced new transmission build-out
Tucson Electric Power	Very infrequent	Local outages
Western Area Power Administration (WAPA)	None	None
Public Service Company of Colorado (PSCO)	1%–2% of wind generation	Oversupply; transmission constraints

3 Curtailment Experiences of Utilities and Grid Operators

This section summarizes the experiences of many U.S. balancing areas with modest and significant renewable energy curtailment. The information was obtained from interviews with utilities, independent system operators (ISOs), wind developers, and non-governmental organizations.

3.1 Bonneville Power Administration

BPA experienced a rapid increase in wind capacity between 2008 and 2012, growing 850 megawatts (MW) annually, to a total of 4,515 MW by early 2013 (BPA 2013a). Most of the wind is geographically concentrated in one area—the Columbia River Gorge in northern Oregon and southern Washington—which at times causes relatively large wind ramps. BPA has implemented two processes that curtail wind generation: Dispatch Standing Order (DSO) 216 and the Oversupply Management Protocol (OMP). BPA uses DSO 216 when planned amounts of balancing reserves are exhausted and OMP when hydropower generation creates oversupply.

3.1.1 Dispatch Standing Order 216

BPA established DSO 216 in 2009 to help manage the under- and over-generation of wind relative to schedule. BPA distinguishes between two types of balancing reserves: DEC balancing reserves, which *decrease* BPA hydro in response to wind over-generation, and INC balancing reserves, which *increase* hydro generation. BPA sets the reserve levels for wind based on installed wind capacity (14% of wind capacity for INC reserves and slightly higher for DEC reserves) and uses the reserves to balance unscheduled or unforecasted changes in generation and load.[3]

[3] Specifically, BPA uses reserves to balance the station control error (SCE) for generation (the difference between the scheduled generation and what is actually produced) and the load error (the difference between the load forecast and actual load).

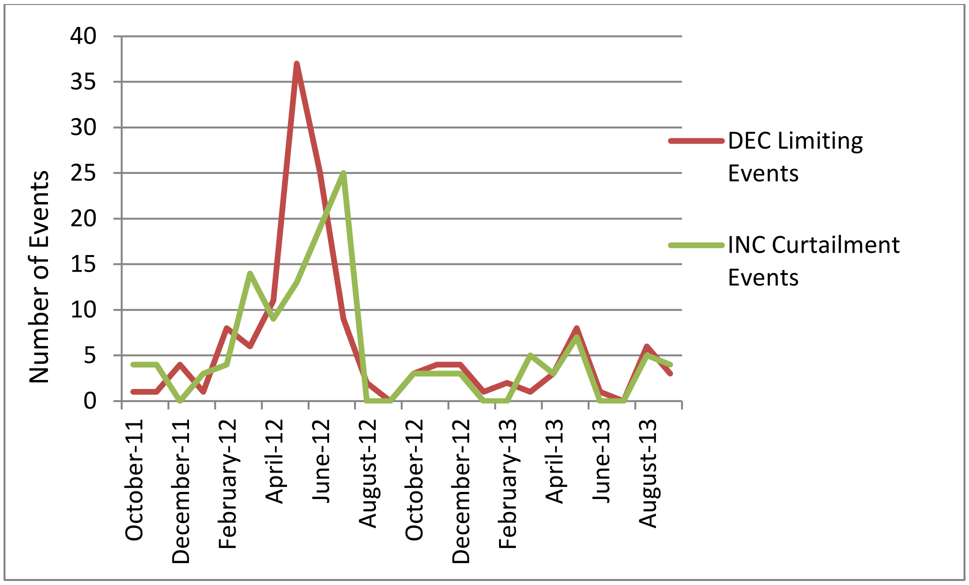

Figure 2. Wind energy curtailment events under the BPA DSO 216 program fourth quarter 2011 through third quarter 2013

Regardless of cause for the imbalance, and regardless of whether BPA has other reserves available, when INC and DEC reserves set aside for wind generation are at least 90% depleted, wind generation that is over- or under-generating compared to forecast will be curtailed. This curtailment is defined as "limiting" when DEC reserves are 90%–100% exhausted and BPA limits over-generating facilities to their forecasted schedule.[4] In under-generation contexts when INC reserves are 90%–100% exhausted, BPA "curtails" under-generating facilities' e-Tags[5] to their actual generation in order to reduce BPA's exposure to further system imbalance.
The financial impact of e-Tag curtailment extends beyond reduced energy sales. Under the *pro forma* OATT, curtailments are permitted only for reliability reasons; however, under BPA's DSO 216 protocol, wind generators can be curtailed for non-reliability reasons and when other balancing reserves are available. Consequently, the market perceives generation schedules subject to DSO 216 as a less firm, and therefore less valuable, product. When generators' e-Tags are curtailed, the generators cannot deliver the expected schedule, and their energy is devalued to a non-firm, interruptible rate.

In addition to the financial impacts associated with DSO 216, wind generators in BPA's balancing authority area are also subject to BPA's Persistent Deviation Penalty Charge, which allows BPA to charge generators a 125% penalty if they have three consecutive hours of schedule deviations that exceed 15% of the schedule and 20 MW. The financial impacts of curtailments and costs of operating in the balancing authority area prompted neighboring

[4] Unless otherwise specified, in this report, "curtailment" includes both limiting events (which are energy curtailments) and grid curtailments (capacity curtailments) as they are defined under DSO 216.
[5] E-tags, also called NERC tags, provide information on real-time energy scheduling and power flows, including where generated energy originates, where it flows, scheduled time, total megawatt-hours, and names of parties. E-tags help identify contributors to congestion and enable system operators to modify dispatch in response.

PacifiCorp to change the telemetry of two wind facilities in early 2013, removing them from the control of BPA's balancing authority and adding them to PacifiCorp's.[6]

Several measures would allow the power system to operate more efficiently, and in the process greatly mitigate wind curtailment. Most importantly, sub-hourly generation dispatch, sub-hourly transmission scheduling, and setting generation schedules closer to real-time would greatly reduce wind, load, and conventional generator deviations from schedule. If the sub-hourly scheduling and dispatch practices were coordinated with neighboring balancing authorities, as would occur under the proposed energy imbalance market, any remaining deviations could be exchanged or netted out with other balancing authorities in the western United States. Discussions about implementing such a system are ongoing in the Pacific Northwest, and CAISO-PacifiCorp are moving forward with implementing an energy imbalance market in October 2014.

BPA has considered using dynamic reserve requirements that vary hourly based on predicted conditions of the system rather than vary only on nameplate wind capacity. At this time, however, BPA has not found this to be viable due to the complexity of the Snake and Columbia River hydro system. Purchasing balancing reserves is another option under consideration so that BPA does not have to hold reserves for all hours. To facilitate more accurate scheduling, BPA has installed 14 wind anemometers that provide data to wind operators and forecast providers at 5-minute intervals. BPA has also created an internal wind forecast to see more accurately what will be generated by the wind in the upcoming hours and days.

BPA has also initiated a self-supply option ("Customer Supplied Generation Imbalance Initiative") in which wind owners/operators provide their own balancing in exchange for a credit against the wind integration rate. Iberdrola Renewables is the only wind owner to use the option so far. Drawing on contracts with a variety of generators (e.g., combined cycle gas turbines and hydro), Iberdrola integrates its trading operations, dispatch operations, and meteorology group to ensure that it provides energy as scheduled. Iberdrola is able to significantly reduce balancing costs by making purchases over multiple timescales (e.g., both days-ahead and intra-hour) and thereby bypass the less flexible hourly dispatch intervals that BPA uses to balance.[7] Iberdrola has reduced its integration costs significantly, compared with charges and penalties incurred as a variable generator under BPA (Froese 2013).

[6] In November 2013, FERC declined to grant BPA reciprocity treatment for its tariff provisions related to the provision of generator imbalance service, finding that BPA's proposal to limit the provision of balancing reserves for variable resources to amounts established in BPA's rate case did not conform with and was not superior to the *pro forma* OATT requirements. Further, FERC stated that, "to the extent [BPA] intends to employ DSO 216 or a similar operational protocol to enforce generator imbalance service limits, it should submit the protocol to FERC in a compliance filing so that the Commission can determine whether it should be included in the tariff (FERC 2013, p. 21).

[7] A BPA program allows scheduling on the half hour, but energy purchases or sales at the half hour require a seller or buyer to complete the exchange. BPA is also working on implementing 15-minute scheduling.

3.1.2 Oversupply Management Protocol

The second formal process for curtailment, implemented in March 2012, relates to the oversupply of electricity due to excess hydro generation. **Table 2** shows curtailments under OMP and its predecessor, Environmental Redispatch, for the last few years. During the spring run-off months when river levels are high (typically April through July), BPA must run water through its turbines and generate power when the use of spillways—the only alternative to generation—would increase total dissolved gases above federal limits and threaten fish. Unlike DSO 216, BPA compensates wind generators for curtailments under OMP. However, in the future, BPA may recover some percentage of this compensation back from the wind generators through a yet-to-be-filed oversupply rate, so wind generators will not ultimately receive full compensation for OMP curtailments. The Federal Energy Regulatory Commission (FERC) has ruled that a previous program that lacked compensation was discriminatory, violating the principle of open transmission access on terms comparable to what BPA provides to its own generators. Under the OMP, BPA initially proposed splitting the cost of the program equally between wind generators and BPA's customers, but FERC rejected this cost-sharing mechanism and directed BPA to submit a revised proposal in a proceeding that is ongoing.[8] Also, wind generators contend that BPA has not exhausted non-curtailment options, such as allowing market prices to go negative in order to increase demand and reduce oversupply by providing market signals to other generators (Renewable Northwest Project 2013).

Table 2. BPA Oversupply Curtailments

Year	Curtailments Under OMP and its Predecessor Environmental Redispatch
2011	97,200 MWh
2012	49,700 MWh
2013	0 MWh

Source: BPA 2013b

DSO 216 curtailments are also exacerbated by the excess hydro generation in the spring season, when fewer DEC reserves are available to balance wind. For example, the number of DSO-216 DEC events, normally about four per month, jumped to nearly 40 in May 2012.

3.2 California Independent System Operator

CAISO had about 5,800 MW wind and 1,350 MW solar as of early 2013 (Blatchford 2013) and is expecting rapid growth to levels of 18,000–20,000 MW wind and solar by 2020. Today curtailment is relatively modest, although CAISO does not track it. Curtailment occurs largely due to congestion or periods of oversupply, and it is expected to increase as additional wind and solar generation are added. At times, the ISO experiences over-generation and minimum generation levels on its inflexible conventional units at night. For solar, the challenge is in the afternoon from 1:00 p.m. to 2:00 p.m. CAISO has undertaken a process to address curtailment

[8] FERC rejected the 50-50 cost-sharing basis on the grounds of undue discrimination, arguing that wind generators are a group that utilizes only a small percentage of the overall transmission system and that placing half of the displacement costs on them does not satisfy FERC's comparability standards under Order 890. This essentially means that BPA must follow the same tariff terms and conditions that it requires of its customers. BPA's final decision in the OS-14 Rate Proceeding is expected in March 2014, at which point, it will go back to FERC for review. If approved by FERC, the cost allocation will retroactively apply from March 2012 to September 2015.

due to over-generation and to estimate how much excess generation could be sold to other balancing areas.

CAISO treats wind and solar generation as must-take resources, provided there are sufficient reserves and no problems on the system. However, CAISO is exploring market-based solutions to addressing over-generation. In the spring of 2014, the ISO will reduce its bid floor to -$150 per megawatt-hour (MWh), from the current -$30/MWh. The current level does not prevent wind generators from bidding in to the system because the value of the federal production tax credit (PTC) makes it economic for them to bid at -$30/MWh. If dropping the bid floor to -$150/MWh does not address over-generation, the floor will drop again to -$300/MWh.

