The Role of Demand-Side Resources in Integration of Renewable Power

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ABSTRACT

This paper explores the potential match (and some mismatches) between variable renewable power production and a range of demand-side resources, including demand response, demand-side storage and peak load- (or renewable nadir-) coincident energy efficiency. To understand the potential contributions and limits of the demand-side resources, and explore strategies to blend them in integrated resource portfolios, we study a range of renewable integration challenges.

We characterize the renewable integration problems in terms of under-generation (too little wind and solar resource relative to load), over-generation (too much wind or solar resource relative to load), and ramping rates (too fast a change in load net of renewable production). We explore the time dynamics of energy available from demand-side resources and evaluate their potential for balancing variations in load and renewable output.

Introduction

Building energy loads are the main resource for electric demand-side management, via energy efficiency and peak load shifting by utilities. To what degree can this demand-side resource also enable deployment of renewable energy generation on the supply side, to further reduce fossil fuel use and emissions from power generation?

The combined time variations of customer loads (mostly heating and cooling buildings) and large renewable power flows will require a substantial increase in the flexibility of the power grid to provide adequate balancing capability to maintain system reliability. Demand-side resources can contribute reliable balancing, by decreasing or postponing power demand when needed. Some demand-side resources (heating or cooling via thermal storage) can also provide flexible load to increase demand when needed to avoid curtailment of renewable sources.

Growth of Renewable Generation

Renewable generation capacity is growing at a dramatic rate and can be expected to continue to grow, including in regions where there has been little development to date. Twenty-nine states plus the District of Columbia have some form of mandated renewable energy standard or renewable portfolio standard (RES/RPS). These standards require utilities to produce or purchase, on behalf of their customers, electricity generated from new, renewable sources to meet or exceed the standard, which is usually expressed as a share of total electricity sales (Wiser & Barbose, 2008).

Existing RES/RPS rules mandate over 30,000 MW of new renewable power by 2020, and over 50,000 MW by 2025.[1] These increments are additions to about 45,000 MW of renewable

[1] Some RES/RPS rules include allowances for energy efficiency and other non-fossil resources, which have been subtracted out to obtain our estimate of mandated new renewable capacity.

capacity existing at the beginning of 2012 (AWEA, 2012). Because of the present cost advantage of wind power compared to solar and other non-hydro renewable sources, wind turbines are expected to produce most of the energy to achieve RES/RPS targets.

Some states set aside specific portions of their RES/RPS requirement solar power. These will require over 1,000 MW of solar generation by 2020 and close to 2,000 MW by 2025 (Wiser, Barbose & Holt, 2010). Some states have voluntary standards or targets, such as California's "Million Solar Roof" program, that could result in the installation of additional solar capacity. If solar costs continue to fall to the point where a kWh of solar generation is closer in cost to one from wind, then a share of the RES/RPS compliance will shift from wind to solar power.[2]

Variation of Renewable Power Production

The emerging, renewables-rich generation fleet will increase the need of utilities and grid operators to balance the time-varying output of renewable sources without curtailing them. The power system already responds to time-varying load, and the flexibility requirements of renewable generation is similar but not identical to the existing reserve capacity and ancillary services that are used to balance load variation.

With growing renewable generation, sufficient flexibility will be needed to respond to the variations and uncertainties of *both load and variable generation*. Note that variability is the expected change in generation and demand balance (e.g., load changing throughout the day and wind power resource change), *while uncertainty is the unexpected change* in generation and demand balance from what was anticipated (e.g., a contingency or a load or variable generation forecast error). Both load and renewable output exhibit substantial variability that can be forecasted with limited, but improving, precision, which is the source of uncertainty.

Therefore, the combined time variations of customer loads (mostly from heating and cooling buildings) and large renewable power flows require flexibility in the power grid to balance this variability. A convenient definition of flexibility is the ability of a resource to respond to changes in *net load* (load minus must-run sources) in a given timeframe. Such changes can be measured in terms of the *ramp rate* (change in net load MW per minute), *its direction* (up or down), the *duration* (i.e., total ramp range), and the *frequency of use*.

