How Do High Levels of Wind and Solar Impact the Grid? The Western Wind and Solar Integration Study

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Technical Report
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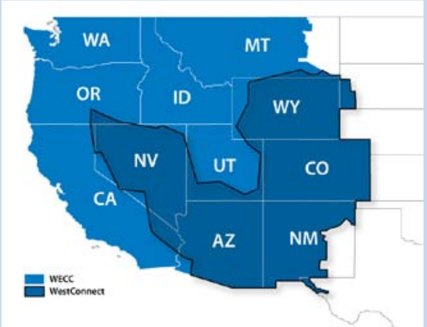
How Do High Levels of Wind and Solar Impact the Grid?
The Western Wind and Solar Integration Study

Introduction

The focus of the Western Wind and Solar Integration Study (WWSIS) is to investigate the operational impact of up to 35% energy penetration of wind, photovoltaics (PVs), and concentrating solar power (CSP) on the power system operated by the WestConnect group of utilities in Arizona, Colorado, Nevada, New Mexico, and Wyoming1. This paper is a brief introduction to the scope of the study, inputs and scenario development, and the key findings of the study. The WWSIS report provides more detail on all aspects of the study [1]. WWSIS was conducted over two and a half years by a team of researchers in wind power, solar power, and utility operations, with oversight from technical experts in these fields. A Technical Review Committee (TRC), composed of members of WestConnect utilities, western utility organizations, and industry and technical experts, reviewed technical results and progress and a broader stakeholder group, met to ensure study direction and results were relevant to western grid issues.

WestConnect is a group of transmission providers that are working collaboratively on initiatives to improve wholesale electricity markets in the West. Participants include Arizona Public Service, El Paso Electric Co., NV Energy, Public Service of New Mexico, Salt River Project, TriState Generation and Transmission Cooperative, Tucson Electric Power, Western Area Power Administration, and Xcel Energy.



The study examined grid operation for the year 2017. That is, system loads and generation expansion were projected to represent year 2017. While 35% renewable energy penetration was not expected by 2017, this year was selected in order to start with a realistic model of the transmission grid. The study examined inter-annual operability by modeling operations for year 2017 three times, using historical load and weather patterns from years 2004, 2005, and 2006.

What this Study Does and Doesn't Cover

While this study undertakes detailed analysis and modeling of the power system, it was meant to be a complement to other in-depth studies. WWSIS is not a transmission planning study, nor a cost-benefit analysis, nor a full-blown reliability study, nor a dynamic stability study.

In 2017, it is anticipated that WestConnect and the Western Electricity Coordinating Council (WECC) will operate differently from current practice. WWSIS assumed the following changes from current operational practice: least-cost economic dispatch in which all generation resources are shared equally and not committed to specific loads; five regional balancing areas (instead of the 37 that exist today) in WECC; existing available transmission capacity, even though currently contractually bound, will be accessible to other generation on a short-term, non-firm basis.

There are also reasons that the study results tend toward the conservative: WWSIS did not model a more flexible non-renewable balance of generation than what exists and is planned in WECC today; the target of 35% wind and solar is more likely to be reached later than 2017 when the load is greater, the balance of generation may be more flexible, and more transmission may be installed; the wind dataset was conservative in terms of overestimating the actual variability found in measured wind plant output; and finally, the base assumption of $9.50/MBTU for gas means that gas is displaced, which leaves coal to accommodate the variability of the wind and solar.

Wind, Solar and Load Data

3TIER Group employed a mesoscale Numerical Weather Prediction (NWP) Model to essentially recreate the weather in a 3-dimensional physical representation of the atmosphere in the western United States for the years 2004-2006 [2]. They then sampled this model at a 2-km, 10-minute resolution and modeled wind plants throughout this region, based on a Vestas V90 3-MW turbine. Over 960 GW of wind sites were modeled. The wind dataset is publicly available [3].

A satellite cloud cover model was used to simulate the United States at a 10-km, hourly resolution [4]. PV was modeled in 100-MW blocks as distributed generation on rooftops because modeling information for large, central station PV plants was not available at the time of the study. Over 15 GW of PV plants were included in the dataset.

