AWEA literature review for DOE Grid Study
May 2017

Reports on the Reliable Integration of Large Quantities of Wind Energy

PJM's Evolving Resource Mix and System Reliability (2017)

- "Newer nonsynchronous generators, such as wind and solar, have the ability to provide frequency response with smart inverters, which can be programmed to provide frequency response for very short periods using power electronics."
- "Load following capability varies by technology and/or fuel type. Modern utility-scale wind and solar plants typically can control their output from the full (currently available) power level down to zero. Conventional generators typically have minimum load levels below which they cannot reduce power. Minimum loads may be 40 percent or higher for coal plants, and nuclear plants typically offer limited load following capability."
- "Both wind and solar resources have the flexibility to be dispatched in the downward direction in response to system constraints or minimum generation situations."
- "Natural gas, wind, and solar do not exhibit the same level of fuel assurance capability as do coal and nuclear. They do exhibit higher levels of the flexibility capability, however."

PJM Renewable Energy Integration Study (2014)

- Finds that with transmission expansion and a modest increase in regulation reserves that PJM would "not have any significant reliability issues with up to 30 percent of its energy (as distinct from capacity) provided by wind and solar generation."
    - Note: Wind energy was 2.2% of PJM's generation in 2016. See Table 3-8 of the PJM State of the Market report.
- "No insurmountable operating issues were uncovered over the many simulated scenarios of system-wide hourly operation and this was supported by hundreds of hours of sub-hourly operation using actual PJM ramping capability."
- "The renewable generation increased the amount of cycling (start up, shut down and ramping) on the existing fleet of generators, which imply increased variable O&M costs on these units. These increased costs were small relative to the value of the fuel displacement and did not significantly affect the overall economic impact of the renewable generation."

SPP Wind Integration Study (2016)

- If recommendations related transmission expansion and upgrades and the establishment of reactive power criteria, margins and incentives were adopted it, "would enable the SPP transmission system to reliably handle up to the 60% wind penetration levels studied."

Minnesota Renewable Energy Integration and Transmission Study (2014)

- "With wind and solar resources increased to achieve 40% renewable energy for Minnesota and 15% renewable energy for MISO North/Central, production simulation and transient/dynamic stability analysis results indicate that the system can be successfully operated for all hours of the year with no unserved load, no reserve violations, and minimal curtailment of renewable energy."
- "Dynamic simulation results indicate that there are no fundamental system-wide dynamic stability or voltage regulation issues introduced by the renewable generation…"
- "No angular stability, oscillatory stability or wide-spread voltage recovery issues were observed over the range of tested study conditions."

- "Wind and Solar resources contribute significantly to voltage support/dynamic reactive reserves. The fast response of wind/solar inverters helps voltage recovery following transmission system faults."

NREL Western Wind and Solar Integration Studies Phases 1-3 (2010-2013)

- Phase 1
    - 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, 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.

Eastern Wind Integration and Transmission Study (2010)

- "High penetrations of wind generation—20% to 30% of the electrical energy requirements of the Eastern Interconnection—are technically feasible with significant expansion of the transmission infrastructure."
- "Transmission helps reduce the impacts of the variability of the wind, which reduces wind integration costs, increases reliability of the electrical grid, and helps make more efficient use of the available generation resources. Although costs for aggressive expansions of the existing grid are significant, they make up a relatively small portion of the total annualized costs in any of the scenarios studied."
- "Wind generation can contribute to system adequacy, and additional transmission can enhance that contribution."

New England Wind Integration Study (2010)

- "The study results show that New England could potentially integrate wind resources to meet up to 24% of the region's total annual electric energy needs in 2020 if the system includes transmission upgrades comparable to the configurations identified in the Governors' Study."

DOE Renewable Electricity Futures Study (2012)

- Included experts from NREL, INL, LBNL, ORNL, SNL, PNNL and others.
- "Electricity supply and demand can be balanced in every hour of the year in each region with nearly 80% electricity from renewable resources, including nearly 50% from variable renewable generation, according to simulations of 2050 power system operations."
- "The operational simulations did not project any hours of unserved load during the peak load hour, lowest coincident load hour, or any other hour of the year."