3.3 Electric Reliability Council of Texas

ERCOT has experienced wind curtailment rates of around 8% in recent years, even jumping to 17% in 2009, but it has since added additional wind capacity and curtailment levels have fallen (Maggio 2013; see **Figure 1**). Two major changes have dramatically reduced curtailments to 4% in 2012 and 1.6% in 2013: transmission expansion and a market redesign to LMP pricing and faster schedules that improved overall system operations. Transmission capacity has expanded as part of the Competitive Renewable Energy Zone (CREZ) initiative, authorized by the Texas Legislature in 2005 to support the build-out of transmission in advance of anticipated wind development primarily in west Texas. The CREZ program was designed to build sufficient transmission to accommodate 18.5 gigawatts (GW) of total wind capacity. The lines were completed in early 2014 at a cost of approximately $6.8 billion (Wolff 2014). Some of the wind development in west Texas came online in advance of transmission, resulting in significant wind curtailment.

The market redesign also helped reduce curtailments. The market redesign included shifting from 15-minute to 5-minute dispatch intervals, more centralized scheduling, and changes to how forecasting was integrated into market operations. The market rules were also modified to allow updates to generation schedules until ten minutes or less before the dispatch period, which greatly minimizes forecast errors. Wind resources participate in the ERCOT real-time and day-ahead markets in much the same way as other resources, except that the first 48 hours of their operating plans must be based on ERCOT's most recent short-term wind power forecast (ERCOT 2013a). Wind and solar resources may submit negative bids. Generation oversupply has contributed to instances of system-wide negative pricing in the middle of the night. ERCOT posts day-ahead and intra-day forecasted system conditions that will be used in unit commitment and dispatch, providing an automated, transparent mechanism to reduce generation output due to congestion, oversupply, ramping, and other aspects of system flexibility. (ERCOT 2013b)

Reductions in output ("downward dispatch") for wind and solar resources in ERCOT are primarily a result of local congestion. Dispatch instructions most often occur automatically as part of normal outputs from ERCOT's security-constrained economic dispatch engine. However, under special circumstances, ERCOT may issue verbal dispatch instructions to specific resources, in which case the resources may be given special compensation based on the settlement prices in effect during the time of the instruction (ERCOT 2013c).

3.4 Midcontinent Independent System Operator

MISO, which has more than 12 GW of wind capacity and a peak demand of 98 GW, implemented the Dispatchable Intermittent Resource (DIR) protocol in mid-2011, which requires wind plants operating on or after April 2005 to bid into the real-time market. Prior to the DIR program, MISO used only manual curtailments to address congestion, which operators used more than 1,000 times in each of 2009 and 2010 (Porter et al. 2012).

Now, DIRs can set the LMP and can be dispatched down through an automated process. Similar to ERCOT, limitations on output due to downward dispatch (e.g., due to oversupply and ramping constraints) are not classified as curtailments. Unlike earlier years, MISO has not had an oversupply case in the past few years, but with downward dispatch, they are also not tracking these events. Moreover, in an integrated market it can be difficult to attribute causes. Ramp-related downward dispatch is not expected to be an issue until wind capacity is double current levels (expected in 2017–2018). Similar to ERCOT's CREZ, new transmission projects are progressing in areas that will mitigate existing curtailment and likely attract significant investment in new wind generation. Of wind generators not participating in the DIR program, curtailment levels reached a high of 3.7% of total wind generation and have since fallen to 0.2% (Ruud 2014; McMullen 2013) and are primarily due to local congestion. **Table 3** shows the number of curtailments, duration, and estimated energy curtailed as well as DIR dispatch down. **Figure 3** compares estimated energy manually curtailed versus dispatched down monthly from July 2011 to January 2013.

Table 3. MISO-Estimated Manual Curtailment and Dispatch Down

	2009	2010	2011	2012	Oct. 2013
Number of wind curtailments	1,141	2,117	2,034	889	N/A*
Estimated manual curtailment (MWh)	292,000	824,000	720,000	266,000	65,010
Duration (hours)	8,005	19,951	20,365	10,430	N/A*
DIR dispatch down (MWh)	N/A	N/A	130,296	582,653	972,580
Manual curtailment as % of wind generation	1.6%	3.7%	2.5%	0.8%	0.2%**
Manual curtailment and DIR dispatch down as % of wind generation	1.6%	3.7%	3.0%	2.5%	3.5%**

*Note: As of April 2013, the number of wind curtailments totaled 148 and the duration (hours) were 2,057. These data were not available for April through October 2013.
**Estimated for full year based on average monthly curtailment and dispatch down rates.
Source: McMullen 2013; Ruud 2013; Ruud 2014

Another advantage of DIR with regard to curtailment is the automation of the process. Manual curtailments require operators to track and judge events and evaluate when to release the curtailment, which could lead to prolonged curtailment events in some cases. Grid operators typically do not want to release the wind power too fast, as it can ramp up very quickly and contribute to reliability problems. To release wind from curtailments, grid operators often check near-term forecasts and grid status to determine when to allow wind to ramp up, or establish ramp-up limitations. DIR reduces the number of manual curtailment events that system operators need to address, enabling them to focus on other system issues. Reliability coordinators have appreciated the shift to DIR because the operator does not need to continue closely monitoring the constraint after the event has been resolved.

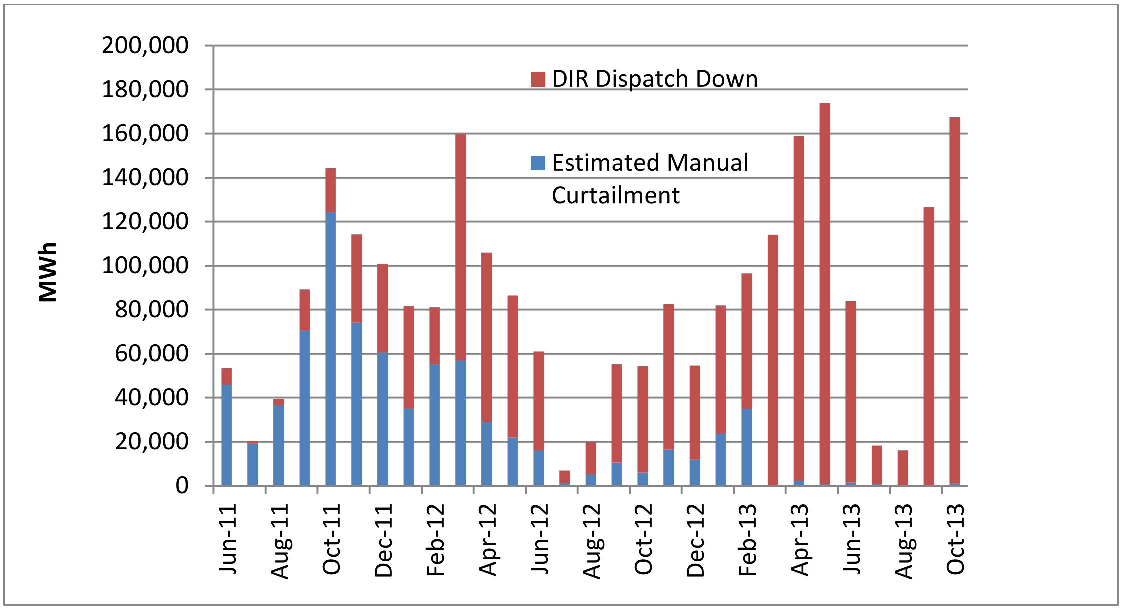

Figure 3. MISO-estimated energy manually curtailed in MWh versus dispatched down

Source: Rudd 2014

One impact of the introduction of DIR is on contract language regarding compensation. Many agreements treat downward energy dispatch differently if the cause is economic rather than a reliability event. Wind generators and off-takers have been addressing these issues on an agreement-by-agreement basis.

3.5 PJM Interconnection

In PJM, most wind energy curtailment is due to transmission constraints, often during maintenance. At this time, PJM does not have minimum load issues; it does allow negative pricing, which can help alleviate oversupply situations. **Figure 4** shows the amount of wind energy reduced and the lost opportunity cost payments made to wind generators in 2012–2013. Wind reductions represented approximately 2% of wind generation in 2013.

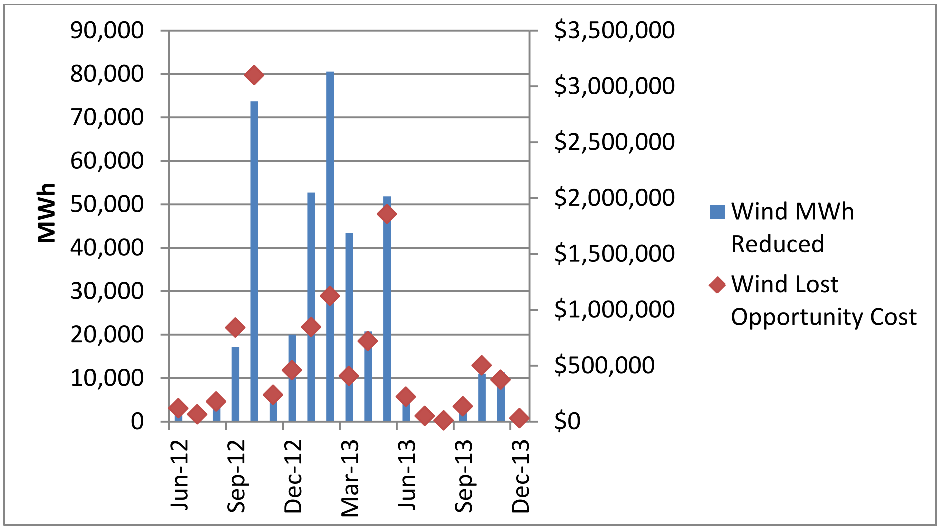

Figure 4. PJM wind reductions and associated lost opportunity cost payments

Source: PJM 2014

PJM has recently changed its curtailment signaling and compensation processes to try to increase efficiency. To initiate curtailment, PJM sends a curtailment flag to generators instructing them to follow base-point signals down to the curtailed level. PJM has typically followed the automatic signals with a phone call, implemented manually by the grid operator. In November 2013, PJM adopted changes so that if wind generators do not follow the automatic base-point instructions and provide meteorological data needed by PJM to produce an accurate wind power forecast, they will no longer be eligible for make-whole payments paid out of operating reserves for curtailed generation. PJM expects this to minimize the need for manual processes, which should in turn reduce curtailment time. Along with these compensation changes, PJM has implemented a process to improve transparency by providing feedback to affected wind generators on their performance following base-point instructions, the day after curtailment events. Finally, to more precisely estimate curtailment, PJM has implemented a "backcast" to calculate what the wind farm could have produced if there was no constraint. Prior to August 2013 curtailment levels were estimated based only on the forecast.

PJM has also made changes that could help reduce future curtailments. PJM has developed a light-load planning process to ensure that the transmission system is capable of delivering the system generating capacity at light load, when wind generation is typically higher. Based on the new criteria, PJM identified a number of required upgrades, the cost of which will be allocated to load, not individual wind generators. Going forward, generators requesting interconnection to PJM must pass this test in order to become a PJM capacity or energy resource. The interconnecting generator is responsible for the cost of upgrades needed to resolve light load criteria violations caused by that generator.

3.6 Public Service Company of Colorado

PSCO has brought considerable wind online in recent years, reaching about 30% of peak demand—and even 60% of load served with wind during one hour in 2013. PSCO has had to curtail wind at times, primarily due to oversupply during low load periods and line constraints and outages, but it has also taken many actions to reduce curtailment and integrate more wind. While total wind generation grew substantially from about 3.7 to 6.5 million MWh between 2010 and 2013, curtailment levels as a fraction of total wind generation declined slightly over that period from 2.2% to 1.7% (**see Figure 5**). PSCO has been able to manage curtailments by implementing a variety of changes to its system operations.

