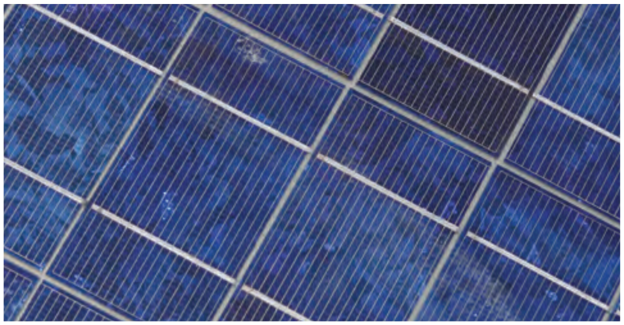
Integrating Renewable Electricity on the Grid

A Report by the APS Panel on Public Affairs



APS physics

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Executive Summary

The United States has ample renewable energy resources. Land-based wind, the most readily available for development, totals more than 8000 GW of potential capacity. The capacity of concentrating solar power is nearly 7,000 GW in seven southwestern states. The generation potential of photovoltaics is limited only by the land area devoted to it, 100–250 GW/100 km^2 in the United States. To illustrate energy capacity vs. projected demand, the US generated electric power at an average rate of approximately 450 GW in 2009, with peaks over 1000 GW during the summer months. By 2035, electricity demand is projected to rise 30%.

To date, 30 states, plus the District of Columbia have established Renewable Portfolio Standards (RPS) to require that a minimum share of electrical generation is produced by renewable sources. In addition to state policies, federal policymakers have put forward proposals to establish a national RPS, making the need for technological developments more urgent.

However, developing renewable resources presents a new set of technological challenges not previously faced by the grid: the location of renewable resources far from population centers, and the variability of renewable generation. Although small penetrations of renewable generation on the grid can be smoothly integrated, accommodating more than approximately 30% electricity generation from these renewable sources will require new approaches to extending and operating the grid.

The variability of renewable resources, due to characteristic weather fluctuations, introduces uncertainty in generation output on the scale of seconds, hours and days. These uncertainties, affect up to 70% of daytime solar capacity due to passing clouds and 100% of wind capacity on calm days for individual generation assets. Although aggregation over large areas mitigates the variability of individual assets, there remain uncertainties in renewable generation that are greater than the relatively predictable uncertainties of a few percent in demand that the grid deals with regularly.

Greater uncertainty and variability can be dealt with by switching in fast-acting conventional reserves as needed on the basis of weather forecasts on a minute-by-minute and hourly basis; by installing large scale storage on the grid or; by long distance transmission of renewable electricity enabling access to larger pools of resources in order to balance regional and local excesses or deficits. At present, renewable variability is handled almost exclusively by ramping conventional reserves up or down on the basis of forecasts. However, as renewable penetration grows, storage and transmission will likely become more cost effective and necessary.

Forecasting

The high variability of renewable generation, up to 100% of capacity, makes forecasting critical for maintaining the reliability of the grid. Improving the accuracy and the confidence level of forecasts is critical to the goal of reducing the conventional reserve capacity, and will result in substantial savings in capital and operating costs.

The variability of renewable energy is easily accommodated when demand and renewable supply are matched—both rising and falling together. However when demand and renewable supply move in opposite directions, the cost of accommodation can rise significantly. For example, if the wind blows strongly overnight when demand is low (as is often the case), the renewable generation can be used only if conventional base-load generation such as coal or nuclear is curtailed, an expensive and inefficient option that may cause significant reliability issues. Alternatively, on calm days when there is no wind power, the late-afternoon peak demand must be met entirely by conventional generation resources, requiring reserves that effectively duplicate the renewable capacity. Reducing the cost of dealing with these two cases is a major challenge facing renewable integration.

Recommendations:

The National Oceanic and Atmospheric Administration (NOAA), the National Weather Service (NWS), the National Center for Atmospheric Research (NCAR) and private vendors should:

- Improve the accuracy of weather and wind forecasts, in spatial and temporal resolution and on time scales from hours to days. In addition to accuracy, the confidence level of the forecasts must be improved to allow system operators to reduce reserve requirements and contingency measures to lower and more economical levels.

Forecast providers, wind plant operators, and regulatory agencies should:

- Agree on and develop uniform standards for preparing and delivering wind and power generation forecasts.

Wind plant operators and regulatory agencies should:

- Develop and codify operating procedures to respond to power generation forecasts. Develop, standardize and codify the criteria for contingencies, the response to up- and down-ramps in generation, and the response to large weather disturbances. Develop response other than maintaining conventional reserve, including electricity storage and transmission to distant load centers.

Energy Storage

As renewable generation grows it will ultimately overwhelm the ability of conventional resources to compensate renewable variability, and require the capture of electricity generated by wind, solar and other renewables for later use. Transmission level energy storage options include pumped hydroelectric, compressed air electric storage, and flywheels. Distribution level options include: conventional batteries, electrochemical flow batteries, and superconducting magnetic energy storage (SMES). Batteries also might be integrated with individual or small clusters of wind turbines and solar panels in generation farms to mitigate fluctuations and power quality issues. Although grid storage requires high capacity and long lifetimes, it often allows a stationary location and housing in a controlled environment, very different from the conditions for portable or automotive storage.

Currently, energy storage for grid applications lacks sufficient regulatory history. Energy storage on a utility-scale basis is very uncommon and, except for pumped hydroelectric storage, is relegated to pilot projects or site-specific projects. Some states such as New York categorize storage as "generation," and hence forbid transmission utilities from owning it. In addition, utilities do not know how investment in energy storage technologies will be treated, how costs will be recovered, or whether energy storage technologies will be allowed in a particular regulatory environment.

Recommendations:

The Department of Energy (DOE) should:

- Develop an overall strategy for energy storage in grid level applications that provides guidance to regulators to recognize the value that energy storage brings to both transmission and generation services to the grid;
- Conduct a review of the technological potential for a range of battery chemistries, including those it supported during the 1980s and 1990s, with a view toward possible applications to grid energy storage; and
- Increase its R&D in basic electrochemistry to identify the materials and electrochemical mechanisms that have the highest potential for use in grid level energy storage devices.

Long Distance Transmission

Renewable sources are typically distributed over large areas in the upper central and southwestern US, including the Dakotas, Iowa, Minnesota and Montana, and far from demand centers east of the Mississippi and on the West Coast. New large area collection strategies and new long distance transmission capability are required to deliver large amounts of power a thousand miles or more across the country. This long distance transmission challenge is exacerbated by a historically low investment in transmission generally: from 1988–1998 demand grew by 30%, while transmission grew by only 15%; from 1999–2009 demand grew by 20% and transmission by only 3%. In denser population areas there are community concerns around new right-of-way for above ground transmission towers. The "not in my backyard" arguments are costly to overcome and can delay or stop above-ground transmission construction.

While high voltage DC is the preferred transmission mode for long distances, the drawbacks of single terminal origin and termination, costly AC-DC-AC conversion, and the decade or more typically needed for approval for long lines create problems for renewable electricity transmission. Superconductivity provides an new alternative to conventional high voltage DC transmission. Superconducting DC lines operate at zero resistance, eliminating electrical losses for any transmission length, and operate at lower voltages, simplifying AC-DC conversion and enabling wide-area collection strategies. Superconducting DC transmission lines carrying 10 GW of power 1600 km can be integrated into the Eastern and Western grids in the US while maintaining transient and short-term voltage stability.

Recommendations:

DOE should:

- Extend the Office of Electricity program on High Temperature Superconductivity for 10 years, with focus on DC superconducting cables for long distance transmission of renewable electricity from source to market; and
- Accelerate R&D on wide band gap power electronics for controlling power flow on the grid, including alternating to direct current conversion options and development of semiconductor-based circuit breakers operating at 200 kV and 50 kA with microsecond response time.

Business Case

Utility renewable energy investments are typically assessed from regulatory, project finance, and technical perspectives. The regulatory assessment focuses on ensuring utility compliance with renewable portfolio standards (RPS) and that costs are kept within prudent limits. The project finance view looks at the merits of the investment within discrete boundaries of the funding and cash flows exclusive to the project under review. The technical assessment evaluates the engineering and operational risks of the project and specific technologies involved.

While these conventional views are important for investors, utilities, regulators and ratepayers, they do not fully capture the set of benefits that a renewable energy investment can deliver beyond the boundaries of a given project, such as the physical benefits of transmission and storage and the organizational benefit of developing an integrated picture of the grid. Inclusion of these additional benefits in an expanded business case will enhance the profile of the renewables investment, and more importantly, begin to recognize the synergies inherent in the integration of renewables with the grid.

Recommendations:

The Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) should:

- Develop an integrated business case that captures the full value of renewable generation and electricity storage in the context of transmission and distribution; and
- Adopt a uniform integrated business case as their official evaluation and regulatory structure, in concert with the state Public Utility Commissions (PUCs).

Introduction

In an October 27th, 2009 speech to mark the start-up of a solar energy plant in Arcadia, Florida, President Obama spoke about the urgent need to update the antiquated U.S. power grid to more efficiently move electricity around the country. He commended Florida Power and Light for building a renewable energy plant that would "produce enough power to serve the entire city of Arcadia" and save 575,000 tons of greenhouse gas emissions over the next 30 years—the equivalent of removing more than 4,500 cars from the road each year for the life of the project." But, the president said, this wasn't enough. The grid would need to be updated to handle these new sources of electricity.