Flexibility in the Power Supply System

Adequate flexibility is essential to maintain system reliability. By definition, there is sufficient flexibility today, as the power system responds to load variations and maintains high reliability. Power markets and grid operation currently recognize certain types of flexibility as ancillary services. These services range from frequency regulation, which is triggered instantly and automatically in response to system variation, to spinning reserves and supplemental reserves, which are activated in case of unplanned contingencies such as a plant outage.

The existing generation that provides intermediate and peaking capacity, which must cycle on and off and ramp up and down as the market or load demands, also generally provides sufficient load-following and ramping capability. However, power market rules tend not to value this capability, as there is no separate ancillary service or capacity market for ramping. Rather, it

[2] If so, the total renewable generation capacity would have to increase to account for the lower annual capacity factor (average power output / rated output) of solar compared to wind.

is considered inherent in the (mostly hydro and gas-fired) generation capacity that is already available for other needs.

In particular, in regions with sub-hourly (5- 10- or 15-minute) energy markets, such as those with an independent system operator (ISO), normal variation in load or generation (not counting contingencies) can be managed at low cost by buying or selling power in the market for a given time period. In regions without an ISO or a fast energy market, including much of the Western U.S., generation is typically arranged on an hour-ahead basis, such that variability in load or generation must sometimes be met with fast, but costly, regulation service. Incremental load or generation forecast errors, for example from renewables, only add to this inefficiency.

Compared to regulation, (spinning and supplemental) contingency reserves are slower and cheaper. Substantial contingency reserves exist, generally over 10% of peak demand, to back-up large central steam plant capacity. In general, significant solar or windpower ramp "events" are relatively infrequent, non-instantaneous, and thus more like contingency events, although they can be predicted to some degree in weather forecasting. Thus, variable renewables do not demand ramping capability that is faster than, or even as fast as, contingency reserves.

Flexibility Required to Balance Growing Renewable Generation

Because variation in renewable generation is not as fast as regulation services, and more predictable than contingency reserves, increasing renewable generation need not impose new requirements for these traditional ancillary services. Studies of renewable integration conclude that such needs can be modest provided that grid operators have access to (GE Energy, 2010):

- State-of-the-art forecasts of weather, load and renewable production,
- Fast (sub-hourly) scheduling, such as that provided under most ISOs,
- Enlarged balancing areas where generation sources are combined,
- Adequate power transmission, and possibly,
- Renewable power technology with the ability to self-provide frequency regulation.

Assuming the above conditions will be met, the flexibility required to balance growing renewable generation is mostly relatively slow, predictable capacity to provide (net) load following and ramping. The main requirements of resources that provide this flexibility are therefore analogous to the qualities that define ramping:

- Availability when needed to balance net load variation
- Adequate ramp rate when needed
- Ability to ramp in the needed direction (up or down),
- Sufficient duration during the time needed
- Sufficient frequency of use throughout the year

To summarize, the criteria to evaluate resources for balancing variable renewable generation are somewhat more complex than for meeting electric demand generally. The resource must be available, with the ability to ramp up *or possibly ramp down*, at the specific times needed, based in variations in both load and renewable energy production, and it must be able to operate with sufficient duration and frequency.

Flexibility Resources on the Demand Side

Given the magnitude and diversity of demand-side resources, it is reasonable to expect that they can contribute reliably to ramping and balancing renewables, by decreasing power demand or shifting it in times as needed. Demand-side resources such as some types of demand response and demand-side thermal storage can also provide flexible load to *increase demand when needed* to avoid curtailment of renewable sources, such as occurs at times with windpower in Texas. In one Texas event, a combination of steeply declining windpower output and forecast errors caused a severe system imbalance that was remedied partly by deploying curtailable load (Ela & Kirby, 2008).