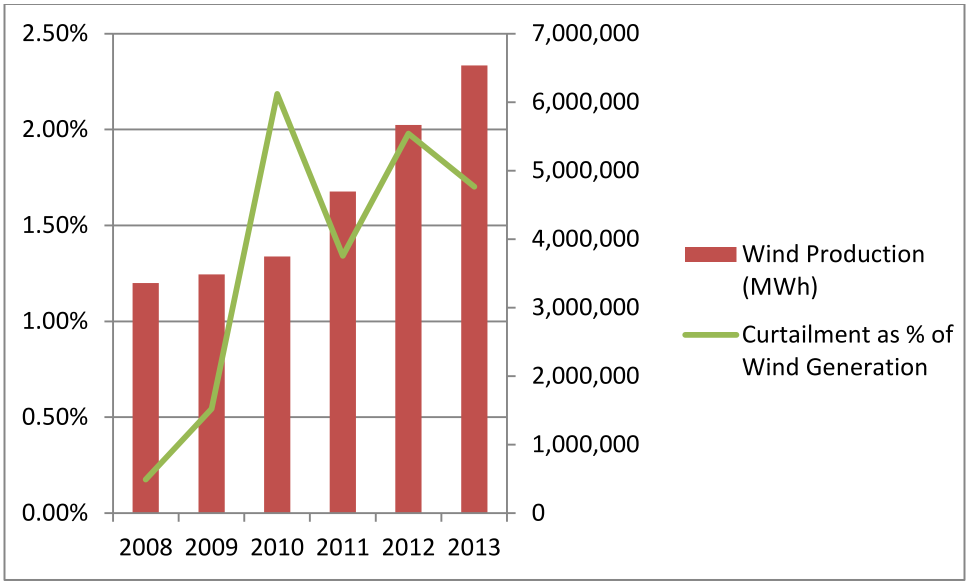

Figure 5. PSCO wind curtailments as a fraction of total wind generation

Source: Xcel Energy (Bartlett 2013)

A primary strategy to mitigate curtailments has been improved use of forecasting. PSCO has worked with the National Center for Atmospheric Research to improve its wind prediction models. Improved forecasting enables PSCO to turn down conventional resources when sufficient wind generation is predicted and to reduce curtailment from oversupply. Improved forecasting also eliminated curtailments related to ramping.

A second strategy to mitigate curtailments is to cycle baseload generating units. Prior to 2010, PSCO's dispatch policy was not to cycle baseload units. Since then, PSCO cycles baseload units to accommodate wind generation during windy periods of the year. In particular, it cycles combined cycle gas units on a daily basis, but it cycles coal units much less frequently due to the significantly higher cycling costs. In 2010, when there was a dramatic increase in wind curtailments primarily due to line outages, PSCO studied the costs of cycling baseload units versus curtailing wind. The costs were similar, so PSCO decided to cycle off thermal units at night to minimize wind curtailments.

Finally, PSCO has also put many wind facilities on automatic generator control (AGC), and it requires AGC on all new wind contracts as a bid condition, which reduces total curtailments. Previously, PSCO would curtail in blocks (e.g., 100 MW) and balance with thermal units. Now PSCO can take thermal units to their minimum and balance with one wind generator on AGC (two-thirds of wind farms have AGC capability, but only one wind project is needed on AGC at a given time due to their fast response provided it is large enough to handle swings in load).

Wind farms on AGC can provide downward regulation to the minimum regulating range of the wind farm. PSCO also uses curtailed wind energy to provide positive reserves (upward regulation).

Looking forward, PSCO is examining participation in an organized energy imbalance market, which would reduce the need for balancing and potentially broaden the supply of resources available to balance system variability. PSCO is also considering changing its use of pumped storage hydroelectricity; instead of pumping at night to serve peak load, PSCO might pump at other times during low net load periods to offset curtailment.

Costs and risks of curtailment are factored into PPAs, and compensation varies by cause. For transmission-related causes, wind generators under some older contracts are compensated, but the majority of contracts do not allow for compensation for transmission causes beyond PSCO's control, such as the unexpected loss of a line. If PSCO curtails for balancing purposes, it will compensate generators for the energy that they would have produced plus the value of PTC earnings. However, PSCO has negotiated annual maximums of free (uncompensated) curtailment hours with five of the fourteen wind farms. Currently PSCO receives a total of 60,000 annual free curtailment hours, but this drops to 30,000 by 2018, at which time a number of coal plants will be replaced by more flexible natural gas units (which begin to come on-line in 2015).

3.7 Southwest Power Pool

Wind generation in SPP has increased substantially in recent years, increasing from 3.5% of total generation in 2008 to 7.6% in 2012. In addition, 3,090 MW of wind was installed in SPP in 2012, representing nearly half of all new capacity additions, and bringing total installed capacity to 7,790 MW (SPP 2013). Much of this wind generation has been brought on-line in advance of planned transmission upgrades in wind development areas, especially in the Texas Panhandle and western Kansas. As a result, some wind generators have informed SPP that they have experienced significant curtailments of production. In 2012, SPP issued 883 wind-related directives to manage congestion, an increase of 450% over the 197 issued in 2011 (SPP 2013). In 2011 and earlier, overall wind curtailment levels in SPP had been less than 1% of potential wind generation, as can be seen in **Figure 1** above (Wiser and Bolinger 2013).

Further exacerbating the curtailments had been the manual process for imposing production caps. As of 2013, when SPP experienced an emergency N-1 event, the grid operator manually called control rooms at each affected wind farm to set new limits on dispatch. Because the notifications could consume 30-40 minutes for a typical event (7-10 wind farms), SPP was reluctant to release these curtailments if they might be needed again soon, and wind generators could spend several days operating at curtailed outputs.

To mitigate curtailments, SPP has been implementing a three-phase approach:

1. Automate curtailments (2013): To automate and shorten the duration of curtailments, SPP planned to reclassify curtailments as congestion management, rather than emergency, which carries the obligation for three verbal communications between the parties. Because this change in classification affects many contracts, in which off-takers bear the costs of economic-based curtailment, SPP had conducted regular meetings with wind developers and other stakeholders to discuss the ramifications of this proposed change.

2. Introduce a day-ahead market, similar to MISO, PJM, and other RTOs with LMP-based markets (March 2014)
3. Build new transmission (mid 2014–2015).

As part of the three-phase approach, SPP has found that stakeholder outreach has been an effective component in their efforts to reduce curtailments. For example, wind project developers who went through the interconnection process and met requirements often understood the reliability risks, but those who purchased a project later sometimes did not. Although SPP provided correct and clear analyses as part of the interconnection agreements, SPP realized that it could improve the investment environment by helping all their members—especially small, independent wind generators that lack operating expertise—to better understand curtailment risks. Other critical stakeholder outreach efforts included increasing the transparency of curtailment practices and causes, proposing cost-sharing with wind developers to conduct 'hot" transmission upgrades in lieu of outages, and soliciting stakeholder ideas and concerns related to the three phases of mitigation.

3.8 Western Area Power Administration

Like BPA, WAPA is one of the U.S. Department of Energy's power marketing administrations responsible for marketing and delivering hydropower in its service territory. One of WAPA's responsibilities is to provide ancillary services, including the use of hydro to provide regulation to its service territory. WAPA has experienced difficulties balancing wind when wind over-generates compared to schedule and WAPA needs to drive its units down to minimum generation. The most significant occasion occurred in May 2013, when aggregate wind capacity exceeded schedules by 125 MW, and WAPA held its hydro below its preferred minimum necessary to meet water release restrictions. WAPA did not curtail the wind in this event because it is required under contract to accommodate the wind, and this contract has no clause that allows curtailment for oversupply.

If wind over-generates compared to its schedule, WAPA assesses an energy imbalance charge on the operational entity. WAPA would like to make these charges more costly to encourage operational entities in the balancing authority to back down their coal and balance their loads during these oversupply periods. WAPA is also offering 15-minute scheduling (a requirement under FERC Order 764), which will allow generators to adjust schedules and reduce the duration spent out of schedule, if transmission can also be scheduled subhourly. As more wind enters its administrative area, WAPA wants to ensure that new contractual arrangements will provide WAPA more control over schedules and provide utilities an incentive to balance their load.

3.9 Other Western Utilities

Other western utilities interviewed for this study—APS, NV Energy, Salt River, and Tucson Electric—have experienced very little curtailment, the causes of which primarily relate to local transmission constraints, although NV Energy has curtailed wind on a few occasions due to oversupply during low load hours. These utilities also are distinguished by their compensation practices, in most cases compensating for curtailments within their control. However, like PSCO, APS holds contract clauses that allow it to curtail a certain number of hours without compensation.

4 Synthesis of Curtailment Practices and Trends

This section synthesizes the experiences of utilities and grid operators along four aspects of curtailment: reasons, implementation methods, compensation practices, and mitigation strategies.

4.1 Reasons for Curtailment

Reasons for curtailment include transmission constraints, including congestion and system balancing challenges related to oversupply situations and ramp events.

4.1.1 Transmission Constraints

Transmission constraints have been the most common reason for wind curtailments in the United States to date. Most curtailment has occurred when the construction of necessary transmission lags behind the pace of wind farm development, resulting in infrastructure that is insufficient for the amount of wind generation on line. In ERCOT and SPP, for example, substantial amounts of wind generation were brought online before the necessary transmission could be built and energized, leading to wind curtailments. ERCOT's reported wind curtailments rose from about 1% in 2007 to a peak of more than 17% in 2009. Since the construction of new transmission and the adoption of new transmission operating procedures that increased the transfer capacity on existing transmission, curtailments fell to 4% in2012, and further to 1.6% in 2013 (Maggio 2014), although some of the reduction could be attributed to market changes. A few wind generators in SPP have reported that in 2012 a substantial fraction of expected generation was curtailed due to insufficient transmission access.

Many utilities have also experienced more modest levels of wind energy curtailment as a result of local congestion on transmission lines. Congestion or local transmission constraints have caused curtailments in MISO, ISO-NE, ERCOT, PacifiCorp, PJM, and SPP, among other areas. In MISO, some generators are not dispatched by the market and can be subject to manual curtailments primarily due to congestion. ISO-NE has also reported curtailments of wind generation when local lines are unable to accept all available wind generation. [9] It is worth noting that, in areas with wholesale electricity markets, the minimum interconnection standard assumes that generation resources will be competing to sell power into the grid and therefore generators in the same local area may not be dispatched at the same time. Consequently, developers may choose to undertake an interconnection review that provides sufficient information to ensure a safe interconnection, but does not indicate whether the resource can deliver into the market while other local resources are also generating. This is particularly problematic for wind generators as the available wind resource tends to be clustered and wind generators end up competing with other wind generators for limited transmission capacity.

While all regions have occasional transmission line outages due to accidents or maintenance, we do not focus on this type of curtailment in this report, as these are common to all forms of

[9] For additional information, see Vermont Department of Public Service 2013 Recommendation on Issues Related to the Curtailment of In-State Electric Generation Plants, https://leg2.vermont.gov/sites/legislature/EGAC/Shared%20Documents/Recommendation%20Issues%20Related%20Curtailment%20In-state%20EG%20Facilities.pdf

generation. Often, these curtailments are not tracked, but many utilities report that such instances are relatively rare.

4.1.2 System Balancing

Some renewable energy curtailment has been attributed to challenges in balancing the system with higher penetrations of wind energy due to oversupply of generation, typically during low load periods. Some utilities or grid operators have curtailed generation from wind plants when minimum generation levels on fossil-fuel plants are reached, because stopping and restarting fossil units within a few hours can be significantly more expensive than paying for a few hours of wind curtailment. This type of situation can occur at night when there are substantial amounts of wind generation but loads are low, and it can be exacerbated in small balancing areas.

For example, PSCO has reported periods of very high levels of wind generation relative to total demand and has curtailed on the order of 1%–2% of wind generation annually in recent years. Curtailments during low net load periods have been reported by several utilities and system operators, including CAISO (CAISO 2010), Hawaii, NV Energy, BPA, Alberta ISO, and ISO New England. Hawaii has reported curtailing wind as a result of significant amounts of solar generation at mid-day. In areas with day-ahead energy markets, such as ISO New England, resources that do not bid into the day-ahead market (DAM) are curtailed during low load events before resources that have participated in the DAM and received a financially binding commitment. Because intermittent resources, unlike other generation types, are not required to participate in the DAM these resources are more likely to be curtailed.