> *"…we've got to do more than just add extra solar megawatts to our electrical grid. That's because this grid—which is made up of everything from power lines to generators to the meters in your home—still runs on century-old technology. It wastes too much energy, it costs us too much money, and it's too susceptible to outages and blackouts. To offer one analogy, just imagine what transportation was like in this country back in the 1920s and 1930s before the Interstate Highway System was built. It was a tangled maze of poorly maintained back roads that were rarely the fastest or the most efficient way to get from point A to point B. Fortunately, President Eisenhower made an investment that revolutionized the way we travel—an investment that made our lives easier and our economy grows."*

In the late 1990s, in tandem with reorganization of their electric utility industries to permit increased competition, a number of states established Renewable Portfolio Standards (RPS) to encourage electrical production from renewable sources such as wind, solar, and biomass.[1] Since that time, 30 states and the District of Columbia have established an RPS. Some of the most ambitious RPS targets are in California, which is mandated by Executive Order to reach 33% by 2020 and New York, with a 30% target by 2015. While a number of states have or will soon reach a 20% RPS, the technological leap to reach 30% or more will pose technological challenges which will make it necessary for the Federal government and utilities to conduct additional research and invest in more resources. Without such investments, it is unlikely that all the required mandates can be met.

In addition to state policies, federal policy makers have put forward proposals to establish a national RPS, making the need for technological developments even more urgent. Federal legislative proposals to establish a national RPS date back to the 105th Congress.[2] In the House of Representatives, the American Clean Energy and Security Act of 2009 (ACES) would require investor-owned utilities to purchase 6% of their power from renewable energy sources by 2012, gradually rising to 20% by 2020. In the Senate, the American Clean Energy Leadership Act of 2009 would require an increasing share of electricity to be generated from renewable sources, and up to a 15% share by 2021.[3]

To begin addressing the technological hurdles incumbent in surpassing the 20% RPS level, the American Recovery and Reinvestment Act of 2009 (ARRA) (Title IV) therefore provides $4.5 billion to the Department of Energy Office of Electricity Delivery and Energy Reliability, including grid modernization and related technologies, such as electricity storage. The funds will support implementation of the Smart Grid programs authorized by the Energy Independence and Security Act of 2007 (Title 13), which includes Smart Grid technology research, development and demonstration projects, and the federal matching fund for Smart Grid technologies with funds distributed through a competitive grant process.

But funding alone may not be enough. To fully prepare for higher levels of renewable energy on an aging grid system, the Federal government and utilities should conduct a comprehensive review and inventory of the technological challenges. They should also establish an adequate business case, which will incentivize utilities to make the large-scale investments needed to meet these RPS levels. Because no such business case has been made to utilities, they have been loath to make these investments in order to accommodate the higher RPS levels.

The definition of renewable energy differs between policy proposals, reflecting regional issues and concerns. While Geothermal, ocean tidal, ocean wave, incremental hydro, biomass, and captured landfill methane are sometimes included in RPS mandates, wind and solar energy are universally included in these mandates. To date, these two sources have received considerably more investment than other renewable energy sources. This report therefore focuses on wind and solar energy and the three principal issues associated with integrating wind and solar resources with the grid: variability of generation addressed by forecasting, energy storage and transmission; remote location of wind and solar resources addressed by transmission; and how the incomplete business case undervalues key resources such as storage and transmission. Our study is unique in addressing the technology and business case issues for renewable energy in a common framework.

Technology Issues

The United States has ample renewable energy resources. Land based wind, the most readily available for development totals more than 8000 GW of potential capacity (see Figure1).[4] The capacity of concentrating solar power (solar thermal energy driving conventional generators) is nearly 7,000 GW in seven southwestern states.[5,6] The generation potential of photovoltaics is limited only by the land area devoted to it, 100–250 GW/100 km^2 in the United States.[7,8] By comparison, the United States generated electric power at an average rate of approximately 450 GW in 2009, peaking to over 1000 GW during the summer months. By 2035, electricity demand is projected to rise 30%.[9] In 2009, wind accounted for about 1.8% and solar about 0.07% of the electricity generated in the US. Wind and solar can easily supply a larger fraction of the nation's electricity needs than the 20%–30% RPS now under consideration.

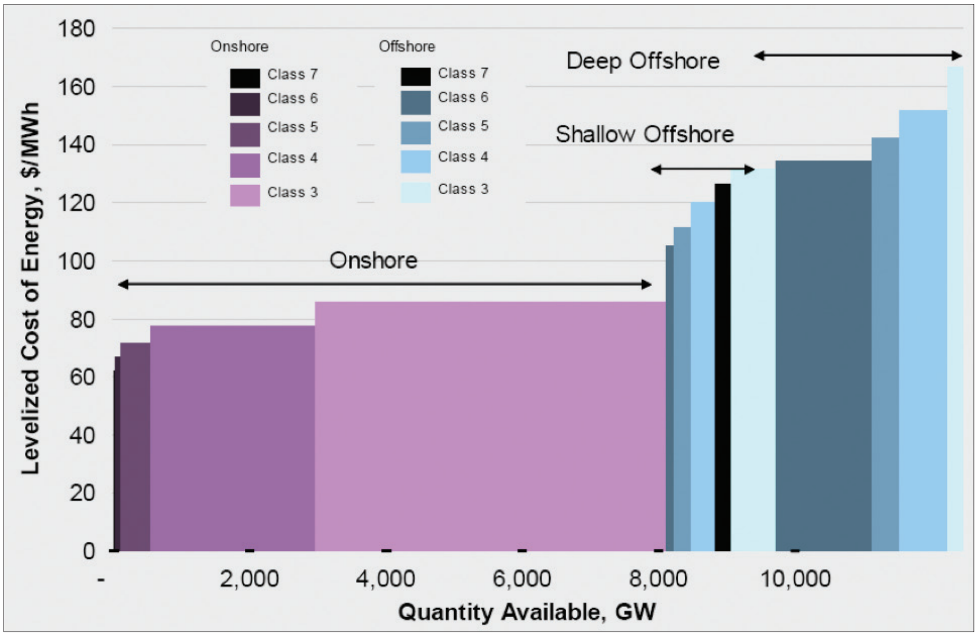

Figure 1.
Wind resources in the United States (after Black & Veatch 2007).

However, developing renewable resources, presents a set of technological challenges not previously faced by the grid: the location of renewable resources far from population centers, and the variability of renewable generation. The grid is an historical patchwork of local or regional generation resources and loads, with electricity generation located as far as 1000 miles from population centers. The ownership and regulation of the grid is likewise divided along local or regional lines.[10] Transmitting wind electricity from their sources to distant population centers strains the physical, ownership and regulatory structure of the grid. Therefore, at higher RPS levels, accommodating these renewable resources requires new approaches to extending and operating the grid.[11]

Another issue is the variability of renewable resources due to the characteristics of weather. This characteristic introduces uncertainty in generation output on time scales of seconds, hours and days. These uncertainties, affecting up to 70% of daytime solar capacity due to passing clouds, and 100% of wind capacity on calm days, are much greater than the relatively predictable uncertainties of a few per cent in demand that system operators now deal with regularly. Variability becomes increasingly difficult to manage as penetration levels increase. But technology can accommodate this variability by: augmenting generation by using fast-acting conventional reserves when renewable energy resources are expected to decrease; by installing energy storage on the grid, or by better long distance transmission which enables access to larger pools of resources to balance regional and local excesses or deficits. Right now, renewable energy variability is handled almost exclusively by ramping conventional reserves up or down on the basis of forecasts. But, as renewable energy penetration grows, large-scale storage, fast-acting resources, and better long distance transmission will become more important to accommodate high-levels of variability in generation.

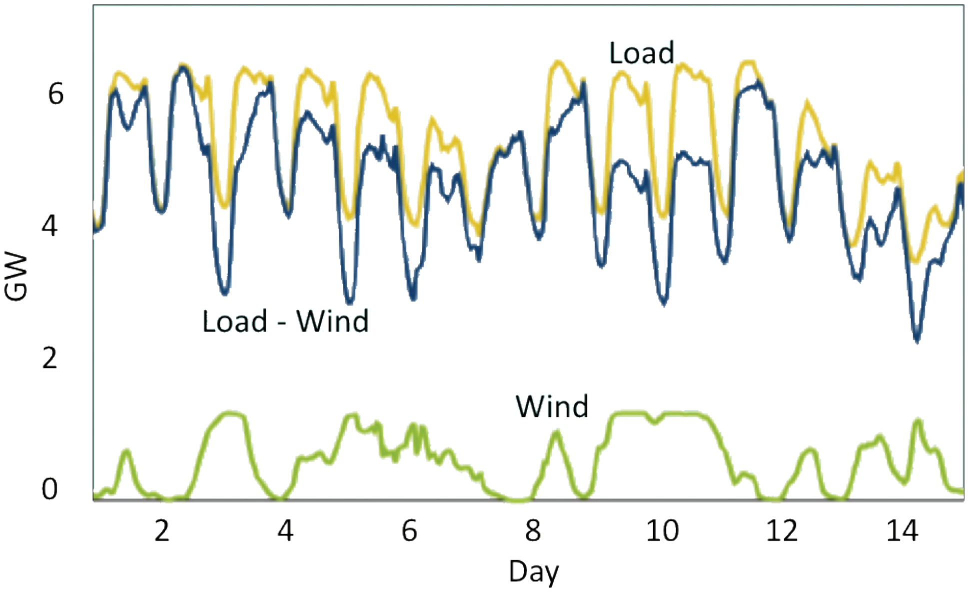

Figure 2.
Wind generation and system load over a two week period in the Xcel system in Minnesota. Wind provides 1500 MW capacity on a 10000 MW peak capacity system. (After *20% Wind Energy by 2030,* Energy Efficiency and Renewable Energy, DOE/GO-102008-2567 (2008))