Recent studies of wind integration options find that, for example, "responsive load would be easily justified as an economic option to help manage variability." (Milligan, et al, 2009) Similarly, the North American Electric Reliability Council (NERC) conclude that "flexible resources, such as demand response, plug-in hybrid electric vehicles, and storage capacity…may help to balance the steep ramps associated with variable generation." (NERC, 2009) A more cautious view of the demand-side resource and its underlying building loads reveals that this resource has a wide variety of capabilities, some of which fit the need for renewable integration better than others.

To explore the potential match (and some mismatches) between variable renewable power production and demand-side resources, we consider a range of demand-side management (DSM) options. The objective here is to assess the degree to which each category of DSM resource helps solve the load-balancing "problem" and thereby avoids use of supply-side resources such as combustion turbines or standby diesel generators to balance renewable generation growth. The relevant demand-side resources can be characterized as:

- Energy efficiency, which is peakload- (or renewable nadir-) coincident
- Demand response and load management to moderate peak (net) load
- Demand-side energy storage, to shift loads in time

Energy Efficiency

Of course, the most important demand-side resource is energy efficiency. Utilities across the country are conducting efficiency programs that represent a significant resource for meeting customer energy service demand, i.e., this resource replaces supply-side resources in the form of generation plants (and sometimes transmission lines) that do not need to be sited, built, operated and fueled. Many such programs are scaling up to deliver increased "negawatts" of energy savings, including in regions such as the South that mostly dismissed efficiency until recently.[3]

On the other hand, efficiency is generally not regarded as a practical option for addressing time-dynamic problems such as balancing variable renewable generation. The reason is that efficiency is not dispatchable, i.e., it cannot be called on to increase its capacity at a given time. Therefore, when a wind forecast error arises in real time, the presence of efficient lighting hardware in the utility's service territory will not help. Efficiency is not an active resource to

[3] The term "negawatt" was originally a typographic error in a Rocky Mountain Institute document that was then recognized as a useful moniker for efficiency as a resource.

balance renewables in real time or the short time horizon of grid operations, for example by providing this ramping capability.

Efficiency can contribute, however, to balancing renewables in the longer time frame of resource planning. This contribution can occur when specific loads can predictably add to the net load, which must be met by dispatchable supply resources, during time periods when variable renewable production will be relatively low. Reducing such loads with efficient end-use technology helps balance the variation in renewable production during these times.

Demand Response

Demand response (DR) is typically used to moderate peak loads that strain the power supply system. Thus, DR is a dispatchable resource that has potential to help balance variable renewable output. Instead of, or in addition to, deploying the DR resource when system load is at its peak, the resource is called when the net load, i.e., load net of variable renewable generation, is especially high, thus relieving the load on (non-renewable) dispatchable generation. Some programs that rely on the dispatching of customer-sited standby generators are considered as DR, because their net utility loads are decreased, but we do not consider such programs here.

Demand response programs are a common resource for managing peak demand among utilities in the U.S. and abroad. Direct load control programs, for example cycling water heaters or air conditioners during peak periods, have been in widespread use for decades. Time-of-use (TOU) pricing is also common, although true price-driven DR seems to require stronger signals, such as critical-peak pricing (CPP) that has been tested by a number of utilities. A CPP program can be especially effective when supported by automated load control technology, and this enabling technology is also effective in enabling incentive-driven DR where the events are triggered directly by signals from the utility (Swisher, Wang & Stewart, 2005).

Existing DR programs are conducted by various utilities and employ a range of technical and program approaches. Most DR programs involve curtailment of air conditioning loads during peak periods, although some also address lighting, refrigeration and other electric end uses. Most DR programs have been shown to be effective in limiting peak demand. In some DR programs, demand rebounds strongly at the end of the DR event period, as comfort conditions are restored, sometimes even exceeds the baseline peak demand level.

DR programs using automated technology have performed particularly well (Piette, et al, 2008). Moreover, some aggregators of demand-response resources can automate remote control, dispatch and monitoring of their operation on behalf of the utility.[4]

The literature on DR suggests that the total potential for peak load reduction is large. A recent study commissioned by the Federal Energy Regulatory Commission (FERC) estimated an achievable potential of 100 GW, or 11% of projected peak demand, assuming no other energy efficiency or load management measures, by 2019 (Brattle Group, et al, 2009). This estimate is based on a scenario where advanced metering is universal, and at least 60% of customers have enabling technologies (e.g., programmable, communicating thermostats) and are subject to time-dynamic pricing.