In some areas with wholesale power markets, such as MISO and ERCOT, the amount of wind generation utilized is a function of market pricing. When prices are low or negative (e.g., due to oversupply or congestion), wind generators that bid above the market-clearing price will not be dispatched.

Similarly, environmental constraints on hydro plants that affect their operations have been a factor resulting in curtailment of wind generators in the Pacific Northwest. Oversupply of hydropower may occur at times when plants have to run water through the turbines rather than spill it over the dam to control dissolved oxygen levels that relate to fish protection. Some hydro units also have constraints related to protecting irrigation or recreation access that affect output levels. In the BPA service territory, seasonal oversupply of hydropower, combined with the absence of negative prices to dispose of excess hydropower, resulted in the curtailment of about 3% of available BPA wind capacity in the spring of 2011 and about half that amount in the spring of 2012 (BPA 2013b). No oversupply-related curtailments had been reported for 2013.

Curtailment has occurred in some instances, such as in ERCOT and AESO, to slow a rapid change in wind output, which can make it difficult to balance the system if other generation sources are not able to change output levels fast enough to compensate. In Alberta, Canada, for example, AESO has curtailed wind at times when it is unable to manage substantial ramps in wind output.

4.1.3 Other Reasons

Curtailment is also used to address voltage issues, address interconnection issues, and maintain frequency and stability requirements. Curtailments have occurred for voltage reasons in ISO-NE in weak areas of the grid and in areas where older wind plants are unable to provide necessary grid support. These events would have been unlikely to occur if the local transmission system were stronger. If grid upgrades are not undertaken to address interconnection issues, particular projects can be subject to curtailment ahead of other generators that have completed required upgrades. In addition, maintaining frequency and stability requirements can be an issue for small or isolated grids, such as Hawaii. In some cases, limits may be placed on nonsynchronous generation levels to address these concerns and to ensure the system can adequately react to a contingency event. Conventional synchronous generation sources typically provide inertial and governor responses in the case of contingencies. If significant amounts of wind and solar generation are on the system, they may either need to provide these services to the grid or be curtailed to maintain frequency requirements and system stability.

Some wind generators have agreed to self-curtail for reasons such as protecting bats and enabling de-icing. For example, in ISO-NE some wind generators have volunteered to self-curtail for up to 120 nights per year to protect bat populations. This has also occurred in other wind plants in the East. Wind generators must also self-curtail when ice forms on the turbines, and many wind farms are installing cameras to more quickly confirm ice-free status and come back online.

4.2 Methods of Implementing Curtailment

Implementation methods include both the method of signaling curtailments and the rules governing the order that plants are curtailed. These implementation methods vary by cause and by grid operator. Lack of automation can pose challenges in regions where significant curtailment occurs, as manual curtailments can prolong curtailment of renewable generators. **Table 4** summarizes methods used to implement curtailment by utilities and grid operators.

4.2.1 Signaling of Curtailment

Automatic signaling is used to curtail wind generators in a number of areas, including wholesale market environments such as AESO and ERCOT, as well as the BPA balancing area and Hawaii. Supervisory control and data acquisition (SCADA) systems, which are a category of software applications used for transferring data and controlling equipment remotely, are used in these areas to send signals in real time to renewable energy facilities. The AESO send *pro rata* directives by SCADA when conditions for wind power management are met. To initiate curtailments, BPA sends a signal via SCADA (initiated in AGC) and requires confirmation from the wind facilities. Similarly, system operators on Oahu and the island of Hawaii use SCADA to send curtailment limits.

In some markets, regular market operator signals can be used to signal curtailments. For example, ERCOT automatically signals base-point instruction to all generators every five minutes and provides a ramped set-point value every two to six seconds. ERCOT sends a flag to generators that need to be dispatched below their highest dispatchable level and assesses penalties to wind and solar generators that deviate from base-point levels when they are flagged. PJM has a similar process, but has typically followed base-point instructions with a phone call to ensure wind generators curtail as required. To try to reduce the need for manual processes, PJM recently made changes in that it will no longer compensate for curtailment if wind generators must be contacted by phone.

Table 4. Summary of Methods Used to Implement Wind and Solar Curtailment

Utility or Grid Operator	Automated Signaling	Manual Signal (Phone)
AESO	x	
APS		x
BPA	x	
ERCOT	x	
HECO; HELCO; MECO	x (Maui, Oahu and Hawaii)	
ISO-NE		x
MISO	X (DIR program)	x
NV Energy	x	x
PacifiCorp		x
PJM	x	x
Puget Sound Energy	x (BPA curtailments)	
Salt River Project		x
Tucson Electric Power		x
WAPA		x
PSCO	x (not all)	x

At least two utilities place wind plants on AGC to control their output. For example, on Maui, AGC controls are used to curtail wind as needed if other units are generating at minimum levels. Maui also uses wind to provide down reserves. Two-thirds of PSCO's wind facilities have AGC capabilities, which allow for more efficient curtailment because of rapid and more precise signaling. PSCO can take thermal units to their minimum and balance with one AGC-equipped wind plant (only one wind plant is needed on AGC at a given time due to their fast response). Remaining wind facilities are manually curtailed via phone or set-point instruction via the energy management system. Because the operators have the ability to adjust the curtailment as often as they wish via set-point control, the curtailments can be fine-tuned to a more precise level than block curtailments done by phone.

In many areas, curtailments are implemented manually whereby grid operators call wind facilities to issue curtailment directives. Manual curtailment instructions are used by APS, Salt River Project, Tucson Electric, ISO-NE, PacifiCorp, SPP, and MISO. PacifiCorp's generation center can manually control wind output levels for wind facilities they own. In MISO, wind generators not participating in the DIR program are subject to manual curtailments; reliability coordinators call wind generators and coordinate these directives with the local balancing authority and transmission authority. In ISO-NE, grid operators call wind facility operators to provide new not-to-exceed instructions to curtail. NV Energy uses a blend of automatic and manual approaches. The operator sets the new not-to-exceed instructions through the automatic system, and in tandem, calls the wind operation staff to explain the situation. In areas such as those covered by AESO, SPP, and ERCOT, the manual approach used in the past has itself contributed to curtailed hours because it takes 30–40 minutes typically to implement curtailment orders, and grid operators have been reluctant to release these curtailments if they were to be needed again soon.

4.2.2 Order of Curtailments

The methods for determining the order in which resources are curtailed can vary. Criteria often depend at least in part on the reason for curtailment. Curtailment order can be influenced by market design, contracts, and plant economics, as well as whether the curtailment relates to local transmission congestion or is caused by balancing-related challenges (e.g., oversupply on the system that affects a broader region).

Typically congestion-related curtailments are based on the effectiveness of generators in alleviating constraints. For example, in CAISO, generators that are most effective in relieving congestion will be curtailed to their scheduled output first. In MISO, the determination of curtailment order is based on which generators impact congestion the most and whether they have firm transmission service. In SPP, wind generators are subject to curtailment if they contribute 5% or greater to a constraint. If more than one generator creates this impact, the curtailment is divided equally. SPP is reviewing its approach for prioritizing curtailments of multiple generators based on who has firm service.

In ISO-NE, curtailments are pro-rated equally among affected generators for renewable resources that self-schedule in the day-ahead market but must be curtailed in real-time. In some cases, required network upgrades were not completed for some wind generating capacity. These generators must back down first if local constraints are the cause for curtailment. Once upgrades (e.g., new breakers and lines) are complete, open access transmission dictates that all generation is treated the same.

A number of utilities and grid operators base curtailments on contracts and wind plant economics. If there are transmission constraints, AESO cuts the most expensive energy first from among all generators, including wind. Occasionally, AESO will place limits on a transmission line and allow the relevant utility to decide which generators to curtail. For PacifiCorp and PSCO, the order of curtailment is based on the cost of the generators as well as contractual issues. PSCO first curtails generators with which they have negotiated “free” curtailment hours under a PPA. Next, PSCO curtails generators that receive the federal investment tax credit (in lieu of the PTC). Those facilities that utilize the PTC must generate electricity in order to take advantage of the tax credit; therefore, their financial losses (tax credit and the energy value) are higher than investment tax credit (ITC) plants if curtailed. Next, PSCO curtails generators on AGC; finally, other wind generators are curtailed as necessary.

In Hawaii, curtailment is generally applied in reverse installation order. However, renewable energy facilities can lose their curtailment priority if they do not produce at least 60% of annual estimated energy production over four years. However, net-metered solar photovoltaic (PV) and feed-in tariff projects are exempt from this requirement and are allowed to operate without curtailment controls. Also, if a cause for curtailment is directly attributed to a specific renewable energy facility, the reverse chronological order may not apply.

4.3 Compensation of Curtailed Generators

Compensation to wind generators for curtailment varies across balancing authorities and off-takers and typically depends upon the cause of the curtailment.[10] **Table 5** summarizes compensation practices for the grid operators and utilities we interviewed.

Table 5. Compensation for Curtailment by Utility and System Operators

Utility or Grid Operator	Compensation Provided?	Limits Specified in Contracts	Reasons for Compensation	Limits to Compensation
AESO	No		Wind generators are not compensated.	
APS	Yes	x		Limited annually; do not pay if directed by other transmission operators
BPA	OMP curtailment is compensated; DSO is not			Wind generators may absorb costs for OMP.
CAISO	Varies	x	Some contracts for RE brought online before sufficient transmission include compensation	No compensation for reliability caused; or issues in interconnection studies
ERCOT	No		Wind generators are not compensated.	
HECO, HELCO, MECo	No			
ISO New England (ISO-NE)	No			No market-based compensation, but off-taker contracts could have some
MISO	Yes	x	Wind generators eligible for MISO's make-whole payments; off-taker contracts may specify	
NV Energy	Yes	x	Compensated for non-emergency situations, or those unrelated to reliability requirements	Curtailment not compensated under specific scenarios

[10] Internationally, some countries compensate renewable generators for curtailment. Compensation varies by type of curtailment, amount compensated, and specific renewable technologies and jurisdictions. Most commonly, generators are compensated at the prevailing market value for the electricity curtailed, but this does not usually include revenue lost from green energy credits or other types of support mechanisms. Examples of this include Ireland and Romania. In other countries, generators are compensated for a fraction of the energy lost—varying from 15% to 50% or more. For example, Greece compensates for 30% of annually curtailed energy, but the compensation only applies to wind facilities. Sometimes, compensation only applies to specific types of curtailments. An often-used dichotomy is that congestion curtailments are compensated while those related to security are not. This is the case in Belgium and Germany. Spain uses another dichotomy: real-time curtailments are compensated (albeit only 15%) while scheduled curtailments due to technical constraints are not. For more information on international curtailment practices, see Lew et al. (2013).

Utility or Grid Operator	Compensation Provided?	Limits Specified in Contracts	Reasons for Compensation	Limits to Compensation
PacifiCorp	Unknown		Unknown	
PJM	yes		If wind curtailed below economic base point	No compensation if wind resource is not providing required data and following PJM dispatch signals
PSCO	Yes	x	Balancing purposes	Transmission causes beyond control; limited annually
Puget Sound Energy	Follow BPA rules			
Salt River Project	Yes		Take-or-pay contracts	
SMUD	Yes		If CAISO curtails due to oversupply, SMUD compensates.	
SPP	Yes (changing with new market rules)	x	Congestion-based curtailment has been compensated.	No compensation for reliability-based curtailment
Tucson Electric Power	Yes	x	For reasons under TEPs control	No compensation for curtailments caused by others
WAPA	No			

Compensation for curtailed energy is typically negotiated and stipulated in PPAs between the off-taker and the generator on an individual basis. Under "take-or-pay" contracts, the off-taker will pay generators for the energy curtailed and usually the value of lost tax credits (e.g., PTCs). Salt River Project is an example of a utility with take-or-pay contracts, as are older PSCO contracts. Under this type of contract, even if the curtailment directive is given by a system operator, the off-taker is responsible for compensation per the terms of the contract with the generator. In many take-or-pay contracts, curtailments due to congestion, scheduled maintenance, and oversupply may be compensated while those due to emergencies are not. Increasingly in some areas, PPAs include an annual curtailment quota before off-takers must compensate.