Figure 2 illustrates the variability of renewable resources by depicting generation and load variation over a two-week period for the Xcel system in Minnesota, a system with 1,500 MW of wind capacity on a 10,000 MW peak-load system.[12] Wind variability is high, showing periods of maximum production for two days, and other times of calm for nearly two days. New levels of accuracy and detail in forecasting to deal with these generation uncertainties will be required as RPS levels increase. This includes: wind predictions on a much more frequent basis (i.e. a sub-hourly, hourly and daily basis) and the translation of those predictions to power generation forecasts for specific wind plants.[13]

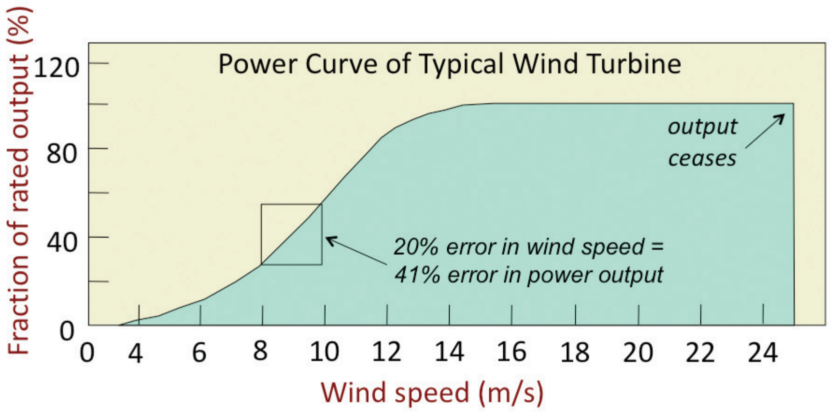

Figure 3.
The power output of a turbine varies with wind speed, turning off at high speed to protect from damage (after H. Sharman, Proceedings of ICE Civil Engineering 158, 161 (2005)).

The magnitude and variability of wind power depends not only on the wind but also on the turbines that convert wind to electric power. The power curve of a typical turbine is shown in Figure 3.[14] The output of a turbine rises steadily with the wind speed and produces maximum power over its designed operating range. At high wind speeds, however, it turns off to protect itself from damage, and the output quickly drops to zero. Turbine performance is also affected by other local conditions, including topographical features and the density of the air, which, in turn, depends on temperature and humidity.

The body of this report, on the following pages, addresses the challenges of dealing with variability and the remote location of renewable resources through forecasting, energy storage and long distance transmission.

Forecasting

It is important to distinguish between variability and uncertainty when discussing planning and operations of the power grid. Variability describes the change of generation output due to fluctuations of wind or sun; uncertainty describes the inability to predict in advance the timing and magnitude of the changes in generation output. The purpose of forecasting is to reduce the uncertainty of renewable generation, so that its variability can be more precisely accommodated.[15]

The variability of renewable resources—70% for daytime solar due to passing clouds and 100% for wind due to calm days—is a major challenge to integrating renewable energy resources on the grid. When scaled by their RPS targets, the variability of renewable energy is comparable to the variability of demand, which changes by 20%–50% between afternoon peaks and overnight valleys. The crucial difference between the variability of renewable generation and the variability of demand is predictability. Demand can be anticipated to within a few percent based primarily on weather forecasts of temperature, humidity and precipitation, on demand history, and on anticipating major energy events such as the broadcast of television programs which a large expected viewing audience. Renewable generation depends primarily on specific weather characteristics such as wind for wind generation and sunlight exposure for solar generation, which do not occur in regular patterns and are not correlated to diurnal patterns of demand. The ability to quickly ramp dispatchable resources—such as natural gas turbines or hydroelectric power to follow the variability of renewable generation—up or down is a major consideration for effectively accommodating renewable resources. [16,17,18,19,20,21,22,23]

System operators consider the reliability of the grid to be the most critical priority. This “sacred principle” drives up the cost of renewable integration, because operators must hold large amounts of reserves to cover an unexpected loss of renewable generation. Increases in forecast quality translate into decreases in reserve requirements and costs. An analysis of wind plant experience to date shows that reserves have been increased up to 9% to accommodate wind penetration of 15%.[24] Reducing the ratio of added reserves to added renewable capacity by better forecasting is a critical objective for reducing the cost of integrating renewable energy resources onto the grid.

Forecasts must improve to accommodate the two most serious challenges in generation variability: up-ramps at times of low demand and down-ramps at times of high demand. In the former case conventional reserves may already be turned off, so that accommodating the up-ramp may require turning down base-load conventional generation or curtailing renewable generation. Both options are inefficient and expensive and may cause significant reliability issues. In the latter case, most conventional reserves may already be turned on, leaving few options for compensating the power lost in the renewable down-ramp. In the ERCOT event of February 26, 2008, service to certain customers was curtailed in a controlled manner due to an earlier-than-expected wind down-ramp.[25] The accuracy of forecasts and timely operational responses for these two worst-case scenarios are critical to maintaining reliability and lowering cost as renewable penetration grows.

Accuracy and Confidence Level

The level of confidence for operators in forecasts is as important as accuracy. Low confidence levels require operators to maintain high levels of reserves even if the forecast itself calls for steady output. Estimating the confidence level of forecasts is becoming more common, but the techniques must become more sophisticated. Once this occurs, operators can have a greater degree of confidence in forecasts which will reduce the cost of balancing supply with demand by as much as 39%.[26]

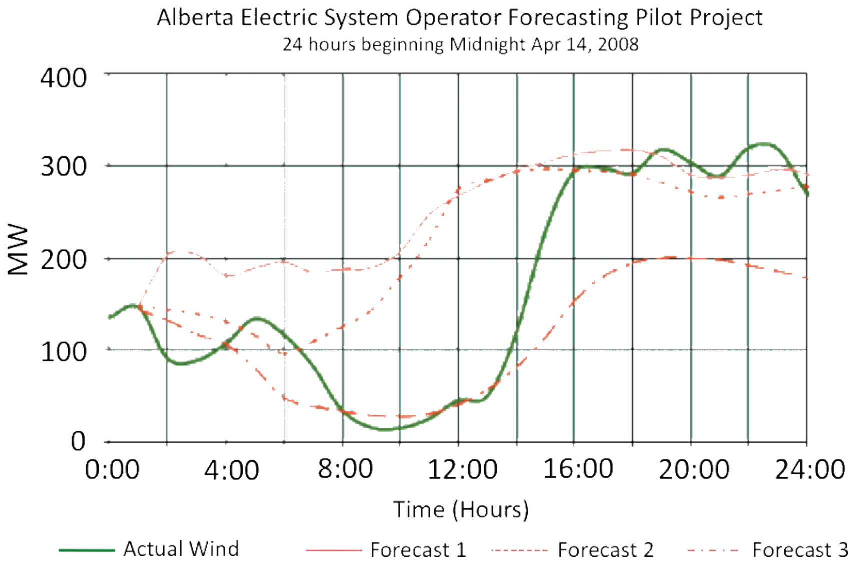

Figure 4.
Three forecasts for wind power in the Alberta Electric System Operator wind system. Only one of the three predicted the four-hour morning lull, and none predicted the range of variability. (After *Accommodating High Levels of Variable Generation: Summary Report* NERC (2009)).

Figure 4 illustrates the present state of wind forecasting.[15] During a 24 hour period predictions of wind power generation for the Alberta Electric System Operator varied by a factor of 20 among three forecasts at times and by a factor of 1.5–2 over most of the range. The actual wind generation level varied over the course of four hours from following the lowest of three forecasts to following the highest. At times, the actual wind was a factor of 10 below the two highest forecasts and at other times 50% larger than the lowest forecast. Discrepancies of this size between predicted and actual wind generation are typical of other wind plants.[27] At the present immature stage of forecasting accuracy, consulting several forecasts from independent providers is a critically important practice.

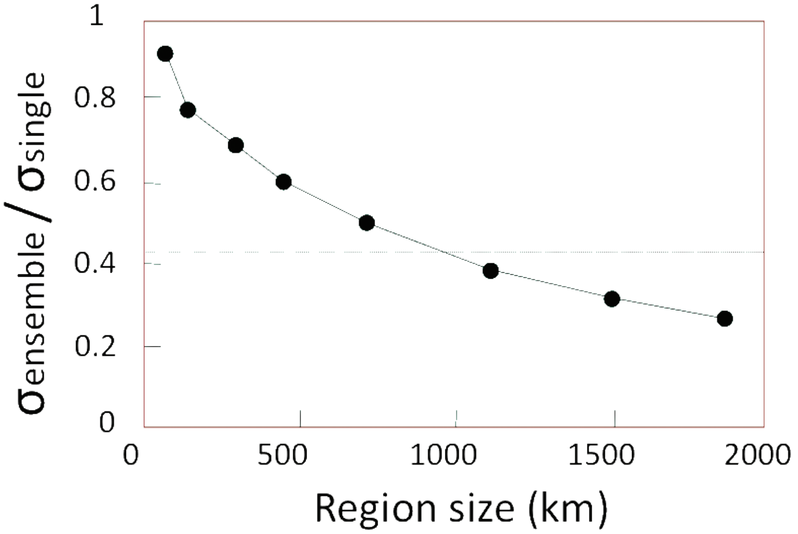

Figure 5.
The reduction in the error of forecasts aggregated over large areas (after Focken et al, Journal of Wind Engineering and Industrial Aerodynamics 90, 231 (2002)).

The accuracy and confidence level of forecasts can be improved by aggregation over a wider area. For example, over a distance of approximately 1000 km, typical for a German forecast, the forecasting error is reduced to 42% of that for a single turbine, as shown in Figure 5.[28] Combining the four forecasting areas of Germany reduces the two-hour ahead forecasting error by 25%.[29]

The benefits of larger areas apply to balancing generation and load as well as to forecasting. Extending the balancing area over which generation and load are matched and eliminating transmission constraints within this area significantly reduce the cost of renewable integration by compensating local up-ramps with distant down-ramps. Consolidating the four balancing areas of Minnesota, for example, reduces ramping requirements by 14%.