MISO Market Monitor Report (2015)

- "MISO introduced the Dispatchable Intermittent Resource (DIR) type in June 2011. DIRs are wind resources that are physically capable of responding to dispatch instructions (from nearly zero to a forecasted maximum)...DIRs are treated comparable to other dispatchable resources. Nearly 85 percent (13.8 GW) of MISO's wind capacity—149 out of 212 units—is currently capable of responding to dispatch instructions…"

Reports on the Reliability Services Provided to the Grid by Wind Turbines

NERC Report: Accommodating High Levels of Variable Generation (2009)

- "Modern wind turbine generators can meet equivalent technical performance requirements provided by conventional generation technologies with proper control strategies, system design, and implementation."
- "As variable resources, such as wind power facilities, constitute a larger proportion of the total generation on a system, these resources may provide voltage regulation and reactive power control capabilities comparable to that of conventional generation. Further, wind plants may provide dynamic and static reactive power support as well as voltage control in order to contribute to power system reliability."

NERC 2014 Long-Term Reliability Assessment (2014)

- "This issue does not exist for utility-scale wind energy, which offers ride-through capabilities and other essential reliability services."
- "Wind resources can offer inertia and frequency response, depending on the design attributes of a given wind plant. However, by causing conventional generators to have their output dispatched down, wind and solar generation can increase generator headroom and, therefore, the amount of total frequency response being provided."

NERC Essential Reliability Services Task Force Report (2015)

- "The increasing penetrations of nonsynchronous resources (including but not limited to wind, solar, and battery storage) could alter system characteristics such as voltage performance and frequency response. These functions have traditionally been provided by synchronous generators, although they can also be provided through fast inverter controls on wind, solar and battery storage plants."
- "Since March 2012, wind generators [in ERCOT] are also required to provide governor-like response. This response is faster than governor response from conventional generators. Governor-like response from wind generators is available for overfrequency events any time a generator is in operation and for underfrequency events when wind generators are curtailed."
- "Some of these new renewable resources have utility-grade inverters such as those used to couple modern wind and PV power plants with the BES, which can provide dynamic reactive power and voltage control capability. New wind and PV power plants are capable of providing dynamic reactive power control whether or not the plant is producing real power, similar to an SVC."

IEEE (Institute of Electrical and Electronics Engineers) Power and Energy Magazine (2015)

- Article finds variable generation can:
  - "Contribute to system balancing needs"
  - "Provide regulation/automated generation control services"
  - "Be economically dispatched"
  - "Contribute to operational security"
- "With electronics coupling the generator to the power system, modern wind turbines are able to control their output much faster and more accurately than conventional synchronous generators. Wind turbine

control is possible in cycles (milliseconds, which is the inertial time frame) rather than in seconds (the response time of conventional generator governors)."

- "The rotating mass of the wind turbine blades themselves coupled to the short term overload capability of the power electronics provides an additional source of completely controllable stabilizing energy. Unlike conventional synchronous generators, which provide uncontrolled inertia response, the response from wind turbines is completely controllable."
- "Studies show that wind turbine 'synthetic inertia' provides benefits similar to those of synchronous inertia to help the power system ride through a disturbance while also dampening undesirable oscillations. Figure S1 shows the superior stability response of doubly fed asynchronous wind turbines compared to conventional synchronous generators following a grid disturbance."
- "Wind power plants currently provide regulating reserves in the Xcel/Public Service of Colorado (PSCO) balancing authority area."
- "Output from individual turbines can be reduced in seconds to provide downward reserves and ramping support. Output from curtailed wind turbines can be increased quickly, on the order of seconds to tens of seconds, to provide frequency, upward reserve, and ramping services."
- "There is increased understanding that VG [variable generation] can provide frequency, inertia, and voltage control capabilities that have been traditionally provided by synchronous generators."
- "Recent research by the National Renewable Energy Laboratory and GE showed that system-wide frequency response can be maintained with high levels of wind and solar generation when local stability, voltage, and thermal problems are addressed using traditional transmission system reinforcements (e.g., transformers, shunt capacitors, and local lines). The analysis also showed that the limited application of nontraditional but commercially available frequency-responsive controls on wind, PVs, concentrating solar power plants, and energy storage are equally effective at improving minimum frequency and settling frequency and therefore overall frequency response."
- "To date, wind turbines are the only generators required to ride through disturbances."