A number of western utilities employ take-or-pay contracts, although more recent contracts have modified the bases for payment. For example, PSCO compensates generators if they are curtailed for balancing reasons, but newer PPAs generally do not compensate for transmission-related curtailments. If PSCO curtails for balancing purposes, it will compensate generators for the energy that they would have produced plus the value of PTC earnings. However, PSCO has negotiated annual blocks of free (uncompensated) curtailment hours with 5 of the 14 wind plants.

Other utilities have also placed limits on compensated curtailments. While APS generally compensates for curtailments unless the curtailment is a directive from other transmission operators, in some contracts, APS has included "emergency curtailment rights," which allow

APS to curtail a certain number of hours per year without compensation. NV Energy compensates for curtailment under specific situations but curtails wind without compensation to day-ahead forecasted levels when the utility cannot back down conventional resources. In Hawaii, there is no direct compensation for curtailment; rather, the cost of curtailment is built into the price of fixed-price contracts.

Compensation for curtailment in the BPA balancing area has changed over time and has been a subject of ongoing litigation. In 2012, BPA developed a mechanism for compensating curtailments related to hydro operations under the OMP, but the proportion of the cost to be shared by the generators is currently being debated in a BPA rate case. At the conclusion of that proceeding, it will be subject to review by FERC. BPA does not compensate for curtailments under its DSO 216 program, which can curtail wind projects to scheduled levels for balancing.

In some wholesale power markets, there is no compensation for economic curtailment unless stipulated in bilateral PPAs between generators and off-takers outside of the market settlement mechanisms. Within the market, the decision to generate is based on the economics of dispatch. If a plant bids higher than the market clearing price, which for wind could occur if prices are negative, the plant is not dispatched and does not generate revenue. Some wind generators in market areas hold contracts with off-takers that allow for compensation outside the market, but the markets in AESO and ISO-NE have few off-taker contracts; therefore, compensation for curtailment is limited.

Other grid operators will compensate at the prevailing settlement price if they issue verbal dispatch instructions to curtail generators below economic dispatch levels. For example, PJM will compensate for curtailment and provide make whole payments if automatic curtailment instructions are followed by wind generators.

In some wholesale market areas, such as MISO, significant wind development occurred in advance of market designs that dispatch wind based on market-clearing prices. As a result, the transitions to markets that automate the dispatch of wind based on market clearing prices have affected contracts that were written to address manual wind curtailments. For example, the initiation of the DIR program in MISO affected the contracts between wind generators and off-takers that compensated curtailment.

In SPP, contract language is also affected by the movement toward a more automated approach as an interim solution to reduce curtailments and the new market design in 2014. The modification to curtailment procedures—the interim solution—is intended to reduce curtailments by increasing automation and reducing the stringency of protocols needed to address reliability events. The change in protocol necessitates that the curtailments be reclassified from reliability-based, which are typically not compensated, to congestion management events, which under many contracts would be compensated. Because this change will not be a formal directive, off-takers and wind generators will need to come to an agreement, and negotiations will likely result in reduced compensation for congestion management events—a trade-off that would still be in the generators' financial interests if overall curtailment levels were reduced as a result.

4.4 Strategies to Mitigate Curtailment

Grid operators have developed a variety of strategies to minimize curtailment of renewable energy sources. These strategies are part of a broader collection of practices to manage the variability and uncertainty of variable renewable generation and thereby reduce curtailments (Schwartz et al. 2012; Cochran et al. 2012). The strategies highlighted in **Table 6** are a subset of the broader suite of practices specifically cited in interviews as tools to reduce the magnitude and duration of curtailment. They include changes in the way reserves and conventional generation are managed, automation of curtailment signals, market design issues such as negative pricing, transmission planning, and renewable energy forecasting.

Table 6. Strategies that Mitigate Wind and Solar Energy Curtailment

Reserves and Generation Management	*Utilities or ISOs That Implement*
Automation (i.e., AGC)	ERCOT, PSCO
Use curtailed generators for positive reserves	PSCO
Reduction of minimum generation levels	HECO (Maui)
Increase scheduling frequency	WAPA (adopting)
Market Integration and Negative Bidding	*Utilities or ISOs That Implement*
Economic dispatch	ERCOT, MISO, SPP (adopting)
Negative pricing	CAISO, ERCOT, MISO, PJM, ISO-NE (adopting)
Energy imbalance market	CAISO, PacifiCorp
Other Strategies	*Utilities or ISOs That Implement*
Wind power ramp management system	AESO
Increase transmission capacity	ISO-NE, ERCOT, MISO, PJM, SPP
Improve forecasting	ISO-NE, PSCO, NV Energy, SMUD

4.4.1 Reserves and Generation Management

Utilities have adopted a number of strategies to change the way they manage system reserves and operate conventional power plants to help minimize curtailment. For example, PSCO has reduced total curtailments by putting many of its wind facilities on AGC and using them to help balance the system.

PSCO also uses curtailed wind energy to provide positive reserves to utilize the otherwise curtailed wind whenever possible. PSCO has moved to cycle baseload generating units more to reduce instances of oversupply at night. In 2010, when there was a dramatic increase in wind curtailments primarily due to line outages, PSCO studied the costs of cycling baseload units versus curtailing wind. The costs were similar, so PSCO decided to cycle off thermal units at night to minimize wind curtailments. PSCO is also considering changing its use of pumped storage hydroelectricity.

To utilize more wind energy and reduce curtailment, HECO (Maui) has adopted multiple strategies, including reducing minimum loads on must-run units, running units at lower load levels, modifying units so that they can turn off daily, reducing reserves for quick start units, incorporating demand response into reserves, and running smart grid demonstrations that improve control over distributed solar. HECO has also begun programs to increase demand. HECO is installing 20 quick charging electric vehicle stations and developing eco-tourism through a fleet of electric vehicles (EVs), which will eventually be sold to the public. CAISO is also studying ways to shift load to different periods to absorb over-generation and is investigating options through conventional units, storage, and demand response.

To reduce balancing-related curtailments (under DSO 216), BPA initiated a program (the Customer-Supplied Generation Imbalance Initiative) that allows wind generators to self-balance, and it has expanded its intra-hour scheduling program. For oversupply-related curtailments (under OMP), BPA has implemented spill exchanges with non-federal hydro dams, asked the regional nuclear plant to schedule maintenance during the high season, maximized pump load during light load hours, and acquired additional reservoir storage. Also, BPA and others in the Pacific Northwest are discussing the potential implementation of an energy imbalance market, which would greatly reduce the need for wind energy curtailment and enable more efficient operation of the power system.

4.4.2 Market Integration, Automation, and Negative Bidding

Several regions have integrated variable renewable energy generators more fully into the market to enable economics to determine which generators curtail their output. For example, in mid-2011, MISO implemented the DIR protocol. Thus, their operations are based on economic market dispatch. Similarly, ERCOT integrated wind into the market and replaced manual curtailments with an automated system that more efficiently uses market bids to set the order of dispatch. SPP is introducing a day-ahead market in March 2014 that will include wind generation and operate similar to the MISO program. In the near term, SPP is shifting toward a more automated system to implement curtailments to reduce the time that generators are curtailed, to address the prolonged curtailments that have occurred using manual processes.

Negative pricing is used in several markets, including MISO and ERCOT, to address periods of oversupply and reduce manual curtailments. Enabling prices to go negative can discourage generators from bidding into the system during low load periods and reduce oversupply, and it can encourage flexible loads to increase demand because they get paid to use electricity. For example, with the expectation of higher renewable energy penetration levels in the future, CAISO is lowering the limit on negative bids from the current -$30/MWh, which is not sufficient to overcome the PTC incentive for wind to generate during oversupply periods, to -$150/MWh. If that were insufficient to address oversupply issues, the limit would be dropped to -$300/MWh.

An energy imbalance market is under development by CAISO and PacifiCorp, which is expected, among other benefits, to reduce curtailments by automating processes and enabling better access to balancing resources in the region. Under the system, imbalance energy will be dispatched at 5-minute intervals. An energy imbalance market could reduce the need for curtailments by broadening the supply of resources available to balance renewable energy generation, more efficiently managing transmission resources to minimize congestion, and better managing wind ramps through an automated process rather than manual.

SMUD is working with CAISO on proposed market changes that would enable CAISO to curtail unscheduled wind. SMUD is also seeking ways to increase the financial cost of congestion.

4.4.3 Strategies to Address Ramping

AESO implemented in December 2011 a Wind Power Ramp Up Management system to manage wind ramps, in which a 10-minute cap can be placed on wind, when the system cannot handle wind ramping up. AESO has only used the tool for a few hours to date but expects the frequency will increase as wind penetration levels increase.

APS is managing solar variability by including thermal storage on its Solana concentrating solar facility. The thermal storage allows the variability to be smoothed and shifted to meet evening peak load.

Because of its large footprint, MISO can handle existing wind energy ramps now (at about 13 GW of wind capacity) but anticipates this could be an issue when wind energy thresholds reach 20–25 GW. Similarly, the value of using curtailed energy for ancillary services is not yet economic, at least in MISO, for the majority of hours.

4.4.4 Transmission Planning Methods

Transmission expansion activities are underway in a number of regions that have or are expected to reduce curtailment. ERCOT has expanded its transmission capacity under the CREZ program, which alleviated what had been the dominant cause for curtailments. Additional 345-kilovolt (kV) lines will be in service by 2014. MISO is also expanding its multi-value transmission projects to move wind to load centers and more robust parts of the grid. SPP is currently building new transmission capacity, an important tranche of which is expected to come online by mid-2014 to 2015 and help alleviate curtailments.

PJM has recently developed a light load planning process to ensure that the transmission system is capable of delivering the system generating capacity at light load, when wind generation is typically higher. Based on the new criteria, PJM identified a number of required baseline upgrades, the cost of which will be allocated to load, not to individual wind generators.

ISO-NE has several plans that can mitigate curtailments, including expanding transmission capacity in Maine. ISO-NE plans to conduct wind interconnection studies in batches of wind plants, rather than individually, to provide more accurate information on impacts of multiple wind plants. This is currently done in PJM and MISO.

4.4.5 Forecasting and Renewable Energy Visibility

Forecasting has been used by a variety of utilities and markets to manage wind on the system more efficiently. Widiss and Porter (2014) provide an overview of forecasting practices in the West. PSCO has undertaken a variety of strategies to accommodate increasing wind penetrations. Foremost is its improved use of forecasting. PSCO worked with the National Center for Atmospheric Research to improve its wind prediction models. Improved forecasting enables PSCO to turn down conventional resources when sufficient wind generation is predicted and to reduce curtailment from oversupply. Improved forecasting also eliminated curtailments related to ramping. NV Energy uses a few different forecasting services to improve short-term (i.e., 1–3 hours) forecasting and avoid curtailments.

ISO-NE plans to improve its wind forecasting to provide generators better information and enable them to participate more fully in the day-ahead market. Currently, lack of adequate forecasting impedes some wind farms from fully self-scheduling in the day-ahead market, and this in turn can restrict wind from producing at full capacity if day-ahead commitments fully meet demand. ISO-NE also plans to acquire more information on wind profiles at each station to be able to automatically and more precisely (at increments of every few seconds) provide not-to-exceed instructions.

ISO-NE has initiated a Distributed Generation Forecast Working Group that will help improve visibility of distributed solar, which appears as reduced load, to help understand system changes that can influence unit commitment and balancing. ISO-NE wants to standardize reporting standards for distributed solar across states to help more accurately assess resources within the system.