The application of DR to the integration of variable renewables is being studied in depth by LBNL, which has evaluated both time-differentiated price-driven DR and incentive-based DR programs. The LBNL authors note that earlier studies tended to “assume that DR is generally

[4] See, for example, www.enernoc.com

able to deal with integration issues that have short advance notification periods, reasonably lengthy durations and relatively frequent events," all of which would enhance the value of DR but might not be realistic (Cappers, et al, 2011).

In particular, LBNL finds "limited ability for time-based rates to affect integration." They suggest that incentive-based DR programs, such as direct load control and curtailment programs, could provide short-duration ramping and load-following, subject to limitations of customer acceptance regarding the frequency of the DR events. The LNBL study also identifies needs for enabling technology (beyond automated metering), as well as extensive marketing, incentives and customer education to deliver sufficient customer response.

Demand-side Thermal Energy Storage

Thermal energy storage typically employs conventional cooling equipment in conjunction with a thermal mass (a material with high thermal capacitance, such as water, ice, or eutectic salt), to store cooling energy generated during off-peak hours, usually at night and early morning. During peak afternoon hours, the stored thermal energy is released to meet cooling loads in place of the installed chiller or unitary air conditioning equipment. This cooling function requires the operation of small pumps only, rather than power-intensive vapor-compression air conditioning equipment. Thermal storage thereby provides the same cooling energy with a minimum of peak-coincident electricity demand.

Much of the early research and development on thermal storage addressed large central chiller plants, based on the assumption that economies of scale would be necessary to deliver adequate economic performance (EPRI, 1985). Recently, viable thermal storage systems have been developed for application to the smaller and far more numerous unitary air conditioning units. These air conditioning systems, which are typically sized in multiples of 5-kW units, are used in the vast majority of office, retail, education, and hotel and restaurant buildings. In addition, control and dispatch of distributed storage can be managed remotely via a two-way communication network and smart grid control system to enable a utility to bundle many such units as a single resource.[5]

Thermal storage can also be used with heating applications to shift peak winter heating loads. In such cases, thermal energy is stored during off-peak hours in heated rocks and then retrieved to meet peak-coincident heating loads.

Comparison of Load-shifting Resources

Table 1 compares the operational and performance characteristics of three types of load-shifting resources. The energy storage technologies have similar properties in terms of performance, and their main difference is in efficiency. Thermal storage performance is similar to that of DR programs, in terms of their ability to reduce customer loads during times of maximum demand. The fundamental difference between thermal storage and DR is that DR generally causes some impact on customer comfort or convenience, most commonly a temporary loss of comfort from the curtailment of heating, air conditioning or lighting.

[5] See, for example, www.ice-energy.com

Table 1. Comparison of Energy Storage and Demand Response Programs for Load Shifting

Characteristic	Supply Side Electric Storage	Demand Side Thermal Storage	Demand Response
Impact on customer comfort or amenity	No impact	No impact	Comfort declines with greater frequency, duration
Impact on end-use efficiency	No impact	Efficiency improves due to lower night-time temperature	Little efficiency gain, but some net energy savings from unmet load
Round-trip storage efficiency	70-80%	~100%	Effectively 100%
Frequency	No limit	No limit (subject to heating/cooling usage)	Usually maximum of 10-25 events per year
Availability, duration	Available daily, duration depends on sizing	Available at least 6 hours/day when heating/cooling is used	Available 2-5 hours, may decline if called on consecutive days
Recovery	Storage recharge can be late at night, clearly off-peak	Storage recharge can be late at night, clearly off-peak	Recovery of thermal comfort increases energy use directly after DR event
Annual hours of operation	600-1800	600-1200	50-125
Dispatchability	Can be dispatched quickly anytime, subject to capacity limits	Can be dispatched daily, designed to run continuously 6+ hours	Can be dispatched quickly anytime, subject to frequency, duration limits

This potential discomfort limits the DR resource in terms of frequency (how often it can be dispatched), duration (how long it can be dispatched on a given day, especially after consecutive curtailment days), and need for recovery (additional heat or air conditioning to restore comfort after the curtailment has ended). In contrast, thermal storage need not curtail heating or air conditioning and impact comfort. Therefore, the thermal storage resource is limited only by the amount of thermal energy that can be stored during the daily cycle, rather than by considerations of customer comfort.