U.S. Department of Energy Maintaining Reliability in the Modern Power System (2016)

- "It is possible to add technology to allow variable resources to decrease generation and, potentially, to increase it if they are not using all available power. This ability to dispatch variable generation is already being used to provide flexibility across the country."
- "Studies have shown that increased levels of variable generation on the grid increase reserve requirements necessary to maintain a steady frequency, but these increases are quite modest."
- "It is possible to make a variable resource act like a large spinning generator through the use of advanced power electronics."
- "As with frequency control, advanced power electronics can give variable generation resources like wind and solar the ability to control reactive power and voltage. FERC has recently issued an order requiring this capability on larger variable generation units."
- "As more variable generation is built, it can be used to maintain reliability in ways similar to the generation it is replacing…"

Western Wind and Solar Integration Study Phase 3

- "With good system planning, sound engineering practices, and commercially available technologies, the Western Interconnection can withstand the crucial first minute after severe grid disturbances with high penetrations of wind and solar on the grid."
- "Adequate frequency response in the Western Interconnection was maintained for the conditions studied."
- "Selected nontraditional frequency-responsive controls on wind and solar power plants and energy storage were examined and could improve frequency response."
- "The transient stability of the system is not fundamentally changed by high wind and solar generation. This does not mean that the system behaves identically. There is, however, nothing to indicate that the

system dynamics have changed so fundamentally that radically different means to ensure stability are required."

NREL Role of Wind Power in Primary Frequency Response (2016)

- "The ability of wind power plants to provide PFR [primary frequency response]—and a combination of synthetic inertial response and PFR—significantly improved the frequency response performance of the system."

NREL Eastern Frequency Response Study (2013)

- "Modern wind turbines and wind plants can contribute to frequency response with governor and inertial response controls."
- "None of the conditions examined, including cases with high levels of wind generation (up to 40% penetration in all NERC regions except FRCC and SERC), resulted in underfrequency load shedding or other stability problems."

NREL/ERPI Active Power Controls from Wind Power (2014)

- "The three forms of APC focused on in this study are synthetic inertial control, primary frequency control (PFC), and automatic generation control (AGC) regulation."
- "In 2008, the New York Independent System Operator (NYISO) started using wind power plants in its dispatch procedure to help manage transmission congestion at a five-minute resolution. Now, essentially all ISOs in the United States and many areas outside the ISO regions are utilizing wind power to provide this form of dispatch capability."
- "These regions have found the tremendous capability that wind power can provide in controlling its output to be extremely beneficial."
- "Our analysis shows that wind power can support power system reliability by providing these controls…"
- "In the past decade, manufacturers have made significant advancements in control methods that can make VER [variable energy resource] power output more responsive to grid-level controls, including frequency response and down regulation."

NREL Active Power Controls Report (2014)

- "Wind power can act in an equal or superior manner to conventional generation when providing active power control, supporting the system frequency response and improving reliability."

CAISO frequency response study (2011)

- "Frequency Response is not in crisis for California. None of the credible conditions examined, even cases with significantly high levels of wind and solar generation (up to 50% penetration in California), resulted in under-frequency load shedding (ULFS) or other stability problems."
- "…fast transient frequency support, via controlled inertial response from wind turbines, fast acting load response, or injection of power from energy storage all help increase the UFLS margin and avoid under-frequency load shedding. The benefit of these responses can be several times greater, per MW, than was observed for governor response in the synchronous fleet."
- Conventional generators are not contributing at the level they are capable: "Nevertheless, there is some anecdotal evidence that generators may be operating differently, e.g., with governors disabled and/or with load reference set-point controls enabled that defeat or diminish governor response."

Renewables and Essential Reliability Services (2016, Mark Ahlstrom)

- Limits of conventional technologies: (1) start up times and costs (2) minimum run times (3) operating ranges (4) ramp rate limitations (5) forced outages and contingencies (6) fuel supply
- Most ISO/RTO systems now include wind in Day Ahead Unit Commitment and Security Constrained Economic Dispatch (SCED)
  - Wind dispatch done with a 10-minute-ahead forecast or faster
- Dynamic reactive power - in today's utility-scale turbines and solar inverters
  - Standard feature of wind turbines for over 8 years
  - Already provided by almost all utility-scale wind and solar plants
  - Now required of all new plants per FERC Order 827
- Primary Frequency Response - proven for wind in ERCOT
  - An available option from utility-scale wind & solar vendors
- Fast Power Injection (arresting period) - proven for wind in Hydro Quebec
  - "Synthetic inertia" is an option on new utility-scale wind turbines (uses the wind turbine's kinetic energy for very rapid power injection)
- Wind and solar plants are modern power plants. Can provide
  - Frequency response
  - Voltage support
  - Ride-through capabilities (required for wind turbines in FERC Order 661A)
  - Ramping and following dispatch signals