5 Conclusions

While a greater number of regions are experiencing some form of curtailment of wind and solar resources, the relative magnitude of curtailment appears to be declining in the largest markets for wind power even as the amount of wind power on the system increases. New transmission capacity and better operating practices, such as greater automation and the use of forecasting and other operational practices, are now resolving challenges for grid operators, often circumventing the need for curtailment. As penetrations of wind and solar energy increase, curtailment practices and the use of strategies to mitigate the potential for curtailment may become increasingly important and may impact wind and solar energy project economics. Nevertheless, as wind and solar energy penetrations increase, there may come a time when changes in operating protocols would not lead to reduced curtailments, and rather that curtailment volumes could rise as a fraction of total wind and solar generation.

Curtailment levels have generally been 4% or less of wind energy generation in regions where curtailment has occurred. A notable exception is ERCOT, where curtailment levels reached 17% in one year, primarily because wind generation came online ahead of transmission capacity. These levels have since receded to less than 2%. Many utilities in the western states report negligible levels of curtailment. The most common reasons for curtailment are insufficient transmission and local congestion, and excessive supply during low load periods. One challenge to determining curtailment levels is that data are not uniformly collected.

Definitions of curtailment vary. Understanding curtailment levels can be complicated by relatively newly implemented market-based protocols or programs that limit wind generation to schedules. Now that economic dispatch is being used in several areas, wind generators can be dispatched down based on market prices, but this reduction of output is not characterized as curtailment. In some cases, wind generators are not able to exceed scheduled levels—a process that is referred to in the BPA balancing area as limiting output rather than curtailment.

Curtailment order varies and is often based on plant economics or ability to alleviate local congestion. For curtailments that are needed to address balancing or system operations, the most expensive generators are often curtailed first. For wind projects, one consideration is whether the project utilizes the federal PTC or ITC. Generators reliant on the PTC, which is provided based on project output, face greater financial impacts from curtailment (the value of the PTC as well as the energy) than wind generators that received the upfront ITC. To address local congestion issues, curtailment is often applied equitably across generators that are most able to alleviate congestion. Hawaii provides preference to projects based on the order that they were installed (i.e., curtailing the most recently installed resources first), which limits the financial impacts and risks of curtailment for existing renewable energy facilities.

Compensation and contract terms are changing for curtailment. Contracts between generators and off-takers have in some cases included provisions whereby the off-taker will compensate for curtailment for reasons such as congestion, scheduled maintenance, and operator errors, but typically not for curtailment ordered by other entities. However, contracts are increasingly reflecting a negotiated number of annual hours in which curtailments are not compensated, despite the cause, and there is greater sharing of risk between the generator and off-taker. In some cases, when new curtailment procedures are adopted, the need to renegotiate contract language has posed implementation challenges. In wholesale power markets, the grid operator sometimes compensates if it calls for units to deviate from initial dispatch orders.

Automation can reduce curtailment levels. Manual curtailment processes for wind have been found to extend curtailment periods because of the time required to implement curtailment and hesitancy to release units from curtailment orders. Automatic communication procedures can speed the implementation of curtailment orders and reduce overall curtailment time.

Market solutions that base dispatch levels on economics offer the advantages of creating transparency and efficiency in curtailment procedures, which apply equally to all generation sources. Programs like the MISO DIR utilize economic dispatch to determine which units will generate at a given time. During periods of oversupply, the use of negative pricing to determine dispatch order can eliminate the need for manual curtailments. Some wind developers have expressed a preference of the market-based dispatch framework because it reduces market distortions and allows wind generators to participate alongside conventional generators. The use of market-based approaches with their associated automation can also minimize curtailment by improving operational efficiency and reducing the burden on grid operators of implementing manual processes.

Curtailed wind resources can provide ancillary services to aide in system operations. PSCO uses curtailed wind resources to provide both up and down regulation reserves for the balancing area. Wind turbines can provide quick response to signals, which can be valuable for the system. MISO assessed this and found it was economically viable only 2% of the time, however. ERCOT requires all wind turbines that can be retrofitted with governor response to do so in order to provide primary frequency response if they are curtailed.

Transmission expansion and interconnection upgrades can be one of the most direct ways to reduce curtailments. ERCOT's expansion of transmission in recent years through CREZ has alleviated wind generator curtailments. A key challenge is that renewable energy projects can be built much more rapidly than transmission lines. The CREZ program identified the need for transmission to particular regions to facilitate wind energy expansion. SPP is building new transmission capacity that is expected to alleviate current curtailment levels, while MISO is pursuing multi-value transmission projects to move wind to load centers and more robust parts of the grid.

Forecasting can decrease uncertainty associated with wind and solar resources, reducing the need for curtailments due to unexpected changes. Improved forecasting can enable utilities or grid operators to turn down conventional resources when sufficient wind generation is predicted and to reduce curtailment from oversupply. Improved forecasting can also reduce curtailments related to ramping. Wind forecasting can provide generators better information and enable them to participate more fully in the day-ahead market. Improved data on wind profiles may help grid operators provide more precise not-to-exceed instructions, enabling increased wind generation output. Grid operators could also improve visibility of distributed solar, which appears to grid operators as reduced load, to help understand system changes that can influence unit commitment and balancing to minimize curtailments.

Firming resources can decrease curtailments and increase financial certainty for generators, but they are not necessarily the most cost-effective system-wide solution. Iberdrola in BPA has found it more cost-effective to balance its own resources than it is to pay integration charges and be exposed to uncompensated curtailments under DSO 216. Nevertheless, developer-specific balancing, through options such as storage and natural gas, may likely be less cost-effective at a system-wide level than it would be for the utility or grid operator to adopt operating practices that minimize the need to curtail, such as dynamic reserves, negative pricing, and improved forecasting.

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Appendix. Summary of Curtailment Experiences of Utilities and Grid Operators

Table 7 summarizes the experiences of the utilities and grid operators that were interviewed for this report had with curtailment of renewable sources of energy. It includes including utilities that reported lower levels of curtailment.

Table 7. Utility and Grid Operator Experiences with Renewable Energy Curtailment

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Alberta Electric System Operator (AESO)	10,600 MW peak demand[11] Wind: 1,090 MW[12]	Curtailment occurs infrequently. Curtailments due to oversupply occur once or twice per year, lasting a few hours. Curtailments due to transmission constraints and outages are not tracked.	Wind generators are not compensated. AESO is a deregulated market with no PPAs; wind generators receive the average pool price per hour (AESO does not use LMPs and instead settles at a single market-wide price).	AESO implemented in December 2011 a Wind Power Ramp Up Management system to manage wind ramps, in which a 10-minute cap can be placed on wind. But, AESO has only used the tool for a few hours.	AESO uses SCADA to signal curtailments to wind generators. If there are transmission constraints, AESO cuts the most expensive energy first from among all generators, including wind. Sometimes AESO will put a limit on a line and allow the relevant utility to decide what to curtail.

[11] Jacques Duchesne interview – June 17, 2013
[12] http://www.energy.alberta.ca/Electricity/682.asp, June 2013; communication from Jacques Duchesne – Jan 16, 2014

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Arizona Public Service (APS)	7,300 MW peak demand[13] Wind: 290 MW[14] Solar: 348 MW[15] (including distributed generation)	Curtailment occurs infrequently. Line overloads occur 2–3 times per year. Wildfires in 2013 resulted in several weeks of local line outages. Curtailment is caused by single-time events (e.g., transmission outage, fire near transmission lines, line constraint). For example, the Solana Generating Station has been curtailed for a few hours due to problems at the delivery location. Many solar facilities are connected to the distribution networks, usually at the substations, and in remote locations. On rare occasions, these substations are taken out of service for maintenance (lasting a few hours).	APS has primarily take-or-pay contracts and compensates for curtailments unless the curtailment is a directive from other transmission operators. APS has included in some contracts “emergency curtailment rights,” which allow APS to curtail a certain number of hours per year without compensation.	APS is managing changes that have emerged from distributed solar, which has affected ramp rates needed to follow load. APS has found the ramps more difficult to predict. But variability from cloud cover is minimized because the solar is widely distributed over an 80-mile east-west span. The Solana plant has thermal storage, which also allows the variability to be smoothed and shifted to meet evening peak load.	Schedulers call wind generators to issue curtailment directives.

[13] Ronald Flood Interview- July 12, 2013
[14] 100 MW within APS’s balancing area (near Williams, Arizona); 190 MW (100 + 90) from two wind farms in a neighboring balancing area (in New Mexico)
[15] Wind and solar installed capacity from APS January 2013 http://www.aps.com/en/Documents/pdf/company/RenewableEnergyPort.pdf

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Bonneville Power Administration (BPA)	11,500 MW peak demand[16] Wind: 4,515 MW[17]	DSO 216 curtailments 2012: 95 events, 683 MW total capacity per event; 2013 January-June: 15 events, 213 MW total capacity per event; 11,855 MW OMP Curtailments 2011: 97.2 gigawatt-hours (GWh); 2012: 49.7 GWh [18]2013 YTD: 0 GWh Curtailment occurs: (1) Under DSO 216 when balancing reserves are exhausted; (2) Under the OMP when mandatory hydropower generation creates oversupply	DSO 216 events are not compensated. OMP curtailment is compensated, but wind generators may absorb some of the costs for compensation.	To reduce curtailments under DSO 216, BPA is considering purchasing balancing reserves, has installed 16 wind anemometers to provide data to wind operators at 5-minute intervals, created an internal wind forecast, and has initiated a program that allows wind generators to self-balance (Customer Supplied Generation Imbalance Initiative). For OMP, BPA has implemented spill exchanges with non-federal hydro dams, asked the regional nuclear plant to schedule maintenance during the high season, maximized pump load during light load hours, and acquired additional reservoir storage.	BPA uses different signaling methods, including SCADA ICCP, GenICCP, and SCADA RTU, as well as a Web application.

[16] GL_2013 Wind Integration AWEA Windpower.pptx, GL Garrad Hassan, *Wind Power 2013: Integrating Wind in Future Markets*
[17] http://transmission.bpa.gov/business/operations/Wind/WIND_InstalledCapacity_Plot.pdf, April 13, 2013
[18] BPA, *Seasonal Power Oversupply in 2012*, February 2013

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
California Independent System Operator (CAISO)	50,270 MW peak demand[19] Wind: 6,000 MW[20] Solar: 2,800 MW	Curtailment is not tracked and is currently a small percentage of load. The reasons for curtailment are not tracked but include transmission constraints and oversupply. Constraints include congestion, and in some locations, wind and solar were brought online in advance of sufficient transmission. Oversupply events have been exacerbated by a decrease in net load in the last five years due to the growth of distributed generation and because CAISO's portfolio contains a high number of non-dispatchable generation units.	No compensation is offered for reliability reasons or issues identified in interconnection studies. For example, some of the contracts for wind and solar brought online in advance of sufficient transmission include provisions for curtailment. CAISO received approval to curtail plants back to schedules, but otherwise, renewable energy generation is must-take based on a 2010 FERC ruling.	CAISO has several strategies to mitigate curtailment from oversupply, particularly with the expectation of higher renewable energy penetration levels. CAISO will lower negative bids from the current -$30/MWh (which is not sufficient to overcome the PTC incentive for wind to generate during oversupply) to a two-step price structure: first -$150/MWh, and if that is insufficient, -$300/MWh. CAISO is also studying ways to shift load to different periods to absorb over-generation, and investigating options through conventional units, storage, and demand response. Additionally, CAISO is creating a scalable energy imbalance market (EIM) that allows balancing areas to share reserves and more cost-effectively balance.	Curtailments are based on effectiveness: generators that are most effective in relieving congestion will be curtailed first; if effectiveness is the same (e.g., between conventional and wind plants), the curtailment is split between them.