CSP was modeled as 100-MW blocks of parabolic trough plants with six hours of thermal storage. Over 200 GW of CSP plants were modeled in the dataset. Because the CSP with thermal storage produces a very stable output, the 10-minute dataset was created simply by interpolating the hourly dataset.

Scenario Description

WWSIS used a multidimensional scenario-based study approach to evaluate different penetration levels for wind and solar power, different geographic locations, and a wide array of sensitivities to assess impacts of different fuel prices, reserve levels, etc.

The **Preselected case** includes wind and solar capacity that was installed by the end of 2008. The **10% case** includes 10% wind energy and 1% solar energy (relative to total annual load energy) in the study footprint, as well as the rest of WECC. The **20% case** includes 20% wind energy and 3% solar energy in the study footprint, with 10% wind energy and 1% solar energy in the rest of WECC. The **20/20% case** includes 20% wind energy and 3% solar energy in the study footprint, as well as the rest of WECC. The **30% case** included 30% wind energy and 5% solar energy in the study footprint, with 20% wind energy and 3% solar energy in the rest of WECC.

Three geographic scenarios were developed via an algorithm that selected sites based on energy value, capacity value, and geographic diversity according to criteria developed for each scenario. The **In-Area** Scenario required each state to meet its wind and solar energy targets using the best resources within its state. The **Mega Project** Scenario used the best available wind and solar resources within the study footprint and built out long distance transmission to bring those resources to load. The **Local Priority** Scenario is an intermediate scenario between the In-Area and Mega Projects Scenario, with modest transmission buildout and modest buildout within each state. Figure 1 shows maps of the study scenarios for the 30% case. New, conceptual transmission infrastructure to increase interstate transfer capability is shown in black.

For all three of these scenarios, the rest-of-WECC scenario remains constant; each state in the rest of WECC meets its renewable energy target using the best available resources within the state boundary. Table 1 shows a summary of the total wind and solar MW ratings by state for the three study scenarios.

Key Study Assumptions

- Scenario development:
    - Specific energy targets for each of three technologies: wind, PV, and CSP were fixed.
    - Capital cost assumptions in 2008$ to develop the scenarios: wind at $2000/kW, PV at $4000/kW, CSP at $4000/kW, transmission at $1600/MW-mile, and transmission losses at 1% per 100 miles. No tax credits are assumed or included.
- Production simulation analysis:
    - All study results are in 2017 nominal dollars with 2% escalation per year.
    - $2/MBTU coal and $9.50/MBTU natural gas.
    - Carbon dioxide costs were assumed to be $30/metric ton.
    - Extensive balancing area cooperation is assumed.
    - The production simulation analysis assumes that all units are economically committed and dispatched, while respecting existing and new transmission limits and generator cycling capabilities and minimum turndowns.
    - Existing available transmission capacity is accessible to renewable generation.
    - Generation equivalent to 6% of load is held as contingency reserves – half is spinning and half is non-spinning.
    - The sub-hourly modeling assumes a 5-minute economic dispatch.