Even longer distance balancing can be achieved with national coordination of forecasts and power flows. An excess of generation in the north central US, for example, might be balanced by a generation deficit in the northeast. This requires not only high capacity long-distance transmission, but also accurate and correlated forecasts for distant regions at the hours-ahead or day-ahead time scale. Such national coordination of forecasts is not currently done. A coordinating body would be required to match forecast excesses with deficits and oversee the required long-distance power transmission.

Forecasting renewable generation and balancing generation with load illustrate the need for new approaches to coordinating the grid across local physical ownership and regulatory boundaries to accommodate renewable energy.

Power Generation Forecasts

To be useful to the system operator, weather forecasts must be converted to forecasts of the power expected to be generated by wind plants. This is typically done with the assistance of a physical model, a statistical analysis process, an artificial intelligence-based learning system, or some combination of these techniques. All of these techniques rely on historical wind plant output data from the site to perform the analysis, correlations, and training of the system to produce an accurate forecast. Such forecasts depend on much more than the wind speed. The availability of turbines, their power curves and the possibility of curtailment due to wind speeds above the cut-off value must be taken into account. Curtailment during high winds may be especially serious, as it can cause a gradual ramp-down of generation over two hours as an increasing number of individual turbines reach their cutoff speeds. Topographical effects that produce local wind currents are important, as is the density of the air that depends on temperature and humidity.

The success of forecasting is dependent upon operator experience and confidence. Just as airline pilots know that weather and turbulence forecasts need not be perfect to be useful, increasingly experienced system operators will be able to better use forecasts to their advantage. It may be more useful to view forecasting in terms of identifying periods of operational risk or uncertainty, and training operators to take mitigating action under those conditions, instead of focusing on the accuracy of forecasting.

Operational Response to Forecasts

To maintain reliability of the grid, forecasts much also be integrated into system operating procedures. As wind and solar plants grow in size and as renewable electricity penetrates the grid to higher levels, new response procedures to the growing generation variability must be developed. As the smart grid is deployed, options for fast automatic response to routine generation ramps can be implemented. However, fully automated forecasting has its limits. A human forecaster can add much value in forecasting ramp events—especially in the one-hour to four-hour timeframe. There are patterns and features (such as rapidly evolving thunderstorm complexes on a radar display) that humans can still detect and interpret far better than numerical models or computational learning systems. The challenge to using automated and human forecasting becomes how to couple the human input with automatic response to best deliver forecasts and information to system operators.

Renewable energy challenges conventional methods of dealing with contingency. Contingencies are traditionally defined as the loss of the largest generation unit. Renewable energy generation is spread over many wind turbines, solar cells, or concentrated solar thermal generators so that a "largest generation unit" cannot be identified. The largest loss that can occur is 100% of the wind generation; if this is 30% of the total capacity (as envisioned by some RPS) and it occurs during peak demand, the loss cannot be handled by ramping up conventional reserves. Additional methods of ensuring reliability of the grid need to be developed. These include energy storage and long distance transmission, which are treated below.

Recommendations:

The National Oceanic and Atmospheric Administration (NOAA), the National Weather Service (NWS), the National Center for Atmospheric Research (NCAR) and private vendors should:

- Improve the accuracy of weather and wind forecasts, in spatial and temporal resolution and on time scales from hours to days. The confidence level of the forecasts must be improved to allow system operators to reduce reserve requirements and contingency measures to lower and more economical levels.

Forecast providers, wind plant operators, and regulatory agencies should:

- Agree on and develop uniform standards for preparing and delivering wind and power generation forecasts.

Wind plant operators and regulatory agencies should:

- Develop and codify operating procedures to respond to power generation forecasts. Develop, standardize and codify the criteria for contingencies, the response to up- and down-ramps in generation, and the response to large weather disturbances. Develop response other than maintaining conventional reserve, including electricity storage and transmission to distant load centers.

Energy Storage

As renewable energy penetration grows, the increasing mismatch between variation of renewable energy resources and electricity demand makes it necessary to capture electricity generated by wind, solar and other renewable energy generation for later use. Storage can help smooth fluctuations in generation inherent in wind or solar energy.

The Case for Grid-Level Energy Storage

Grid level or stationary utility energy storage includes a range of technologies with the ability to store electricity on the grid and that allow it to be dispatched as needed.[30, 31] Energy storage can enhance the reliability and resilience of the grid through short-term storage for peak-shaving and power quality uses and longer-term storage for load-leveling and load-shifting applications. As larger amounts of intermittent renewable energy sources such as wind and solar energy enter the market, grid energy storage becomes a means of compensating for generation fluctuations of these sources on timescales ranging from seconds to hours. Some estimates suggest that 300 GW of additional wind energy requires 50 GW of conventional reserve to account for the variability added to the grid system.[32]

Large-scale energy storage on the electric grid is not a new concept. The current grid uses pumped hydro and to a lesser extent, compressed air energy storage (CAES) (Figure 6) for these purposes. These options could be expanded, but are limited to geographically-appropriate sites. They have the advantage of fast response; a few minutes or less for pumped hydro and about 10 minutes for CAES.

Batteries offer another means of grid-level energy storage by converting electricity to chemical energy during times when electrical supply exceeds demand. Unlike pumped hydro and CAES, battery storage is feasible for any geographical location.

Thermal storage using molten salts or other media is effective for concentrating solar power plants like the solar energy generating systems in the U.S. Mojave desert, and the Andasol plants near Granada, Spain.[33] Thermal storage stabilizes fluctuations due to passing clouds and allows electricity to be produced after the hours of peak sunshine.

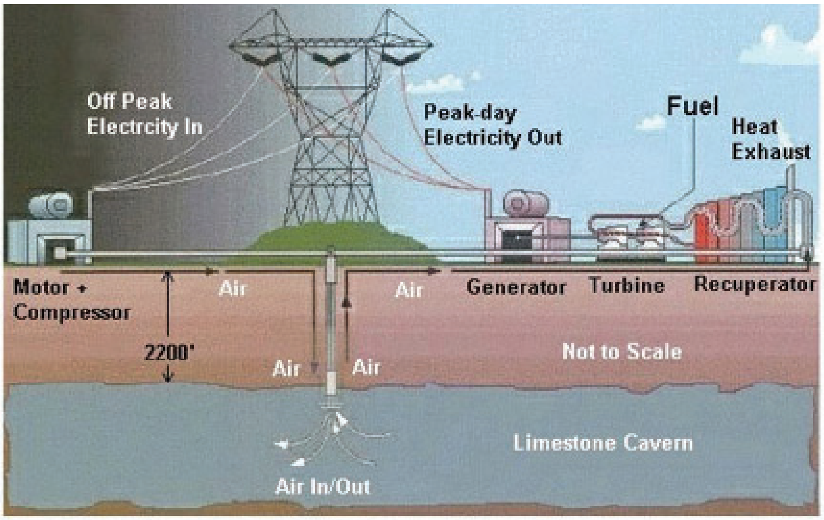

Figure 6.
Compressed air energy storage system. Compressed air mixed with natural gas is stored in a geological formation, to be released and ignited to drive a turbine to produce electricity. Photo courtesy of CAES Development Company.

Flywheels are being effectively used in California and New York for frequency regulation, which will become more important with increased integration of variable power sources. The international fusion community uses flywheels to store. Superconducting magnetic energy storage (SMES) with a capacity of a few MJ is used for regulating power quality. Much higher power and energy SMES—that can deliver 100 MW of power for seconds to minutes—has been developed for fusion applications. The opportunities for lower cost and higher energy storage capacity are related to the cost and maximum magnetic field strength of superconducting wire. Synergies between DC superconducting transmission and SMES offer cost and technology savings opportunities.

Increased interest in this area has led ARPA-E to recently issue a broad call for proposals for utility scale energy storage including each of the categories described here.[34, 35]

Use of energy storage for utility applications can be divided into three categories: (1) for base load bulk power management, (2) for grid support in the form of distributed or load leveling storage, or (3) for power quality and peak power storage, including uninterruptable power supply applications. Within each of these broad categories, different timescales from seconds to hours apply. The purpose of the storage and the timescale of response determine which energy storage technologies are best suited for a given application. Figure 7 depicts a number of energy storage options, including several different battery chemistries.

Currently, the most pervasive use of large-scale chemical energy storage is for power quality in the form of uninterrupted power supplies (UPS). UPS is used to protect expensive electrical assets such as computer data centers and critical infrastructure. Such systems do not require high-energy content since most power outages are less than a minute in length. Lead acid and metal hydride batteries are the mainstays of this industry.