Types of Renewable Integration Challenges

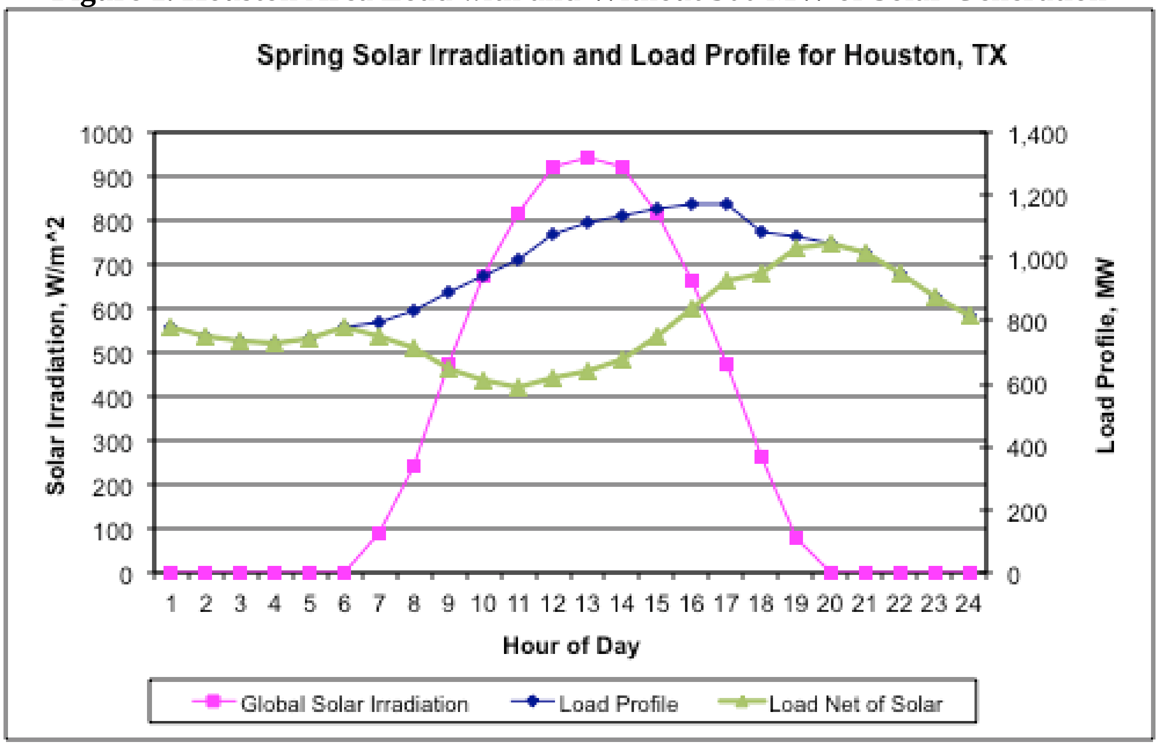
To understand the potential contributions and limits of the demand-side resources, we study a range of renewable integration challenges. First, we characterize the main renewable integration problems, based on the criteria developed above, in terms of the following categories:

- Under-generation (too little wind and solar resource relative to load),
- Over-generation (too much wind or solar resource relative to load), and
- Ramping rates (too fast a change in load net of renewable production).

Under-generation occurs when *net load*, i.e., system load net of renewable production, is relatively high. When renewable production is low, the load on the generation fleet is similar to the load that was experienced before much renewable capacity was connected. The difference today is that there may be less non-renewable generation capacity available, because renewable generation is considered to provide some capacity value that substitutes for conventional generation capacity.