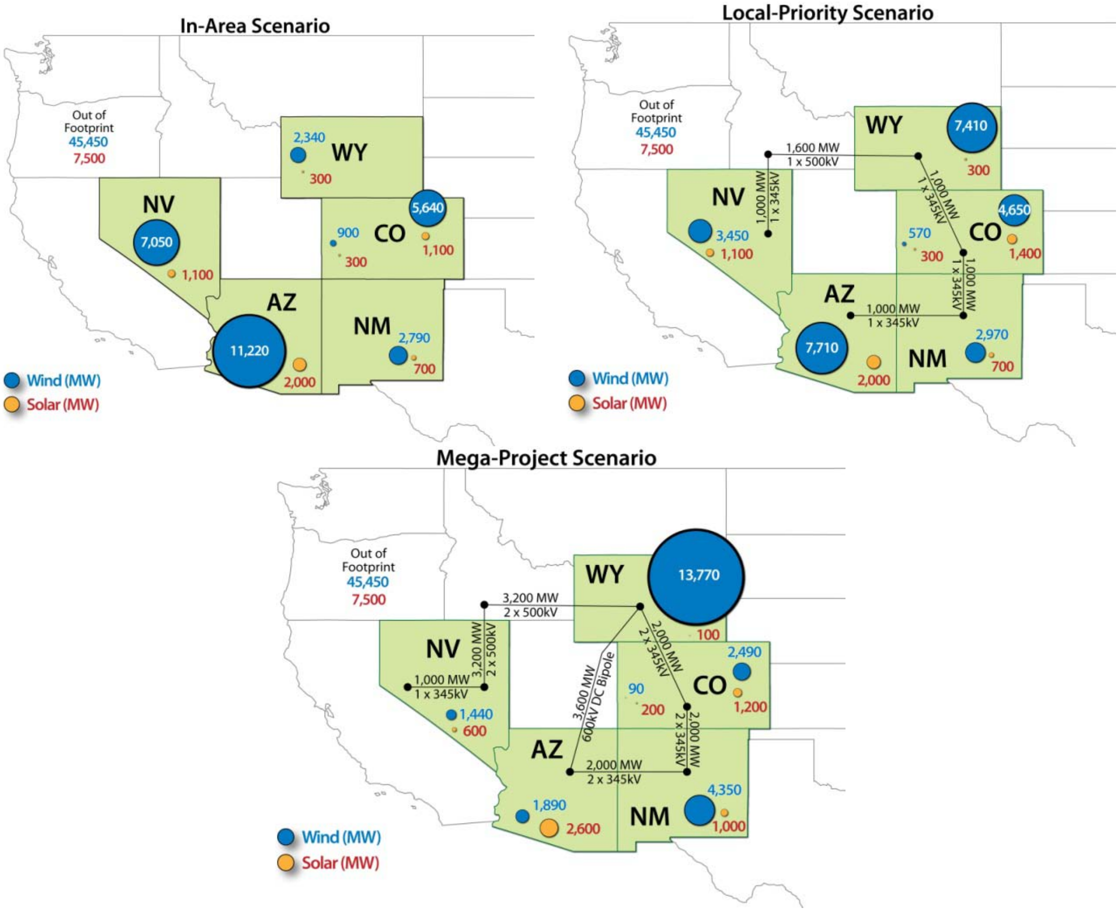


Figure 1 – Three geographic scenarios developed for siting of wind and solar plants in the 30% case, with appropriate, conceptual interstate transmission included to bring resources to load.

Analytical Methods

Four primary analytical methods were used to evaluate the performance of the system with high penetrations of wind and solar generation; statistical analysis, hourly production simulation analysis, sub-hourly analysis using minute-to-minute simulations, and resource adequacy analysis.

- Statistical analysis was used to quantify variability due to system load, as well as wind and solar generation over multiple time frames (annual, seasonal, daily, hourly, and 10-minute).
- Production simulation analysis with GE's MAPS (Multi-Area Production Simulation) program was used to evaluate hour-by-hour grid operation of each scenario for 3 years with different wind, solar, and load profiles. WECC was represented as a set of 106 zones, which were grouped into 20 transmission areas.
- Minute-to-minute simulation analysis was used to quantify grid performance trends and to investigate potential mitigation measures during challenging situations.
- Resource adequacy analysis involved loss-of-load-expectation (LOLE) calculations for the study footprint using the Multi-Area Reliability Simulation program, MARS.

Table 1 − Summary of aggregated wind and solar MW ratings by state for WWSIS scenarios

In Area

			10%	1%	20%	3%	30%	5%
Area	Load Minimum (MW)	Load Maximum (MW)	Wind Rating (MW)	Solar Rating (MW)	Wind Rating (MW)	Solar Rating (MW)	Wind Rating (MW)	Solar Rating (MW)
Arizona	6,995	23,051	3,600	400	7,350	1,200	11,220	2,000
Colorado East	4,493	11,589	2,040	300	3,780	800	5,640	1,400
Colorado West	712	1,526	300	0	600	200	900	300
New Mexico	2,571	5,320	1,080	200	1,920	400	2,790	700
Nevada	3,863	12,584	2,340	200	4,680	700	7,050	1,100
Wyoming	2,369	4,016	930	100	1,620	100	2,340	300
In Footprint	21,249	58,087	10,290	1,200	19,950	3,400	29,940	5,800