[19] CAISO 2012 http://www.caiso.com/Documents/CaliforniaISOPeakLoadHistory.pdf, August 2012
[20] Clyde Loutan Interview – August 23, 2013

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Electric Reliability Council of Texas (ERCOT)	68,000 MW peak demand[21] Wind: 11,000+ MW	2013: 479 GWh, 1.6% of total annual potential wind generation[22] 2012: 1,038.0 GWh, 3.7%[23] 2011: 2,621.5 GWh = 8.5% Curtailment is a function of market bids—-when market-clearing prices are negative (e.g., due to oversupply or congestion), renewable energy generators that bid above the market-clearing price will not be dispatched.	The treatment of compensation in PPAs is unknown. Higher prices in west Texas have helped alleviate the financial impact of curtailments in that area.	ERCOT made two major changes to reduce curtailments: (1) Transmission expansion under CREZ, which alleviated what had been the dominant cause for curtailments. Additional 345-kV lines will be in service by 2014. (2) Market integration of variable renewable energy and use of negative prices. Curtailments, which had been conducted manually, have largely been replaced by an automated system in which market bids, including negative bids, set the order of dispatch.	ERCOT uses telemetry to signal base-point instruction to all generators every five minutes. A ramp value is also provided every six seconds. ERCOT sends a flag to generators that need to be dispatched below the limit. Penalties occur for wind and solar generators when they are flagged and deviate from base point.

[21] GL_2013 Wind Integration AWEA Windpower.pptx, GL Garrad Hassan, *Wind Power 2013: Integrating Wind in Future Markets*
[22] Maggio (2014)
[23] LBNL_2013_2012 Wind Technologies Market Report.pdf, page 44

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Hawaii Electric Co. [HECO], Hawaii Electric Light Co. [HELCO], and Maui Electric Co. [MECO])	2,237 MW peak demand:[24] HECO: 1,200 MW MECO: 200 MW HELCO: 195 MW[25] Total wind:-206 MW[26] Total solar: 166 MW[27] (including distributed generation) HECO: 100 MW wind,[28] 135 MW solar MECO: 73 MW wind, 31 MW solar HELCO: 33 MW wind	Curtailment levels have been considerable in Maui (MECO) and on the island of Hawaii (HELCO) due to oversupply and negligible in Oahu (HECO). Curtailment in MECO and HELCO occur primarily during low load hours, which has been exacerbated by the rapid growth in PV installations (from single digits to 30 MW over a few years). The small balancing areas with limited interconnection make it especially challenging to integrate renewable generation without curtailment.	HECO contracts do not compensate for curtailment, but the curtailment estimates are built into the contracts in the form of tiered pricing. For example, the contract with the third wind farm on Maui presumes around 40 GWh in annual sales (50% of potential). The price reflects revenue needed to cover the cost of capital at that generation level. If HECO can take more of that energy, the energy price for that amount is much cheaper.	The exponential growth in PV was not anticipated when the initial wind integration studies were conducted—-hence wind sales have been less than expected, and HECO finds itself buying net-metered PV at close to $0.40/kWh, which displaces less expensive wind. To try to take more wind, HECO (Maui) has adopted multiple strategies to reduce curtailment, including reducing minimum loads on must-run units, running units at lower load levels, modifying units so that they can turn off daily, reducing reserves for quick start units, incorporating demand response into reserves, and running smart grid demonstrations that improve control over distributed solar. HECO has also begun programs to increase demand. HECO is installing 20 quick charging EV stations and developing eco-tourism through a fleet of EVs, which will eventually be sold to the public.	On Oahu and the island of Hawaii, system operators use SCADA to send curtailment limits. On Maui, AGC controls are used to curtail wind as needed if other units are at minimum. Maui also uses wind to provide down reserves. Generally, curtailment is applied in reverse installation order. If a renewable energy plant cannot produce at least 60% of annual estimated energy production over four years, the plant loses its curtailment priority over later entrants for the portion that could not be delivered. The exceptions are net-metered PV and feed-in tariff projects that are allowed to operate without curtailment controls and if a cause for curtailment is directly attributed to a specific facility, in which case reverse chronological order may not apply.

[24] http://energy.hawaii.gov/wp-content/uploads/2011/10/DBEDTEnergyFactSheets_6.13.12.pdf, *Hawaii Energy Facts and Figures*, June 2012
[25] http://puc.hawaii.gov/wp-content/uploads/2013/04/RSWG-Facilitators-Report.pdf, p. 478, *Reliability Standards Working Group, Silverstein, Alison*
[26] http://www.windpoweringamerica.gov/wind_installed_capacity.asp, Data derived from the *American Wind Energy Association Fourth Quarter Market Report*, December 2012
[27] http://www.seia.org/state-solar-policy/Hawaii, *Solar Energy Industries Association*, 2012
[28] Marc Matsuura Interview – August 8, 2013

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
ISO New England (ISO-NE)	27,379 MW peak demand[29] Wind: 700 MW[30]	Some individual plants have experienced substantial curtailments. The development of wind generation has occurred in western and northern Maine and northern Vermont—areas with strong wind resources, but low load, and transmission capacity (e.g., a single 115-kV line) is inadequate to move the energy to higher load areas. Some of these areas also have hydro that competes for transmission capacity. Conditions are most challenging during spring—a confluence of low load, high wind, and strong hydro from snow melt. Northern Maine and Vermont also have weaker standards for voltage control—older wind plants do not provide necessary grid support—causing curtailments for voltage reasons.	Ninety-three percent of all generation in ISO-NE are merchant-generators and are compensated exclusively from energy sold in the wholesale market; there is no market-based compensation for curtailed energy. If wind contracts directly with a utility off-taker, compensation for curtailment is unknown.	ISO-NE has plans to mitigate curtailments, including expanding transmission capacity in Maine. ISO-NE plans to conduct wind interconnection studies in batches of wind farms rather than individually to provide more accurate information on impacts of multiple wind farms. ISO-NE is working to improve visibility of distributed solar, which appears as reduced load. Currently, each state has different reporting standards for solar distributed generation, and ISO-NE wants to standardize this. ISO-NE also plans to acquire more information on wind profiles at each station to be able to automatically and more precisely (every few seconds) provide not-to-exceed instructions. Finally, ISO-NE will improve its wind forecasting to enable generators to more fully participate in the day-ahead market. Currently, lack of adequate forecasting impedes some wind farms from fully self-scheduling in the day-ahead market, and this in turn can restrict wind from producing at full capacity if day-ahead commitments fully meet demand.	Curtailments are pro-rated equally among affected generators for renewables that self-schedule in the day ahead market but must be curtailed in real time. In some cases, wind generators have not completed required upgrades to the network. These generators must back down first if local constraints are the cause for curtailment. Once upgrades (e.g., new breakers, lines) are complete, open access transmission dictates that all generation is treated the same. During curtailments, grid operators call wind facility operators to provide new not-to-exceed instructions.

[29] ISO-NE Top 10 Demand Days, http://www.iso-ne.com/nwsiss/grid_mkts/demnd_days, accessed December 10, 2013
[30] ISO-NE (2013), Summary of Wind Power and Curtailment in New England, June 28, 2013 http://www.iso-ne.com/pubs/pubcomm/corr/2013/curtailment_summary_2013.pdf

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
ISO New England (ISO-NE)		To protect bat populations, some wind generators volunteered to self-curtail up to 120 nights/year, which they have since reduced to only nights of greatest concern for the bats. Wind generators also must curtail when ice forms on the turbines, and many are installing cameras to more quickly confirm ice-free status and come back online.			

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Midcontinent ISO (MISO)	98,000 MW peak demand[31] Wind: 12,270 MW[32]	Manual wind curtailments have fallen from nearly 4% in 2010 to about 0.2% in 2013. Wind reductions from DIR plus manual curtailments have ranged from about 3-4%. Manual curtailment experienced by wind generators exempt from DIR protocol[33] As in ERCOT, curtailment is a function of market bids for wind participating in DIR. Wind that does not clear the market price (e.g., due to negative pricing that results from oversupply or ramping constraints) is not classified as curtailment. Manual curtailments are caused primarily by local transmission congestion.	The introduction of DIR, with the shift from reliability-based curtailments to market-based dispatch, affected contract language, and many contracts have been adjusted as a result. Also with DIR, wind generators are eligible for MISO's make-whole payments if they follow dispatch. Despite the uncertainties created by this shift, developers that we interviewed preferred the market framework, which reduces market distortions and in which wind generators can participate as regular generators.	In mid-2011, MISO implemented the DIR protocol, which requires all wind plants operating on or after April 2005 to bid into the real-time market. MISO is also expanding its multi-value transmission projects to move wind to load centers and more robust parts of the grid.	For manual curtailments, reliability coordinators call wind generators and coordinate these directives with the local balancing area and transmission authority. Determination of curtailment order is based on who is impacting congestion the most and whether they have firm transmission service.

[31] https://www.misoenergy.org/Library/Repository/Report/IMM/2012%20State%20of%20the%20Market%20Report.pdf, 2012, p. ii
[32] Rudd 2014; McMullen 2013, MISO, Presentation to UVIG Forecasting Workshop, February
[33] Rudd 2014; McMullen 2013, MISO, Presentation to UVIG Forecasting Workshop, February

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
NV Energy	North balancing area: 2,100 MW peak demand South balancing area: 6,100 MW peak demand[34] Wind: 149 MW Solar: 170 MW[35]	Curtailment occurs infrequently. Oversupply during low load hours (early morning hours in fall and spring): NV Energy has curtailed generation to forecast but not yet below forecast, on 6–7 occasions over a calendar year. Each event lasts no longer than 2–3 hours and ends by the morning ramp. Line outages (planned and unplanned) have also resulted in curtailments (e.g., in late summer 2012, two fires caused three weeks of line outages that affected renewable energy generation).	The PPA with wind includes a provision to curtail without compensation under specific scenarios, including curtailing output to day-ahead forecasted levels when NV Energy cannot back down conventional resources.	NV Energy uses a few different forecasting services to improve short-term (i.e., 1–3 hours) forecasting and avoid curtailments.	The operator sets the new not-to-exceed instructions through the automatic system, and in tandem, calls the wind operation staff to explain the situation.

[34] Communication from Rich Salgo, NV Energy, 1/17/2014

[35] NV Energy 2013 Renewable Energy: https://www.nvenergy.com/brochures_arch/RenewablesBrochure.pdf, 2012

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
PacifiCorp	9,830 MW peak demand[36] Wind: 2,500 MW[37] (1,000 MW owned, 1,000 MW purchased, 500 in balancing areas that are neither owned nor purchased)	The biggest reason for curtailment—much less than the 1% total annual production within PacifiCorp's balancing area—is transmission congestion (e.g., not enough export capability, transmission outage). The second reason for curtailment is ACE control, for example, if wind output increases quickly. In both instances, thermal is curtailed first, but if those plants cannot respond quickly enough, wind is backed down until thermal can respond (duration of minutes or tens of minutes, not hours).	PacifiCorp's PPAs address compensation, but this information was not made public. When PacifiCorp had two wind plants exposed to BPA's DSO 216 and OMP, PacifiCorp lost expected revenue most significantly from PTCs but also from energy sales and renewable energy certificates (RECs).	In February 2013, PacifiCorp began telemetering its two wind facilities out of BPA's balancing area into its own. PacifiCorp also plans to also enter into an EIM with CAISO, in which some wind generation will be dispatched by the EIM at 5-minute intervals. In this larger footprint, wind ramps will be managed better automatically (rather than manually).	PacifiCorp's generation center can manually control wind output levels for wind facilities they own. The order of curtailment is based on the cost of the generators as well as contractual issues.