Under-generation from a diminished wind resource can occur during any time of peak demand. The solar resource tends to correlate with system loads, so under-generation may occur in late afternoon or evening hours, even where the maximum peak load occurs earlier (Figure 1).

Figure 1. Houston Area Load with and Without 500 MW of Solar Generation[6]



Over-generation is very l*ow net load*. This condition requires coincidence of relatively strong renewable output when system load is relatively low, as renewable generation is unlikely to overtake load during peak periods. For solar generation, over-generation is most likely during morning hours, when the solar resource is already strong but the load has not yet reached peak levels (Figure 1). To date, there has been little incidence of solar generation being curtailed due to over-generation, although there has been concern about problems with specific distribution circuit in locations where distributed solar penetration is high such as Hawaii (Vonsen, 2011).

Already, wind generators are sometimes curtailed due to over-generation in some regions, especially where coal plants are the dominant off-peak source. Wind curtailment has been most frequent in the ERCOT (Texas) region, which currently produces about 7% of its

[6] Solar data are from TMY, 2009. Houston area load profile is adapted from load data in E3, 2009.

electricity from wind. In 2009, 17% of Texas' potential wind generation was reported as curtailed (Wiser & Bolinger, 2010). The specific conditions causing curtailment in Texas are partly related to transmission constraints, but the curtailment events occur when the system is operating at its minimum output level and baseload generation (mostly nuclear and coal-fired) cannot be ramped down further.

For example, the GE/NREL Western Wind and Solar Integration Study simulated generation dispatch with 30% wind penetration and 5% solar in Texas, which has a large share of inflexible nuclear and coal-fired steam plants in the generation fleet. In a "difficult week" with high wind and low load, the net load falls so low that all the gas-fired sources and much of the coal-fired generation would not be needed, resulting in the need to curtail windpower despite its advantages of zero fuel cost and emissions (GE Energy, 2010).

Ramping events are related to under- and over-generation in that they are caused by the same types of imbalance between load and renewable generation. However, ramping depends on the *relative rate of change in net load*, rather than the absolute level of renewable production, system load or net load. Strong wind ramps, for example, can increase or decrease output by 15% per hour pr 50% in 3-4 hours. If such a change occurs when load is also changing, but in the opposite direction, a ramping event occurs based on the *relative rate of change in net load*.

Wind ramping events are observed when the wind resource subsides suddenly during a time of increasing but not necessarily peak load. This condition usually occurs during mid-day, or when the wind accelerates as load is falling in the evening. Solar ramping events are less likely due to the correlation of the solar resource, but an event could be triggered by the sudden onset of heavy clouds when the system load is increasing during an otherwise warm day.

Renewable Integration and DSM

For each of the above integration problems, we explore the dynamics of energy available from DSM resources and assess their performance in balancing load and renewable variations.

Under-generation and DSM

The under-generation problem is the result of high net load, defined as load net of variable renewable generation. If the renewable portfolio is dominated by wind capacity, high net load corresponds to peak loads. This correlation is the result of wind output varying independently of load, such that minimum wind production can occur during times of peak demand. Even where the geographic variation of wind resources reduce the overall variability of the resource, its minimum production on a regional basis can still overlap with peak load.

Therefore wind under-generation is most likely during calm summer afternoons, and it can be balanced by ordinary demand response programs, where customer load is reduced by some combination of manual, automated or pricing-based adjustment of demand, when called by the utility. Similarly, energy efficiency programs that target energy end-uses that drive peak demand, particularly air conditioning in most U.S. climates, can help balance wind under-generation. The difference between the two resources in that efficiency provides a permanent load reduction that can be built into resource planning and load forecasting, while demand response provides a dispatchable resource that can be called when needed. In addition to demand response, demand-side thermal storage can provide a dispatchable load shifting resource.