Local Priority

			10%	1%	20%	3%	30%	5%
Area	Load Minimum (MW)	Load Maximum (MW)	Wind Rating (MW)	Solar Rating (MW)	Wind Rating (MW)	Solar Rating (MW)	Wind Rating (MW)	Solar Rating (MW)
Arizona	6,995	23,051	2,850	400	5,250	1,200	7,710	2,000
Colorado East	4,493	11,589	2,190	300	3,870	800	4,650	1,400
Colorado West	712	1,526	210	0	450	200	570	300
New Mexico	2,571	5,320	1,350	200	2,100	400	2,970	700
Nevada	3,863	12,584	1,350	200	2,490	700	3,450	1,100
Wyoming	2,369	4,016	1,650	100	4,020	100	7,410	300
In Footprint	21,249	58,087	9,600	1,200	18,180	3,400	26,760	5,800

Mega Project

			10%	1%	20%	3%	30%	5%
Area	Load Minimum (MW)	Load Maximum (MW)	Wind Rating (MW)	Solar Rating (MW)	Wind Rating (MW)	Solar Rating (MW)	Wind Rating (MW)	Solar Rating (MW)
Arizona	6,995	23,051	810	400	1,260	1,800	1,890	2,600
Colorado East	4,493	11,589	2,010	300	2,400	400	2,490	1,200
Colorado West	712	1,526	60	0	90	0	90	200
New Mexico	2,571	5,320	1,860	400	2,700	1,000	4,350	1,000
Nevada	3,863	12,584	570	100	1,020	200	1,440	600
Wyoming	2,369	4,016	3,390	0	8,790	0	13,770	100
In Footprint	21,249	58,087	8,700	1,200	16,260	3,400	24,030	5,700

			10%	1%	10%	1%	20%	3%
Out of Footprint	46,328	119,696	22,950	2,500	22,950	2,500	45,450	7,500

Operations with 35% Wind and Solar Energy

The power system is designed to handle variability in load. With wind and solar, the power system is called on to handle variability in the *net load* (load minus wind minus solar), which can be considerable during certain periods of the year. Figure 2 shows the load (purple line along top edge), wind (green), solar (PV in orange and CSP in yellow), and net load profiles for the 30% case during two selected weeks in July and April. In the July week, (left plot), the net load (blue line along bottom edge) is not significantly impacted by wind and solar variation. However, in the April week (right plot), the high, variable wind output dominates the net load, especially during low load hours, leading to several hours of negative net load during the week. This week in April was the worst week in terms of operational challenges of the three years modeled.