IEEE paper on Reactive Power Performance of Wind and Solar Plants

- "The technology used in variable generation plants are capable of providing voltage support, but will require a shift from how these plants are traditionally operated."
- "Variable generation technologies are technically capable of providing steady-state and dynamic reactive power support to the grid."
- "Advances in the technology used for variable generation has now provided them with the ability for voltage regulation and reactive support…"

Powering into the Future: Renewables and Grid Reliability (MJ Bradley, 2017)

- "Renewable generators also can provide frequency control. Many new wind and solar facilities have components called 'active power controls,' which allow their output to be increased or decreased to help maintain reliability. These controls allow renewable generators to provide primary frequency response that is similar to that of the automatic governors on conventional power plants. Using these components, they can quickly and automatically adjust their output to help stabilize grid frequency."
- "These technologies can respond to automatic generation control signals every few seconds to rapidly increase or decrease output to help balance the system. They can also follow detailed, five-minute schedules that are shared with the central grid operator ahead of time, meaning that the dispatcher can count on a certain level of output on a short-term basis."

Cost of Integrating Renewable Energy and Conventional Generators

DOE Wind Vision (2015)

- DOE Wind Vision analyzes feasibility of achieving 10% of electric generation from wind energy by 2020, 20% by 2030 and 35% by 2050. Among the findings:
  - "$149 billion (3%) lower cumulative electric sector expenditures."
  - "Increased wind power adds fuel diversity, making the overall electric sector 20% less sensitive to changes in fossil fuel costs."

- “The predictable, long-term costs of wind power create downward price pressure on fossil fuels that can cumulatively save consumers $280 billion from lower natural gas prices outside the electric sector.”

Powering into the Future: Renewables and Grid Reliability (MJ Bradley, 2017)

- “MISO needed almost no additional fast-acting power reserves to back up 10,000-plus MW of wind power on the system.”
- “ERCOT needs only about 50 MW on average of fast-acting stand-by reserves to reliably integrate 10,000 MW of wind into the grid.”
- “PJM found that a 30 percent regional variable renewable penetration level— adding over 100,000 MW of renewable power—requires no additions in operating reserves, and only 1,500 MW (or 1.5 percent of renewable capacity) of quick-ramping regulation generators such as flexible natural gas generation.”
- “Large geographic size also helps to improve the collective capacity value of renewable generators (and reduces the need for other balancing services).”

NREL Cost Causation and Integration Cost Analysis for Variable Generation (2011)

- “No power plant or transmission line is 100% reliable and the power system must be continuously prepared to respond to the sudden failure of any resource. A series of reserves are maintained to provide immediate and sustained response to a contingency.”
- “Wind and solar generators typically have little impact on contingency reserve requirements because individual wind turbines and solar panels or plants are small compared with the largest conventional power plants, and contingency reserves must be constantly maintained so they are ready to deal with the largest credible event.”
- “Large wind and solar ramping events differ from conventional contingency events in that they are much slower.”
- “Other generation technologies impose integration costs which are not allocated to those technologies. Large generators impose contingency reserve requirements, block schedules increase regulation requirements, gas scheduling restrictions impose costs on other generators, nuclear plants increase cycling of other baseload generation, and hydro generators with dissolved gas limitations create minimum load reliability problems and increased costs for other generators. None of these costs are allocated to the generators that impose them on the power system.”
- “Generation integration costs are typically broadly shared because the benefits are also broadly shared. Contingency reserves are shared within a large reserve sharing pool because physical aggregation genuinely reduces the physical reserve requirement and therefore reduces everyone’s costs.”
- “Variable renewables bring fuel diversity, price stability, energy security, and environmental benefits that accrue widely to all users of the power system so it is reasonable that integration costs should likewise be broadly shared.”