[36] Porter_2013_EIM Coordination CAISO PacifiCorp_UVIG presentation, slide 2, 2012
[37] Interview w/ John Apperson of PacifiCorp 8/6/13

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PJM	155,185 MW weather normalized summer 2013 [38] Wind: 6500 MW Solar: 200–300 MW, not including distributed[39]	Most curtailment is due to transmission constraints, particularly during maintenance periods. Oversupply is not typically a problem; PJM has negative pricing.	PJM recently modified compensation protocols to compensate only with make-whole payments for curtailment when generators follow automatic base-point instructions. If a phone call is needed to implement curtailment, no compensation is provided.	PJM implemented forecasting and negative pricing in 2009. In 2011, PJM implemented a light-load planning process to identify transmission reinforcements needed to improve generator deliverability. In 2013, PJM modified compensation protocols to reduce reliance on manual processes to reduce curtailment.	PJM sends curtailment flag to generators to follow base-point instructions down, and they follow these with a phone call to ensure the order is followed. They now have a "backcast" for assessing actual curtailment.
Puget Sound Energy (PSE)	5,000 MW peak demand Wind: 733 MW,[40] 500 MW in BPA balancing area Solar: 0.5 MW	Wind curtailments in the PSE balancing area are minimal and are not tracked. Because much of PSE's wind fleet is in BPA's balancing area, PSE's generators are subject to OMP and DSO 216 curtailments. Curtailments happen infrequently in PSE's balancing area because wind is fully integrated and PSE has an hourly economic dispatch process.	Facilities within BPA's balancing area receive compensation for OMP curtailments. Within PSE's balancing area, PSE has no PPAs with wind generators.	PSE is advocating for a regional EIM.	For BPA curtailments, BPA sends a signal via SCADA ICCP and requires confirmation from the wind facilities.

[38] PJM Load Forecast Report, January 2014. http://www.pjm.com/~/media/documents/reports/2014-load-forecast-report.ashx
[39] Interview w/ Ken Schuyler and Dave Souder of PJM 12/19/13
[40] Puget Sound Energy IRP_2013_Appendices.pdf, page D-7, 2012

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Salt River Project (SRP)	6,660 MW peak demand[41] Wind: 177 MW, including a contract for 50 MW firm (backed) energy, which will end in 2013[42] Solar: 100 MW (60 MW rooftop; 40 MW connected to transmission network)	Wind has been curtailed once or twice; solar has never been curtailed. Wind has been curtailed on a few occasions due to transmission or equipment issues and for maintenance.	Currently, all PPAs in SRP are take-or-pay, so facilities are compensated.	Solar ramps have been small and more predictable than wind, although high, fast-moving clouds can cause spikes that are faster than the regulating machines. But installed capacity is still low enough that overall impacts are small, and SRP has not experienced difficulties forecasting load affected by distributed solar, even without good measurements of PV output. (Distributed solar output is estimated based on installed capacity factors). No additional mitigation strategies are planned.	To curtail, operators manually call the wind generator's control center.
Sacramento Municipal Utility District (SMUD)	3,300 MW peak demand[43] Wind: 200–300 MW in CAISO's service territory; none in SMUD. SMUD owns but does not schedule this wind. Solar: Significant PV (rooftop and farms): ~200 MW	SMUD does not track curtailments. SMUD is not affected by wind curtailments because CAISO ensures firming and fuel availability. SMUD operations absorb variability of solar. For wind in CAISO, all curtailments have been transmission-related.	Some of SMUD's wind generation in CAISO is owned by third parties. If CAISO curtails due to oversupply, SMUD will fully compensate for the value of the lost generation and PTC; SMUD would absorb the loss of those.	SMUD is working with CAISO on a study on impacts of variable resources. SMUD's focus has been on how much thermal generation and hydro capacity it needs to compensate for the variability of renewable energy. SMUD is also working with CAISO on proposed market changes that would enable CAISO to not accept unscheduled wind. SMUD would also like to increase the financial cost of congestion and encourage merchants to develop better forecasting tools.	

[41] http://www.srpnet.com/about/Facts.aspx#power, Fiscal Year (FY) 2013 May 1, 2012- April 30, 2013
[42] Salt River Project – 7/15/13 – Mark Avery (Manager of Transmission Services) and David Crowell (Principal Analyst) (Interview)
[43] SMUD Interview: Vicken Kasarjian and Mark Willis September 13, 2013

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Southwest Power Pool (SPP)	47,142 MW peak demand[44] Wind: 7,790 MW[45]	Unknown but isolated reports by generators to SPP have suggested curtailment levels as high as 40%–50% at some locations. Local transmission constraints are the primary cause for curtailment; wind generators connected to the grid ahead of planned transmission upgrades. Further exacerbating the curtailment levels historically have been the manual processes for imposing production caps. SPP manually called control rooms at each affected wind farm to set new limits on dispatch. Because the notifications could consume 30–40 minutes for a typical event, SPP has been reluctant to release these curtailments if they might be needed again soon, and wind generators might spend several days operating at curtailed outputs.	Reliability-based curtailments are typically not compensated. The proposed reclassification of most curtailments from reliability to congestion management affects contract language on compensation.	To mitigate curtailments, SPP has been implementing a three-phase approach: (1) Automate and shorten curtailments by reclassifying them as congestion management, rather than emergency (2) Introduce a day-ahead market, which will include wind generation, similar to MISO (, March 2014) (3) Build new transmission (mid 2014–2015).	If a wind generator contributes 5% or greater to a constraint, that generator is subject to curtailment. If more than one generator creates this impact, the curtailment is divided equally. SPP is reviewing the legality of prioritizing curtailments of multiple generators based on who has firm service. SPP curtails wind using three-way verbal communication.
Tucson Electric Power (TEP)	2,300 MW peak demand	Curtailment occurs infrequently. Curtailments can take two forms:	PPAs specify that events outside of TEP's control (e.g., outages, WECC curtailments) are not	TEP currently does not experience difficulties with balancing as a result of its wind and solar—cloud impacts are	TEP manually calls wind generators.

[44] SPP-2012-State-of-the-Market-Report.pdf, p. 24, May 17, 2013
[45] SPP-2012-State-of-the-Market-Report.pdf, p. 36, May 17, 2013

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Tucson Electric Power (TEP)	Wind: 60 MW: 50 in PNM control area, 10 in Unisource area[46] Solar: 103 MW	(1) WECC-initiated curtailments can occur (but have not yet) if generation that uses TEP's transmission contributes to an unscheduled flow event in WECC. TEP would implement the curtailment, which is based on a set methodology (e.g., if a unit contributes to 20% of overload and WECC is curtailing the overload by half, WECC will curtail the 20% contribution by half). This type of curtailment could occur in the future if TEP adds more remote generation, which might impact the qualified paths most at risk for WECC curtailment. (2) TEP-initiated curtailments rarely occur; for example, once in 2012 TEP curtailed two solar projects radially connected to the same distribution circuit when a breaker tripped. The event lasted about a half hour.	compensated. TEP compensates wind generators for curtailments based on events that occur under TEP's control (e.g., scheduled maintenance, operator errors, balancing). The calculations used to assess compensation vary between wind and solar contracts. In general, wind payments are based on lost revenue (including electricity sales, PTCs, RECs). Solar compensation is based on the average generation over the same period before and after the incident. In future contracts, TEP might include "curtailment rights" (i.e., rights to curtail without compensation for a certain number of hours).	noticeable but manageable. As TEP adds wind and solar, it might import more power, allowing TEP to back off conventional generation and use that generation instead for regulation and ramping. If renewable penetration levels get so high that TEP cannot maintain balance, even with imports, TEP might curtail renewable energy generation to stay in compliance with ACE.	

[46] Tucson Electric Interview - C. Tilghman July 25, 2013

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
WAPA	7,027 MW[47]" peak demand Wind: WAPA has wind in the balancing area, which it regulates but does not own or operate wind. They have 300 MW installed and are expecting shortly another 300 MW.[48]	None. WAPA has experienced difficulties balancing wind when wind over-generates compared to schedule and WAPA needs to drive its units to minimum generation. The most challenging occasion occurred in May 2013 when wind over-generated by 125 MW, and WAPA held its hydro below its preferred minimum necessary to meet water release restrictions. WAPA did not curtail the wind during this event because it is required under contract to regulate the wind, and this contract has no clause that allows curtailment for oversupply.	If wind over-generates, the operational entity where wind is located (e.g., Tri-State, Platte River) must pay energy imbalance charges.	WAPA would like to make these charges more costly to encourage operational entities in the balancing authority to back down their coal and balance their loads. WAPA is also offering 15-minute scheduling (a requirement of FERC). As more wind enters its administrative area, WAPA wants to ensure that new contractual arrangements will provide WAPA more control over schedules and provide utilities an incentive to balance their load.	WAPA calls the operational entities in the balancing area but does not communicate directly with wind farms.

47 on July 16, 2010, http://ww2.wapa.gov/sites/Western/newsroom/FactSheets/Pages/glance.aspx
48 WAPA Jeff Ackerman Interview September 13, 2013

Entity	Total Peak Demand and Wind and Solar Capacity	Current Wind and Solar Curtailment Levels and Reasons for Curtailment	Compensation	Mitigation Strategies	Curtailment Procedures
Xcel Energy / Public Service Co. of Colorado	7,000 MW peak demand[49] Wind: 2,200 MW[50] Solar: 266 MW[51] (includes utility-scale and distributed generation)	Curtailment has been less than 2% of wind generation in recent years. The primary cause for curtailment in any given year varies between balancing (e.g., oversupply) and transmission (e.g., line constraints and outages). Ramping constraints had been a cause for curtailment before forecasting improved but are almost never a cause now. Curtailment levels peaked in 2010 due to transmission outages.	Costs and risks of curtailment are factored into PPAs, and compensation varies by both PPA cause. For transmission-related causes, wind generators under some older contracts are compensated, but the majority of contracts do not allow for compensation for transmission causes beyond PSCO's control (PSCO will compensate for planned outages). If PSCO curtails for balancing purposes, it will compensate generators for the energy that they would have produced plus the value of PTC earnings. However, PSCO has negotiated annual blocks of free (uncompensated) curtailment hours with 5 of 14 wind farms. Currently, PSCO holds a total of 60,000 curtailment hours, but this drops to 30,000 by 2018, at which time	PSCO has taken many strategies to accommodate increasing wind penetrations. Foremost is its improved use of forecasting. PSCO has worked with the National Center for Atmospheric Research to improve its wind prediction models. Improved forecasting enables PSCO to turn down conventional resources when sufficient wind generation is predicted and to reduce curtailment from oversupply. Improved forecasting also eliminated curtailments related to ramping. A second strategy to mitigate curtailments is to cycle coal units more. In 2010, when there was a dramatic increase in wind curtailments primarily due to line outages, PSCO studied the costs of cycling base load units versus curtailing wind. The costs were similar, so PSCO decided to cycle off thermal units at night to minimize wind curtailments. Finally, PSCO has also put many wind facilities on AGC, which reduces total curtailments. Previously, PSCO would curtail	Curtailment to units on AGC is signaled through AGC. The rest of the facilities are curtailed manually by phone. The order of curtailment is based on economics. PSCO will first curtail generators with which they have negotiated free curtailment hours; then, PSCO will curtail generators that do not receive PTC (older farms or ones that have elected the ITC in lieu of the PTC); next, PSCO will curtail generators on AGC (which allows more efficient curtailment); and finally, manually operated farms are curtailed based on random assignment.

49 Drake Bartlett –Xcel Interview, August 23, 2013
50 Xcel Energy http://www.xcelenergy.com/Environment/Renewable_Energy/Wind/Colorado_Wind_Power, Accessed July 2013
51 At the end of 2012, *Xcel Energy* http://www.xcelenergy.com/Environment/Renewable_Energy/On_Our_System/Solar_Power_on_Our_System

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Xcel Energy / Public Service Co. of Colorado			many coal plants will be replaced by more flexible natural gas (which begin to come on-line in 2015).	in blocks (e.g., 100 MW) and balance with thermal units. Now PSCO can take thermal units to their minimum and balance with one wind generator on AGC (two-thirds of wind farms have AGC capability, but only one wind farm is needed on AGC at a given time due to their fast response). PSCO also uses curtailed wind energy to provide positive and negative reserves. Looking forward, PSCO is advocating for an organized EIM, which will broaden and the supply of resources available to balance renewable energy generation. PSCO is also considering changing its use of pumped storage hydroelectricity—instead of pumping at night to serve peak load, PSCO may pump during the day during low net load periods to offset curtailment	