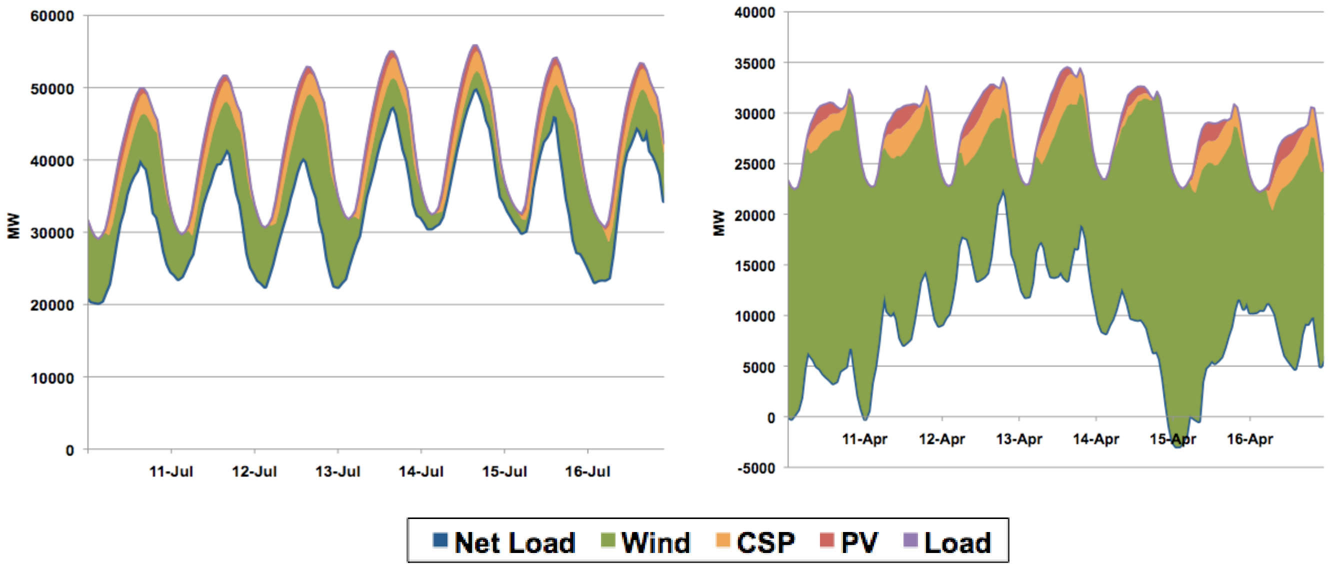


Figure 2 – With 35% wind/solar, system operators must now balance generation against the net load (blue) line. This may be straightforward (left, July) or challenging (right, April). WestConnect total load and net load for a week in July and a week in April, 2006, 30% In-Area Scenario

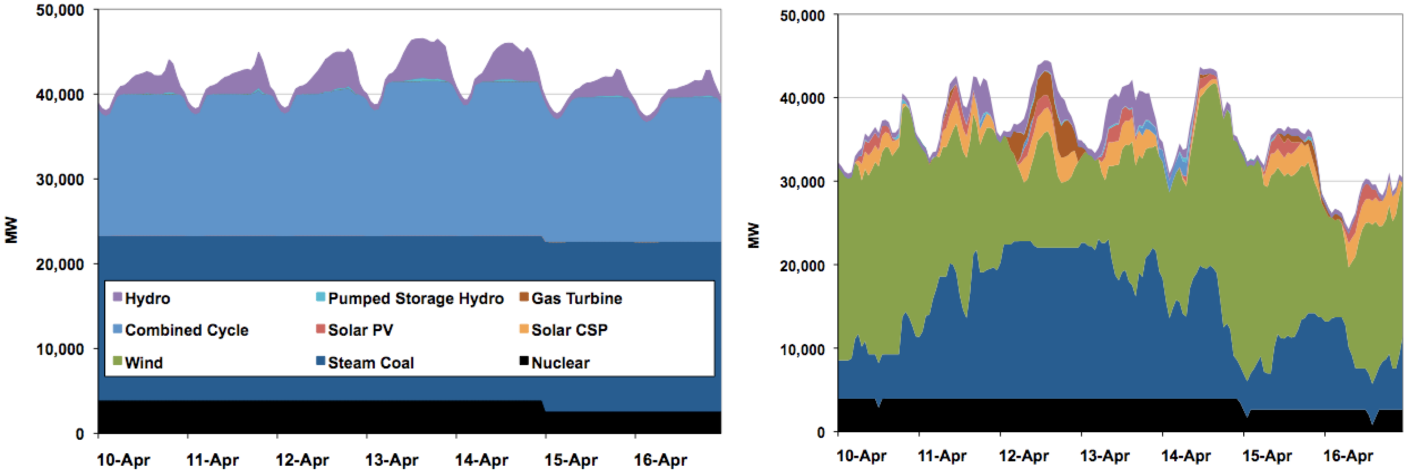


Figure 3 – 35% wind and solar has a significant impact on other generation during the hardest week of the three years (mid-April 2006). WestConnect dispatch - no renewables (left) and 30% case (right)

Figure 3 shows similar information for the April week shown in Figure 2. Here, operating the system with wind/solar generation is much more challenging. The combined cycle generation has been almost completely displaced, as have significant levels of coal generation. Nonetheless, the system can operate reliably with balancing area cooperation. Without balancing area cooperation, operations during this week would be extremely difficult, if not impossible, for individual balancing areas.