Western Wind and Solar Integration Study Phase 2

- “The negative impact of cycling on overall plant emissions is relatively small. The increase in plant emissions from cycling to accommodate variable renewables is more than offset by the overall reduction in carbon dioxide (CO_2), nitrogen oxide (NO_x), and sulfur dioxide (SO_2). In the high wind and solar scenario, net carbon emissions were reduced by one-third.”
- “Operating costs increase by 2%–5% on average for fossil-fueled plants when high penetrations of variable renewables are added to the electric grid.”
- “From a system perspective, these increased costs are relatively small compared to the fuel savings associated with wind and solar generation.”

Update to Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements (2013)

- "Although additional regulation is necessary with increasing wind penetration, the main driver is still load variance rather than wind variance."

NREL Integration Costs are the Unique to Wind and Solar? (2012)

- Integration costs attributable to other types of generation that are not imposed on those generators:
    - Some conventional power plants are unable to follow a regulation signal precisely, increasing the regulation needs of the system;
    - New inexpensive baseload can impose cycling costs on other generators and causing them to operate at lower capacity factors;
    - Contingency reserves, which are typically based on the loss of the largest generating unit (cost is currently socialized to all load);
    - In areas were power is scheduled hourly, it has a larger cost imposed than that from variable generation;
    - Mismatch between gas scheduling via pipelines for power plants and the flexibility needed in the electricity system at times or during extreme events; and,
    - Extreme weather conditions can cause gas shortages, which is a larger contingency than the system is planned around.

Flaws in the Institute for Energy Research's report "The Levelized Cost of Electricity from Existing Generation Sources" (AWEA, 2015)

- Cost assumptions used for wind energy well above the market price and well above the latest government estimate;
- The Energy Information Administration (EIA) has already developed a calculation that accounts for the "costs" IER attributes to wind energy (differing levels of dispatchability, differing capacity values etc.), and their estimate is lower than IER's by a factor of four;
    - Further, EIA's method shows wind's cost is offset by wind's economic value, meaning wind energy provides a net benefit to consumers;
    - The benefits in the calculation are conservative since they don't account for wind energy's benefits in hedging against fuel price risk, lack of air emissions, water conservation etc.
- Debunking the "imposed costs" concept:
    - The addition of wind does not require the addition of new capacity, as almost all regions of the U.S. have more than enough generating capacity;
    - Existing plants are a "sunk cost." There is no cost to society for building a power plant that is already built;
    - Existing coal and nuclear generators "impose" a many times greater impact on the dispatch of other generators than wind (as does electricity demand variability);
    - The authors falsely assume that any lack of capacity value in wind resource must be made up for by pairing with another resource. On the real power system there is no need to "pair" resources, just as there is no need to attach a battery or a gas combustion turbine to your house to manage the variability in your electricity demand;
        - The reality is that all sources of supply and demand variability are combined on the power system, and many cancel each other out so that the total variability is far less than the sum of its parts. As a result, the job of balancing supply and demand is far more cost-effectively done by a central grid operator through an electricity market than by pairing individual resources.

PJM Renewable Energy Integration Study (2014)

- "Every scenario examined resulted in lower PJM fuel and variable Operations and Maintenance (O&M) costs as well as lower average Locational Marginal Prices (LMPs)."

- “The renewable generation increased the amount of cycling (start up, shut down and ramping) on the existing fleet of generators, which imply increased variable O&M costs on these units. These increased costs were small relative to the value of the fuel displacement and did not significantly affect the overall economic impact of the renewable generation.”

Reports finding limited instances of wind energy setting prices (and therefore impacting prices paid to other generators)

- MISO Market Monitor Report (2015)
  - See Table A1, System Marginal Price (SMP) column, where wind set prices only 1% of the time.

- PJM State of the Market Report (2016)
  - Table 3-6, shows wind energy set the marginal price only 2.98% of the time in the real time market and Table 3-7 show wind set the marginal price 0.06% of the time in the day ahead market.

- The Facts About Wind Energy’s Impacts on Electricity Markets, AWEA (2014)
  - The Production Tax Credit is almost never factored into the electricity market prices that other power plants receive;
  - Negative electricity prices at nuclear plants are extremely rare;
  - The majority of those negative prices are not caused by wind; and,
  - Across the U.S., transmission upgrades are eliminating the remaining instances of negative prices.