In addition to peak shaving, storage can also help manage the transmission capacity for wind energy resources. By adding energy storage, wind plants located in remote areas can store energy from peak periods, allowing for lower cost. Because the generated electricity can be stored rather than used in real time it lowers the need for transmission

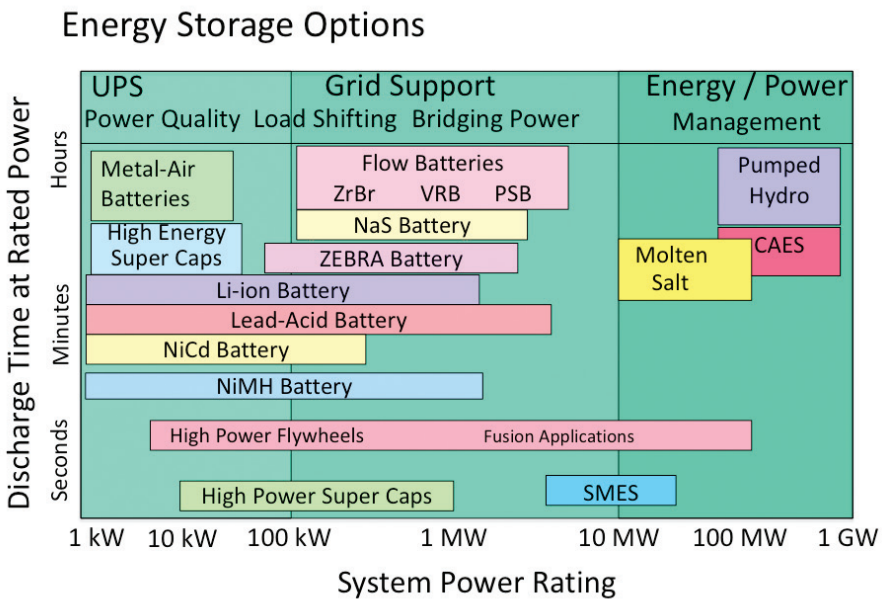

Figure 7.
Energy storage options (after Electric Power Research Institute and B. Roberts, *Capturing Grid Power,* IEEE Power and Energy Magazine, 32, July/August (2009)).

lines, and also allows retailers to maximize profits by selling power during peak usage periods, which do not usually correspond with peak wind output periods. For these applications to become economically favorable, more advanced battery materials must first become widely available.

The Physical Scale of Grid Energy Storage

The availability of wind and solar energy sources can vary significantly, sometimes in a matter of seconds and at other times over hours or even days. The different time frames impose different energy storage requirements: (1) relatively low capacity but fast response for changes that occur within seconds or over a period of a few hours and (2) high capacity but slower response for changes that extend over one or more days. We term the first storage need a "power application" and the second an "energy application." Although storage requirements extend continuously across the time spectrum, and many storage technologies span the two applications, the simplifying classification allows us to provide a sense of the physical scale of the storage challenge.

In the accompanying table, we illustrate the power application storage need for a 70% reduction in solar photovoltaic (PV) electricity generation or 20% reduction in wind generation, assuming each occurs over a one-hour period. We also illustrate the energy application storage need for accommodating 12 hours of solar production and 24 hours of wind production. The table shows the physical sizes of various kinds of storage units required for a 100 megawatt solar installation—the generating capacity of typical large photovoltaic and moderate concentrating solar power (CSP) plants—and for a 750 megawatt wind farm—the capacity of typical large wind installations. Note that a molten salt thermal storage unit is appropriate only for a CSP plant.

Power Applications

Storage Technology	100 MW Solar PV or CSP 70 MWh Storage Capacity	750 MW Wind 150 MWh Storage Capacity
Lead-acid battery	1170 m^3	2500 m^3
Lithium-ion battery	194 m^3	417 m^3
Sodium-sulfur battery	269 m^3	558 m^3
Flow battery	2340 m^3	5000 m^3
Molten salt thermal	5300 m^3	Not Applicable

Energy Applications

Storage Technology	100 MW Solar PV or CSP 1200 MWh Storage Capacity	750 MW Wind 18000 MWh Storage Capacity
Flow battery	40000 m^3	600000 m^3
CAES	385000 m^3	5.77 x 10^6 m^3
Pumped hydro	2.14 x10^6 m^3 (500 m head)	32.1 x 10^6 m^3 (500 m head)
Molten salt thermal	90900 m^3	Not Applicable

Battery Energy Storage Technologies

Interest in electric drive vehicles is driving a great deal of investment in energy storage R&D for mobile applications. There is the potential that technological developments for the mobile application will yield benefits for stationary, grid-scale application as well. However, the electric vehicle application is considerably more demanding than the grid-energy storage application. The requirement to store large quantities of energy per unit weight or power delivery per unit weight is less rigorous in stationary applications than immobile applications. Moreover, vehicle applications require the technology to be highly impervious to a wide range of temperature and humidity variations, as well as to extreme vibration environments. The utility application allows a much greater ability to control the ambient environment, making the battery design challenges less demanding.

Because of this, battery technologies developed under the DOE's vehicle technology program in past years—but later discontinued because of their unsuitability for vehicle applications—may, once again, be feasible alternatives for stationary applications associated with the grid. In the 1980s and early 1990s, the DOE maintained a diverse portfolio of battery chemistry technologies for research support under its vehicle technologies program. During the Clinton administration as part of the Partnership for the New Generation of Vehicles (PNGV) program DOE focused on two battery chemistries: nickel metal hydride and lithium ion. However, in light of the potential need for battery storage with greater integration of renewable energy resources on the grid, it may be useful to revisit the discontinued battery chemistries to assess whether or not any of them are suitable candidates for today's utility applications.

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Battery Materials for Energy Storage

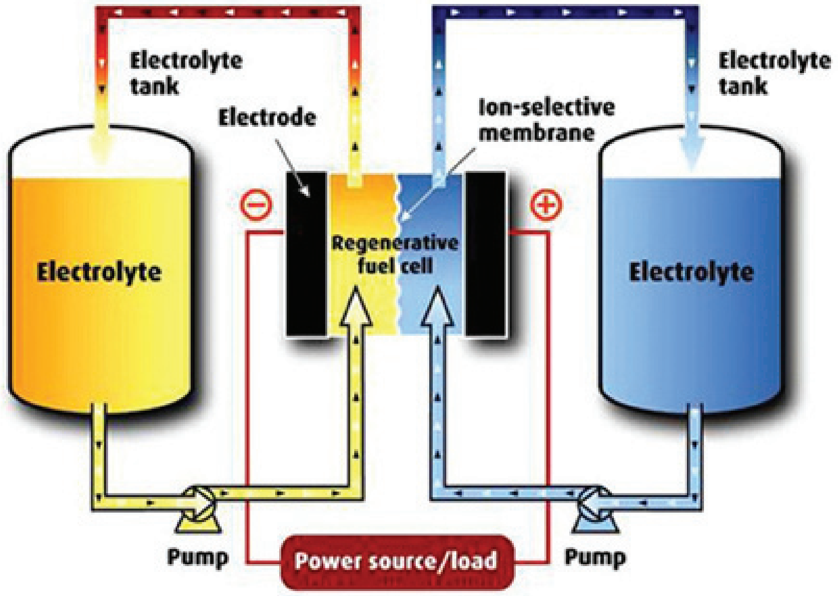
Currently, lead acid and sodium sulfur systems have the most extensive track record for large-scale energy storage.

Lead Acid In the 1980s, lead acid batteries for utility peak shaving were tested, but the economics at that time did not support further deployment. However, continued incremental improvements in lead acid technology and increased energy costs are making use of lead acid more economical. Recent innovations in lead acid technology demonstrated three to four times the energy density with improved lifetimes over conventional lead acid batteries. One promising technology is the combination of ultra capacitors and lead acid batteries into integrated energy storage devices sometimes referred to as "ultra batteries."

Sodium Sulfur Sodium sulfur batteries use molten sodium and sulfur separated by a ceramic electrolyte. This battery chemistry requires an operating temperature of about 300°C to maintain the active materials in a molten state. These batteries have a high energy density, a high efficiency, and a projected long cycle life. Of emerging battery technologies suitable for utility applications, sodium sulfur batteries are the most technologically mature, and are deployed on a limited scale in Japan and in the United States. A Japanese firm, NGK Insulators, is responsible for most of the development and commercialization of sodium sulfur for utility applications.

With additional research and demonstration, other battery technologies also could prove useful for large-scale energy storage.

Figure 8.
The principle of the flow battery, where energy is stored in liquid electrolytes and recovered as electricity.



Flow Batteries A flow battery is a rechargeable battery that converts chemical energy to electricity by reaction of two electrolytes flowing past a proton-exchange membrane, illustrated in Figure 8. The principle is similar to a fuel cell except that the reaction is reversible and the electrolytes are reused instead of being released to the atmosphere. Additional electrolyte is stored in external tanks and pumped through the cell to charge or discharge the battery. The energy storage capacity is limited only by the size of the tanks, making scale-up relatively easy, with cost-per-unit of energy storage generally lower than for non-flow batteries, which improves the attractiveness for larger sizes. Flow batteries offer potentially higher efficiencies and longer life than lead acid batteries. Flow batteries such as vanadium and zinc bromide (ZnBr) show great promise. Flow batteries have good efficiencies (over 75%) and long lifetimes (over 10,000 charge discharge cycles) and are scalable because battery size is determined by the electrolyte holding tank size.

Vanadium Redox Flow batteries are a relatively new technology. Energy is stored chemically in different ionic forms of vanadium in a dilute sulfuric acid electrolyte. The electrolyte is pumped from separate storage tanks into flow cells. Vanadium flow batteries of 800 kW to 1.5 MW are being successfully demonstrated outside of the United States in applications such as UPS for semiconductor manufacturing, island grid capacity firming and grid peak shaving applications.

Zinc bromide flow batteries are regenerative fuel cells based on a reaction between zinc and bromide. An aqueous solution of zinc bromide is circulated through two compartments within the cell from separate reservoirs. While zinc bromide batteries use electrodes as substrates for the electrochemical reaction, the electrodes themselves do not take part in the reaction; therefore, there is no electrode degradation with repeated cycling. Several zinc bromide systems in the 200 to 500 kW range have been demonstrated for peak shaving and island grid applications.