How much wind and solar generation can the system handle? No significant adverse impacts were observed up to the 20% case in WestConnect, given balancing area cooperation. Increased wind/solar generation in the rest of WECC (20/20% case) led to increased stress on system operations within WestConnect, with some instances of insufficient reserves due to wind and solar forecast error. These can be addressed, but the system has to work harder to absorb the wind/solar. Operations become more challenging for the 30% case in which load and contingency reserves are met only if the wind/solar forecasts are perfect.

Benefits of 35% Wind and Solar

Wind and solar generation primarily displace gas resources nearly all hours of the year, given the fuel prices and carbon tax assumed for this study. Across WECC, operating costs drop by $20 billion/yr ($17 billion/yr in 2009$) from approximately $50 billion/yr ($43 billion/yr in 2009$), resulting in a 40% savings due to offset fuel and emissions. Figure 4 (left plot) shows the overall impact on the operating costs of WECC for the various penetration levels under the In-Area Scenario with a state-of-the-art (SOA) forecast. The 30% case shows WECC operating cost savings of $20 billion/yr ($17 billion/yr in 2009$) due to the wind and solar generation resources. Figure 4 (right plot) divides these values by the corresponding amount of renewable energy provided. In the 30% case, this equates to $80/MWh ($60/MWh in 2009$) of wind and solar energy produced. These operating cost savings would be applied toward the costs of wind and solar energy, and depending on the magnitude of these costs, may or may not be sufficient to cover them. At a $3.50/MBTU gas price, wind and solar primarily displace coal generation. With lower gas price assumptions, operating cost savings are about 40% or $46/MWh ($39/MWh in 2009$).

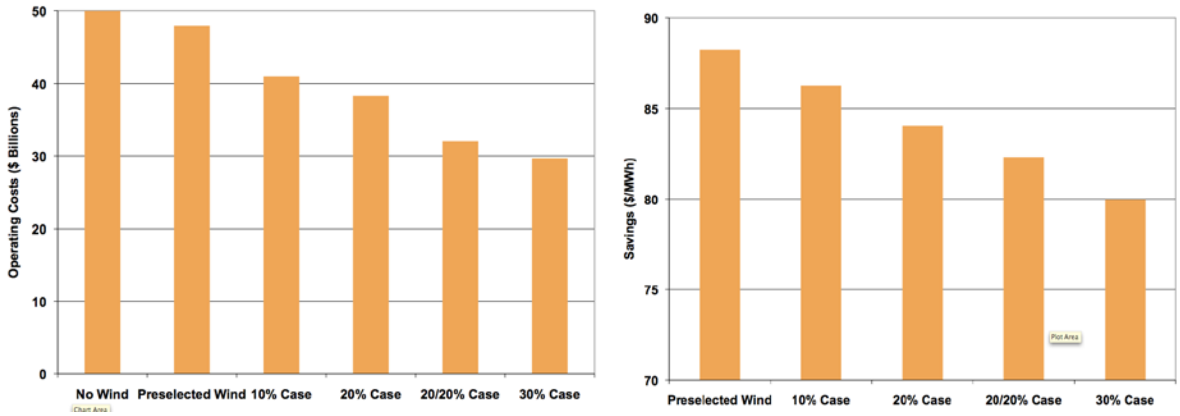


Figure 4 − WECC saves $20 billion ($17 billion in 2009$), or 40%, in fuel and emissions costs in the 30% case, which is equivalent to $80 ($60 in 2009$) per MWh of wind and solar energy produced.

Total WECC reductions for the 30% case of CO_2 emissions were nearly 120 million tons per year, or approximately 25%. SO_x emissions would be reduced by approximately 45,000 tons (~5%) and NO_x would be reduced nearly 100,000 tons per year (~15%). At a $3.50/MBTU gas price, CO_2 emissions are reduced by nearly 200 million tons/year (45%), and NO_x and SO_x by 300,000 tons/year (50%) and 220,000 tons/year (30%), respectively.