Further development of liquid metal batteries, polysulfide bromide cells and metal air batteries could also prove useful. Liquid metal batteries are another class of batteries that potentially could provide up to 10 times the current energy storage capacity of current batteries. Like the sodium sulfur battery, liquid mental batteries are a high temperature stationary technology. Polysulfide bromide (PSB) cells are flow batteries, based on regenerative fuel cell technology, that react two salt solution electrolytes, sodium bromide and sodium polysulfide. Metal air batteries have the potential to deliver high energy densities at low cost, but challenges with recharging have so far precluded commercialization of the technology.

Barriers and Recommendations

Energy storage for grid applications lacks a sufficient regulatory history. This is due to the fact that utility scale energy storage is very uncommon and, except for pumped hydroelectric storage, is only being used in pilot projects or site-specific projects. Utilities are therefore uncertain how investment in energy storage technologies will be treated, how costs will be recovered, or whether energy storage technologies will be allowed in a particular regulatory environment.

Energy storage applications can provide functions related to both generation and transmission, further confusing the question of regulatory treatment of investments in grid level energy storage. For example, a utility can use bulk energy storage to store electricity generated during a low-cost period, such as late at night, to a time of high-cost generation, such as during peak daytime use. From a regulator's perspective, the energy provided from the batteries during the peak period may look like generation. At the same time, however, this strategy could also reduce transmission congestion, provide voltage support at a time of peak use, and provide other ancillary services that support transmission functions.[27] The ability of energy storage technology to fill multiple roles in both transmission and generation has created confusion and uncertainty about how energy storage should be regulated.

Moreover, the current system does not fully credit the value of storage across the entire utility value chain. Generation, transmission, and distribution have been viewed historically as independent components of the grid system. As a result, cost recovery for grid-level energy storage investments is challenging. Without clear rules governing cost recovery, utilities tend to under-invest in energy storage. It is comparatively easier for utilities to invest in conventional approaches to grid instability, such as natural gas spinning reserves. These more conventional investments are more likely to be included in the utility's rate base.

Vehicle-to-Grid Considerations

If plug-in electric hybrid vehicles (PHEVs) succeed in achieving significant market growth in the coming decades, the potential will exist to use the on-board energy storage of these vehicles as distributed energy storage that would be available to the larger grid while the vehicles are plugged in, or recharging. PHEVs could bring the capability of discharging back to the grid to improve grid utilization, level demand, and improve reliability.

However, one challenge to such an application will be determining how PHEV usage will interact with high levels of renewable energy generation capacity, especially wind and solar power. Both solar and wind power vary diurnally. If the PHEV charging load matches peak renewable energy production—such as wind power generation in areas where the wind blows more consistently overnight—then the PHEV load and renewable source will be well matched temporally. If the PHEV charging does not match daily renewable energy generation cycles well, then the mismatch is problematic, and deployment of energy storage technology will take on an even more important role in supporting the attainment of high renewable portfolio standards. Smart grid technologies that enable time-of-use pricing could encourage consumers to match their vehicle charging with times of higher renewable generating capacity.

Recommendations:

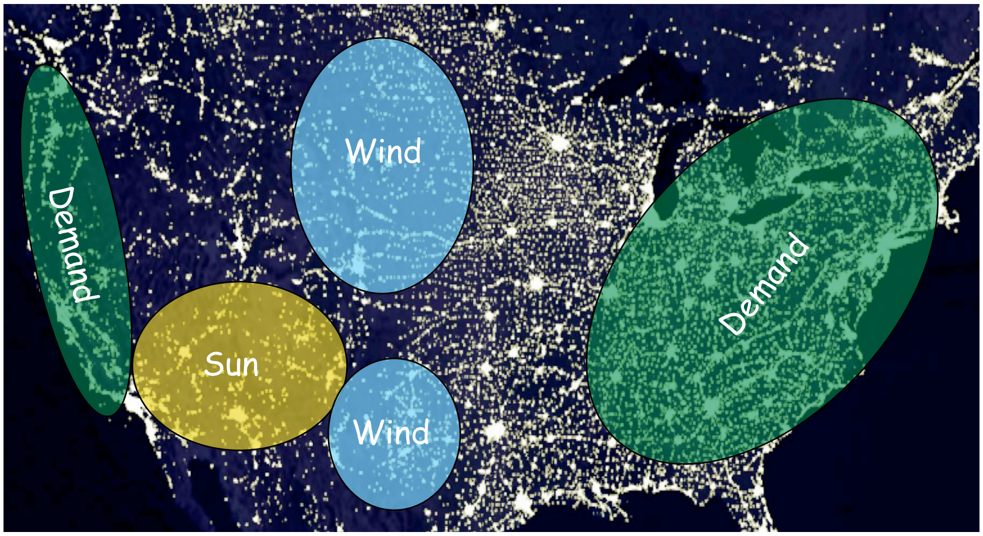
The Department of Energy (DOE) should:

- Develop an overall strategy for energy storage in grid level applications that provides guidance to regulators to recognize the value that energy storage brings to both transmission and generation services to the grid;
- Conduct a review of the technological potential for a range of battery chemistries, including those it supported during the 1980s and 1990s, with a view toward possible applications to grid energy storage; and

- Increase its R&D in basic electrochemistry to identify the materials and electrochemical mechanisms that have the highest potential for use in grid level energy storage devices.

Long-distance Transmission

The advent of solar and wind renewable energy generation brings new challenges for the collection and long distance transmission of renewable energy, and for distribution of renewable electricity in power-congested urban areas. Renewable sources are typically distributed over large areas in the upper central and southwestern United States, far from demand centers east of the Mississippi and on the West Coast (see Figure 9). This means new large area collection strategies and new long distance transmission capability are required to deliver large amounts of renewable power a thousand miles or more across the country. Like the US road system before interstate highways, the power grid is designed to serve local and regional customers with local and regional generation and delivery infrastructure. To adequately address our national energy needs in the renewable energy era, the grid must change its character, from a locally-designed, built and maintained system to one that is regionally and nationally-integrated. Delivery of increased renewables-based power to urban areas also presents new challenges. Today, 82% of the US population lives in urban or suburban settings[36] where power use is high and demand for increased energy is, and will continue to be, strongest. Renewable electricity from remote sources helps to meet this demand without increasing carbon dioxide emissions. However, the additional power currently must be distributed over infrastructure designed and installed to meet much smaller needs. Congestion on existing lines inhibits growth, and as urban areas expand and merge, the area over which power distribution needs to be coordinated grows. The urban setting makes installation of new lines to meet demand growth expensive and challenging because of the difficulty in securing new "right of way" permits. This delays the installation of new distribution lines up to 10 years and loads the existing lines well beyond their design limits.



Source: Map based on information from NASA and the National Renewable Energy Laboratory.

Figure 9.
The large separation between renewable sources and demand centers requires new long distance transmission lines.

Long Distance Transmission Options

Until recently, long distance delivery of electricity over several hundreds of miles remained a specialized area of technology with a fairly small demand and footprint. Most cities are served by nearby fossil coal or gas generation plants, requiring transmission over short distances. An exception is hydroelectric generation in Canada and the northwest US, which produces large amounts of power far from demand centers and justifies long distance transmission. For distances greater than a few hundred miles, direct current (DC) transmission is favored over alternating current (AC) for its lower electrical losses and lower cost. The challenge for DC transmission is the conversion technology from AC sources to DC transmission and back to AC for use. The first commercial high voltage DC transmission lines in 1954 used mercury arc converters for AC-DC conversion, replaced by semiconductor thyristors[37] in 1972, and by insulated gate bipolar transistors (IGBTs) in the 1980s. Although technical progress is reducing the cost of semiconductor power electronics, the cost and technical challenge of AC-DC conversion is still a major barrier for increasing DC transmission.

The mandated growth of wind and solar generation through Renewable Portfolio Standards (RPS) to 20% or 30% of electricity supply by 2020 or 2030 dramatically changes the landscape of long distance transmission. Such large fractions of renewable power often are not found within a 100 miles of urban load centers, and community concern about visual esthetics creates barriers to installation of the large scale wind or solar plants needed to supply such population centers. Rooftop photovoltaics can alleviate some of the need for long-distance transmission, but often at a higher cost than wind or concentrating solar power, and with smaller but significant esthetic concerns. Renewable portfolio standards and the development of large-scale wind and solar resources require a significant investment in raising the capacity and efficiency of long-distance electricity transmission. This long distance transmission challenge is exacerbated by the historically low investment in transmission in the U.S. From 1988–1998 electricity demand grew by 30% while transmission increased by only 15%. From 1999–2009 demand grew by 20% and transmission by only 3%.[38]

Direct Current Transmission Options

The looming investments in long distance electricity transmission justify a close look at the technology choices available to meet the need. Electric power is proportional to the product of current and voltage, while losses are proportional to the square of current. Raising voltage and significantly lowering current reduces losses when transmitting high power over long distances requires. For example, the largest high voltage direct current transmission project, the Xiangjiaba line terminating in Shanghai, China, operates at 800 kV and delivers 6 GW of power over 2000 km.[39] Such high voltages strain the capability of semiconductor power electronics to interconvert between AC and DC, driving up the cost and limiting the penetration of conventional DC technology. The losses in such a long DC transmission line can be as high as 10%.[40] While high voltage DC is the preferred transmission mode for long distances, there are drawbacks to implementing it for renewable electricity transmission. It requires a single point of origin and termination, precluding wide area DC collection and end user distribution schemes. In addition, the high voltage requires expensive and technically challenging conversion by semiconductor power electronics between AC and DC, and

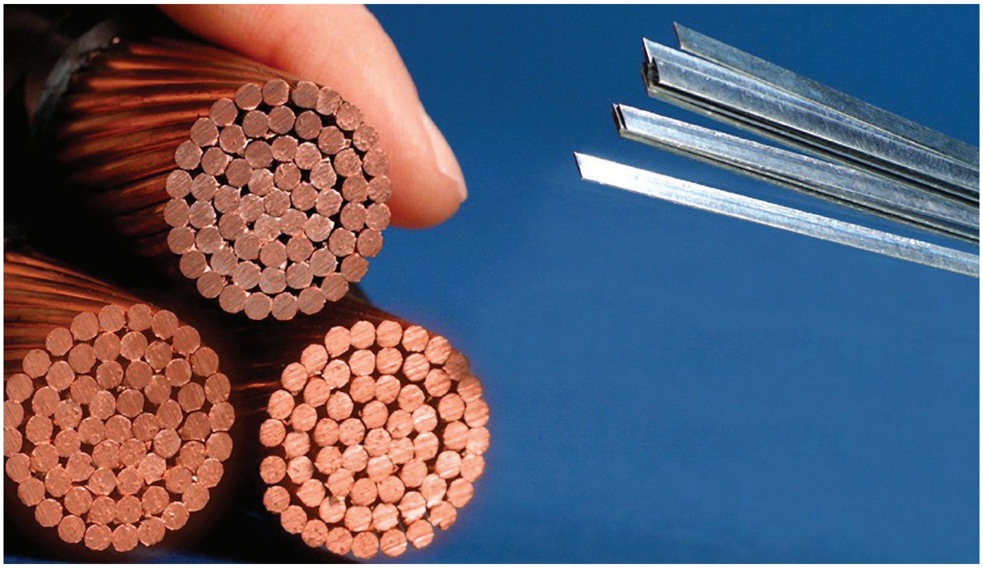


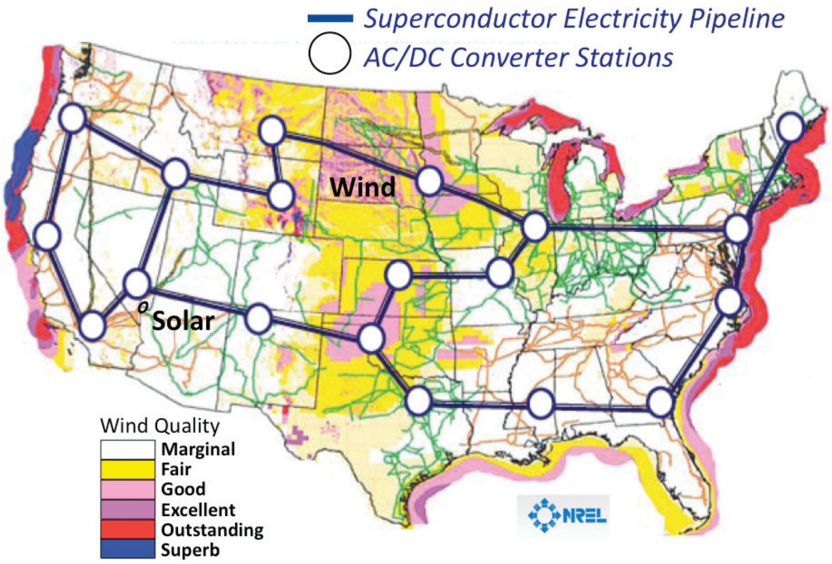
Figure 10.
Superconducting cables made from tapes like those shown on the right carry up to five times the power of conventional copper in the same cross sectional area. (Courtesy of American Superconductor)

it requires unsightly towers and substantial right of way that can take a decade or more to gain approval in all the relevant—but uncoordinated—regulation zones. Despite these drawbacks, conventional high voltage DC transmission is a mature technology that can be implemented to meet renewable electricity transmission needs over moderate distances. Additional high voltage DC transmission within one- or two-state regions is needed to link regional renewable electricity sources to population centers.

Underground superconducting DC transmission lines are an emerging option that offers a potential route to a national renewable electricity transmission system.[41, 42, 43, 44] Superconducting DC lines operate at zero resistance, eliminating electrical losses for any transmission length. Because they eliminate loss and produce no heat, superconductors carry much more current and power than conventional conductors (see Figure 10). Without losses to minimize, there is no need to raise voltage and lower current to extreme levels. Operation at 200 kV–400 kV enables multi-terminal "entrance and exit ramps" that collect power from several wind or solar plants and deliver it to several cities as it makes its way east or west. Recent feasibility studies by EPRI show that superconducting DC transmission lines carrying 10 GW of power 1600 km can be integrated into the grid, while maintaining transient and short term voltage stability.[45]

While superconducting DC cables have no electrical losses, they require refrigeration to maintain tham at superconducting temperatures, often to the point of liquid nitrogen, 77 k. Technology development of refrigeration systems and dielectric for electrical insulation that operate effectively at these temperatures are needed to lower the cost of long-distance superconducting transmission. Superconducting DC transmission couples naturally with superconducting magnetic energy storage (SMES), where electrical energy is stored in superconducting magnets with low loss, deep discharge capability and fast response time. The potential synergies of DC superconducting transmission and SMES are promising and remain to be evaluated. Laboratory demonstration of DC superconducting cable has been carried out at Chubu University in Japan.[46] A proposal for a DC superconducting electricity "pipeline" is shown in Figure 11.

Figure 11.
The proposed DC superconductor electricity pipeline for carrying large amounts of renewable power long distances. This network provides an interstate highway system for electricity. (Image courtesy of American Superconductor.)



Long distance transmission offers a partial solution to the variability challenge of renewable energy. Balancing generation with load typically takes place within a local or regional balancing area with sufficient dispatchable conventional resources to meet load fluctuations. Aggregating wind power over many wind plants substantially increases reliability and decreases fluctuations, reducing the need for conventional reserves and lowering cost.[47, 48, 49, 50]

The complexity of balancing over large areas with many generation and load resources eventually limits the size of the balancing area. Even in this case, however, long distance transmission plays a role. Generation excesses and deficits across the country can be anticipated by forecasting and matched over long distances to balance the system. An excess of wind power in the upper central US might be balanced by transmission to a power deficit in the East. Under these conditions specific excesses and deficits are identified and balanced much like conventional generation is switched in or out to balance load at present. With adequate forecasting, such specific opportunities can be identified and arranged in advance and executed dynamically as the situation develops.[43, 44] This distant generation balancing requires additional high-capacity long distance transmission that is operator controllable by power electronics, allowing excess generation in one area to be directed to specific targets of deficit far away, instead of getting sidetracked in the grid by local conditions

Urban Power Distribution

Urban distribution capacity remains a significant challenge to the user side of the grid. Congestion of power lines in cities and suburbs and the high cost and long permitting times needed to build new lines could all hold back increasing the use of renewable electricity. However, the use of superconducting AC cables that carry five times the current of conventional cables in the same cross-sectional area could solve this problem. Three demonstration projects in the US have used superconducting AC cables to deliver electricity in the grid, proving that this approach is technically sound. For example, the Long Island Power Authority has relied on a superconducting underground AC cable to deliver 574 MW of power since 2008. Replacing key conventional cables in urban grids with superconducting counterparts would provide sufficient capacity for decades of growth without the need for new rights-of-way or infrastructure.[51]

Although the performance of superconducting cables far exceeds that of conventional cables, the cost is still too high to achieve widespread penetration. Research and development is needed to bring this technology to the commercial tipping point. Despite the promise of superconductivity for renewable electricity transmission and for urban power distribution, DOE's Office of Electricity Delivery and Energy Reliability (OE) program for research into high temperature superconductivity for electric applications will be eliminated in 2012.

Recommendations:

DOE should:

- Extend the DOE/OE program on High Temperature Superconductivity for 10 years, with focus on DC superconducting cables for long distance transmission of renewable electricity from source to market; and
- Accelerate R&D on wide band gap power electronics for controlling power flow on the grid, including alternating to direct current conversion options and development of semiconductor-based circuit breakers operating at 200 kV and 50 kA with microsecond response time.

The Business Case

Utility renewables investments are typically assessed from the regulatory, project finance and technical perspectives. The regulatory assessment focuses on ensuring utility compliance with renewable portfolio standards (RPS), and that imprudent cost overruns are avoided. . The project finance oversight looks at economic merits of the investment within discrete funding and cash flow boundaries exclusive to the project under review. The technical assessment evaluates project's engineering and operational risks and the specific technologies involved.

While these conventional views are important for the investors, utilities, regulators and ratepayers, they do not fully capture the set of benefits that a renewables investment can deliver beyond the boundaries of a given project. Accounting for these additional benefits in an expanded business case can enhance the profile of the renewables investment, but more importantly, such an evaluation will recognize the synergies inherent in the integration of renewables with the grid.

Significant Value at Stake

Before discussing the current structural challenges that prevent the full accounting of value created from the integration of renewable energy and the grid, it is important to outline the benefits that are delivered and those typically overlooked.

Understanding of the benefits of combining centralized and distributed renewable energy is in its early stages.

Through a number of recent studies to assess different value drivers associated with grid integration, the Department of Energy (DOE), along with several national labs, is beginning to understand the value of renewables on the grid. Because grid-based large-scale storage is in its infancy, there is limited knowledge and a cautious approach remains when extrapolating potential benefits from pilot, one-off projects, to larger scale deployment on the grid.

However, as the deployments continue and grow in penetration, as technology improves significantly for hardware and in power electronics, and as software and information technology is created to derive further value from the integration of renewables into the grid, there is growing confidence in the nature and size of benefits that can be generated.

There are a number of benefits at stake, which can be synthesized into several key areas:

- Flexibility in generation that can lower overall system peak consumption requirement
- Distributed generation that goes beyond peak reduction to overall consumption reduction
- Addition of storage of renewables increases the capabilities in managing peak and overall energy consumption
- Additional grid stability with the capability to provide ramp-up/ramp-down of power
- Distributed generation that helps maintain local supply continuity

A variety of secondary and tertiary benefits is also generated, but may be less certain at this point. These benefits will become clearer as deployments of both centralized and distributed renewables generation increase.