Key Findings

WWSIS comprised a significant body of work to investigate reserves, storage, transmission, flexible generation, etc., which is detailed in the final report [1]. The key findings can be summarized as:

- **Balancing area cooperation is essential –** Variability for small areas such as Colorado-West or Wyoming increases significantly as renewable penetrations increase from the 10% to the 30% case. This effect becomes even more extreme at a more granular level, e.g., for specific balancing areas within a state. However, when the balancing areas across WestConnect are aggregated, there is only a slight increase in variability with increased renewables penetrations, and even a slight decrease in variability WECC-wide. From an operational perspective, balancing area cooperation can lead to cost savings because reserves can be pooled. A sensitivity analysis was performed, running WECC as 106 zones versus 5 large regions. Savings in WECC operating costs in the 10% case were $2 billion ($1.7 billion in 2009$).

- **Sub-hourly scheduling is critical –** The current practice of scheduling both the generation and interchanges only once each hour has a significant impact on the regulation duty. At high penetration levels, such hourly schedule changes can use most, if not all, of the available regulation capability to compensate for Area Control Error (ACE) excursions during large scheduled ramps. This can leave no regulation capability for the sub-hourly variability. The minute-to-minute simulations showed that the current practice of hourly scheduling has a greater impact on the regulation requirements than does the wind and solar variability. Sub-hourly scheduling can substantially reduce the maneuvering duty imposed on the units providing load following. In the 30% case, the fast maneuvering of combined cycle plants with sub-hourly scheduling is about half of that with hourly scheduling.

- **Integration of wind/solar forecasts into unit commitment process is essential –** Integrating day-ahead wind and solar forecasts into the unit commitment process is essential to help mitigate the uncertainty of wind and solar generation. Even though SOA wind and solar forecasts are imperfect and sometimes result in reserve shortfalls due to missed forecasts, it is still beneficial to incorporate them into the day-ahead scheduling process because this will reduce the amount of shortfalls. Over the course of the year, use of these forecasts reduces WECC operating costs by up to 14%, or $5 billion/yr ($4 billion/yr in 2009$), which is $12-20/MWh ($10-17/MWh in 2009$) of wind and solar generation. The incremental cost savings for *perfect* wind and solar day-ahead forecasts would reduce WECC operating costs by another $500 million/yr ($425 million/yr in 2009$) in the 30% case, or $1-2/MWh ($0.90-1.70/MWh in 2009$) of wind and solar generation.

- **Demand response may be more cost-effective than increasing spinning reserves –** Severe over-forecasts in wind power can result in contingency reserve shortfalls; severe under-forecasts can result in curtailment of wind. If the forecast is perfect, there are no contingency reserve shortfalls, even in the 30% wind case. With a SOA forecast, these contingency reserve shortfalls become an issue at the 30% wind penetration level. Instead of holding additional spinning reserve for each of the 8760 hours of the year, a demand response program could address those 89 hours of the year when there is a contingency reserve shortfall and comprise a total participation of approximately 1300 MW of load. An alternative to demand response or increased spinning reserve for every hour of the year could be dynamic allocation of spinning reserves based on better forecasting, improved reserve policies, and more accurate prediction of when shortfalls are likely to occur.

- **Wind curtailment is on the order of 1% or less of the total wind energy –** Uncertainty drives both curtailment and reserve shortfalls. With a perfect forecast, no wind or solar curtailment was necessary in any of the scenarios. Even in the few hours when the renewable generation exceeded the load in WestConnect, there was sufficient flexibility within WECC to absorb all of the generation. With a SOA forecast, no curtailment occurred up through the 20% case.

- **No need to commit additional reserves to cover increased variability –** In addition to contingency reserves, utilities are required to hold variability or load following reserves to cover 10-minute load variability 95% of the time. With wind and solar, the net load variability increases and in the 30% case, the average variability reserve requirement doubles. However, when wind and solar are added to the system, thermal units are backed down because it is sometimes more economical to back down a unit rather than to decommit it. This results in *more* up- reserves available than in the case when there is no wind and solar. Regulating reserves are a subset of the fast variability requirement, but are held separately from the 10-minute variability reserves. While WWSIS did not evaluate which units were on AGC, the minute-to-minute analysis showed that sufficient regulating reserve capability was available. Down reserves can be handled through wind curtailment when other resources are depleted. A wind plant can reduce its output very quickly in response to a command signal. Simulations in this study show that down reserves can be implemented through command signals (ACE signals) from system operators.

- **Up to 20% wind penetration could be achieved with little or no new long distance, interstate transmission additions, assuming full utilization of existing transmission capacity –** Sufficient *intra-area* transmission within each state or transmission area for renewable energy generation to access load or bulk transmission is needed. However, the In-Area Scenario, which included no additional long distance, *interstate* transmission, worked just as well *operationally* as the other scenarios. A sensitivity case examined the impact of the interstate transmission build-outs in the Local Priority and Mega Project Scenarios (which required $3.4 and $11 billion dollars [2008$] of interstate transmission respectively). It found that annual operating costs increased modestly when the new interstate transmission build-outs associated with the Local Priority and Mega Project Scenarios were eliminated because wind/solar displaced other generation which freed up transmission capacity. Assuming wind/solar have full access to this newly opened up capacity, there is less need for new transmission.

- **Increased wind and solar penetration slightly increases use of existing storage, but additional storage was not found to be needed –** WWSIS evaluated only the price arbitrage part of the value proposition for pumped storage hydro (PSH) and found it much less than sufficient to economically justify additional storage facilities. To examine a best-case scenario for storage, a new 100-MW PSH plant was added to the system and given perfect foresight of spot prices so that it could be dispatched to optimize revenue. With 30% penetration and a perfect forecast, the 100-MW PSH plant only had an annual operating value of \$0.5 million (\$0.4 million in 2009\$), which would only yield a capitalized value of about \$35/kW (\$30/kW in 2009\$). With a SOA forecast, spot prices are higher due to forecast error, and the 30% case increased the PSH annual operating value to \$3.8 M (\$3.2M in 2009\$). However, this is several times less than would be required to recover costs for a new PSH plant.

- **System flexibility in the rest of the generation fleet helps to accommodate wind and solar –** WWSIS finds that at higher (30% case) penetration levels, decreased flexibility of either the coal or hydro facilities made operation more difficult and increased the costs of integrating the renewable generation.

- **Wind and solar contribute to resource adequacy –** Wind generation resources selected for this study were found to have capacity values in the range of 10% to 15%. PV solar plants have capacity values in the range of 25% to 30%. The PV output was based on the DC rating of the system; it would be 23% higher if based on the AC rating and included inverter and other losses from the outset. Concentrating solar plants with thermal energy storage have capacity values in the range of 90% to 95%, similar to conventional thermal generating plants.

Conclusions

The technical analysis performed in this study shows that it is operationally feasible for WestConnect to accommodate 30% wind and 5% solar energy penetration, assuming the following changes to current practice could be made over time:

- Substantially increase balancing area cooperation or consolidation, real or virtual;
- Increase the use of sub-hourly scheduling for generation and interchanges;
- Increase utilization of transmission;
- Enable coordinated commitment and economic dispatch of generation over wider regions;
- Incorporate state-of-the-art wind and solar forecasts in unit commitment and grid operations;
- Increase the flexibility of dispatchable generation where appropriate (e.g., reduce minimum generation levels, increase ramp rates, and reduce start/stop costs or minimum down time);
- Commit additional operating reserves as appropriate;
- Build transmission as appropriate to accommodate renewable energy expansion;
- Target new or existing demand response programs (load participation) to accommodate increased variability and uncertainty;
- Require wind plants to provide down reserves.

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This paper is a brief introduction to the scope of the Western Wind and Solar Integration Study (WWSIS), inputs and scenario development, and the key findings of the study.

15. SUBJECT TERMS
WWSIS; GE Energy; WECC; grid integration; WestConnect; wind; solar; CSP; PV; photvoltaics; integration study; utilities; power industry; renewables

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