Current Challenges

A number of challenges continue to drive a more narrow view of the value of renewables benefits. Some of these challenges are driven by the structure of the utilities and renewables industry, while others reflect the lack of knowledge—given the early stages of the industry—that the industry has in technically integrating and seamlessly operating renewables into the grid. The key factors include:

- *Beyond the grid boundary:* renewables projects are typically seen as generation projects and, therefore, the value they bring to the grid is not seen as a primary benefit

- *Uncertainty on what the benefits are:* there are significant challenges in actually estimating the benefits that an intelligent connection from a renewable into the grid delivers. This requires a complicated engineering and financial analysis involving power markets, storage potential, time shifting of usage, peak consumption reductions and the consequences on prices paid. This enters a level of complexity with many unknowns.

- *The mandatory "game":* The mandatory nature of RPS often negates the need to account for the full benefits that a given project delivers. As long as project economics work the project is justified. The corollary to this is that utilities and renewables developers often perceive the actual integration as an exercise in justifying the rate basing of enabling equipment (such as inverters, instrument transformers, and back-up generation). In addition, many stakeholders (e.g., regional transmission operators) view system investments to enable integration as critical to maintaining system stability; hence, investments are made based on risk/consequence rather than with an understanding of the financial upside

- *Too theoretical:* Given that technologies are still developing and industry experience is still limited, skepticism is common and many view these benefits as too theoretical. To date, the focus has been on getting renewables to run well operationally rather than on the full benefits that the grid integration can deliver.

These challenges are preventing the inclusion of value that is generated by integrating renewables with the grid.

The Importance of Uncaptured Benefits

Appropriately accounting for the full benefits that renewables can deliver strengthens the case for the renewables investments and their integration with the grid. Key factors important to consider include:

- *Achieves a strengthened net present value:* as additional sources of value beyond the project boundaries are incorporated, the overall net present value of the project is enhanced. The value of renewables to both the generation and the transmission and distribution sides of renewables investments can be captured.

- *Brings a broader set of stakeholders into alignment:* pushing to assess and include the benefits to *both* the grid and the generation side will also help push alignment across multiple stakeholders which include regulators, utilities, developers, cogeneration, commercial and industrial customers, and ratepayer groups. A number of stakeholder groups have conflicting views on the costs of renewables and who and how to pay for these investments. Defining the additional sources of value should help create additional ground for agreement across stakeholder groups.

- *Creates an important fact-base:* by bringing attention to the additional benefits that can be included into the broader renewables business case, an important fact-base is created which goes a long way to mitigate the skepticism around both the sources and estimation of value from renewables and grid integration

- *Develops an integrated picture:* bringing the generation and the transmission and distribution aspects into a single view unifies the operation of the grid with distributed resources such as non-centralized wind-based renewables. This is a key issue given the significant discussion taking place on the utility of the future, and the role of distributed generation and renewables.

Documenting these benefits spans both hard benefits—such as net present value—and soft benefits such as developing an integrated picture. All these benefits are important and are collectively required to enhance the capabilities of the grid.

Recommendations:

The Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) should:

- Develop an integrated business case that captures the full value of renewable generation and electricity storage in the context of transmission and distribution; and

- Adopt a uniform integrated business case as their official evaluation and regulatory structure, in concert with the state Public Utility Commissions (PUCs).

Conclusion

The demand for carbon-free electricity is driving a growing movement of adding renewable energy to the grid. Renewable Portfolio Standards mandated by states and under consideration by the federal government envision a penetration of 20-30% renewable energy in the grid by 2020 or 2030. The renewable energy potential of wind and solar far exceeds these targets, suggesting that renewable energy ultimately could grow well beyond these initial goals.

The grid faces two new and fundamental technological challenges in accommodating renewables: location and variability. Renewable resources are concentrated at mid-continent far from population centers, requiring additional long distance, high-capacity transmission to match supply with demand. The variability of renewables due to the characteristics of weather is high, up to 70% for daytime solar and 100% for wind, much larger than the few percent uncertainty in load that the grid now accommodates by dispatching conventional resources in response to demand.

Solutions to the challenges of remote location and variability of generation are needed to meet the Renewable Portfolio Standards now in place in 30 states and the District of Columbia. The options for DC transmission lines, favored over AC lines for transmission of more than a few hundred miles, need to be examined. Conventional high voltage DC transmission lines are a mature technology that can solve regional transmission needs covering one- or two-state areas. Conventional high voltage DC has drawbacks, however, of high loss, technically challenging and expensive conversion between AC and DC, and the requirement of a single point of origin and termination. Superconducting DC transmission lines lose little or no energy, produce no heat, and carry higher power than conventional lines. They operate at moderate voltage, allowing many "on-ramps" and "off-ramps" in a single network and reduce the technical and cost challenges of AC to DC conversion. A network of superconducting DC cables overlaying the existing patchwork of conventional transmission lines would create an interstate highway system for electricity that moves large amounts of renewable electric power efficiently over long distances from source to load. Research and development is needed to identify the technical challenges associated with DC superconducting transmission and how it can be most effectively deployed.

The challenge of variability can be met by switching conventional generation capacity in or out in response to sophisticated forecasts of weather and power generation. This can be done by large scale energy storage by heat; by pumped hydroelectric or compressed air: by stationary batteries designed for the grid, or by national balancing of regional generation deficits and excesses using long distance transmission. Each of these solutions to variability has merit and each requires significant research and development to understand its capacity, performance, cost and effectiveness. Variability is likely to be met by a combination of these three solutions, and the interactions among them and the appropriate mix needs to be explored.

The long distances from renewable sources to demand centers span many of the grid's physical, ownership regulatory boundaries. This introduces a new feature to grid structure nd operation: national and regional coordination. The grid is historically a patchwork of local generation resources and load centers built, operated and regulated to meet local needs. Although it is capable of sharing power across moderate distances, the arrangements for doing so are cumbersome and inefficient. The advent of renewable electricity with its enormous potential and inherent regional and national character presents an opportunity to examine the local structure of the grid and establish coordinating principles that will not only enable effective renewable integration but also simplify and codify the grid's increasingly regional and national character.

Case Study: New York State

New York State serves as a microcosm of the nation's renewable energy challenges. New York faces significant transmission challenges with its renewable resources largely upstate and consumption largely downstate. There are substantial power congestion challenges near dense population areas. By executive order, New York has mandated an 80% reduction in greenhouse gas emissions by 2050, goals that are not atypical. New York's Renewable Portfolio Standard calls for an aggressive 30% renewable electricity penetration by 2015. All paths toward meeting these goals require significant electrification of the state's energy portfolio including light vehicle transportation.[52] Replacing fossil fuels for transportation with electricity is an effective carbon mitigation strategy provided the electricity is generated from renewable sources.

In 2008, New York's electricity consumption was 166,547 GWh, corresponding to an average power consumption of 19 GW and a summer peak consumption of 34 GW.[53] The summer generating capability in New York in 2009 was 38 GW with approximately 70% from fossil fuels.[47] In March 2009 the installed wind nameplate capacity (the maximum designed output in strong winds) in New York was 1.275 GW,[47] with a winter rating of 30% of nameplate capacity and a summer rating of 10% of nameplate capacity.[47] There are approximately 4.5 GW of hydroelectric power in the state.[54] The challenge is clear: to meet 10% of New York's electricity consumption with wind (hydropower, biomass and solar can supply the remaining RPS) requires 1.9 GW of wind electricity or 9.5 GW of nameplate capacity, about 7.5 times the current installed capacity. New York's aggressive renewable energy goals are consistent with its leading position on energy—in 2008 it was the second most energy-efficient state on a per capita basis, accounting for 4.1% of the nation's energy footprint despite having 6.4% of the nation's population.[55]

New York is ahead of much of the nation in having significant energy storage capability including two pumped hydro facilities providing 1.3 GW[47] and development of compressed air energy storage (CAES) of about 150 MW is under way.[56] The "spin-up" times of energy storage, about two to three minutes for pumped hydro and about 10 minutes for CAES, allow quick response to renewable generation variability; fossil fuel powered turbine startup times are somewhat longer, 20–30 minutes. However, pumped hydro and CAES are not broadly deployable. The scale of renewable generation envisioned will require significantly enhanced storage, possibly from utility-scale conventional or flow battery installations, and from distributed systems such as community storage, home storage, and plug in electric vehicles. The system management issues include forecasting renewable generation and balancing it with demand using reserves and storage.

The geographical separation of renewable generation from consumption is compounded by transmission system congestion during times of peak load; both challenges require significant investment in transmission. Although it is not discussed in this report, New York has significant investments in smart grid infrastructure through the recent Smart Grid Investment Grants and Smart Grid Demonstration Projects that will promote the integration of storage, forecasting, and transmission advances as they mature. These investments are laying the groundwork for demand management, two-way communication (which also enables distributed storage management), better demand prediction and control, and the potential for enhanced monitoring of the distribution and transmission systems.

Like the nation, New York has ample renewable resources to meet its renewable portfolio standards. The challenge is not capacity, but implementation: developing technology to harvest the plentiful renewable resources, operating procedures to integrate them on the grid, and regulatory structures to ensure that the grid is reliable and that value and cost are shared appropriately among stakeholders. The remote location of renewable energy resources and their high variability requires a new level of wide-area coordination across traditional physical, ownership, and regulatory boundaries. Developing the necessary technological, operating and regulatory structures to address these integration challenges is the major energy task for New York and the nation in the coming decades.

Endnotes

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