Solar generation, on the other hand, tends to correlate with peak loads that are driven by air conditioning, although not perfectly. The solar resource tends to peak earlier in the day than summertime electric demand, but maximum net load can be delayed by solar generation. Solar under-generation is most likely during warm summer evenings in late summer, when days are warm but shorter in length, and the solar resource declines earlier in the afternoon than in June.

Reducing air-conditioning loads permanently through peak-coincident energy efficiency, or controllably with demand response or demand-side thermal storage, can offset the solar under-generation problem. This strategy is similar to the wind under-generation solution, except that the timing of deployment of demand response or thermal storage is likely to be different. Also, the amount of load available to shift, or to reduce via energy efficiency, may decrease as the time of net load peak moves farther from that of the original load peak.

Over-generation and DSM

The over-generation problem can be more complex. Over-generation is the result of low net load, defined as load net of variable renewable generation. In theory, solar over-generation is most likely during sunny spring or early summer mornings, when temperature-driven loads may be moderate but the solar resource is relatively strong early in the day due to the long day length at that time of year. The timing of wind over-generation is less predictable, but the observed occurrences appear to be concentrated mostly during windy nights in the late winter or spring, when loads are near their lowest levels of the entire year.

At these times, the demand-side solution to balancing the renewable resource variation would be to increase load. Clearly, energy efficiency is not relevant in this situation. Most demand response programs, which are designed to reduce peak loads, would have difficulty increasing loads as needed. Although some DR programs result in increased load during the post-event recovery, it would be difficult to plan and deploy a DR event with such precise timing that its recovery would match an over-generation event.

An exception would be situations where a building's thermal mass could be used by the demand control technology. For example, if the control system can over-cool an air-conditioned building, it would increase the morning load to absorb over-generation, and then moderate the peak demand later as the thermal mass discharges cooling to the conditioned space (possibly supplemented by additional demand response). Harnessing building thermal mass to balance renewable over-generation in the way would require advanced building controls, integrated with grid operations, on a large scale. Widespread deployment of smart grid technology might make this a possibility in the future.

Today, demand-side thermal storage may be able to address over-generation problems, by using the surplus electricity to charge the thermal battery, which can then reduce the electric load during discharge later. The use of thermal storage to balance over-generation would require that the corresponding thermal load (heating or cooling) occur predictably at sometime during the same day of the over-generation event, in order that the thermal storage battery can discharge and be available for the next cycle. This load need not necessarily occur during the over-generation event, only in the same 24- or 48-hour cycle and in a pattern that is predictable by the storage controller. The controllable, two-way load shifting ability of thermal storage is key.

Generation Ramping and DSM

The ramping rate problems are also complicated. The need for ramping upward results from a steep *increase in the net load*, due to a simultaneous combination of increasing load and falling renewable production. The need for ramping downward results from a *decrease in the net load*, due to a simultaneous combination of decreasing load and rising renewable production. To contribute to balancing these ramping problems, a demand-side resource must be available when ramping occurs, and it also needs to be able to deliver power capacity (ramping upward) or absorb capacity (ramping downward) in the needed direction and at a fast enough rate (in MW/minute) to balance the net load ramp rate.

To explore the renewable ramping problems, we consulted a series of NREL papers that are based on a detailed study, conducted by NREL and GE, of the integration of solar and windpower at high penetration rates in the Western Interconnection (roughly the western third of the U.S.). These studies show the coincidence of renewable production ramps with load ramps, allowing us to identify potential ramping problems.

With regard to solar, the need for ramping upward tends to peak during late afternoons in autumn and winter, when load increases as the solar resource diminishes (Lew, et al, 2010). With regard to wind, however, the need for ramping upward as load increases while the wind slows can occur during a variety of time periods, from winter in late afternoon to summer in later morning (Lew, et al, 2009). Not only is the resource variable, but the timing of its variability relative to load is uncertain. Thus, ramping upward would be difficult for most demand-side resources to provide, including thermal storage, which may not be capable of discharging when needed in the colder months.

Some demand response programs might be suitable to address the need for ramping upward, if the relevant load is active when ramping occurs, and it can deliver capacity and at an increasing rate (in MW/minute) to balance the net load ramp rate. The difficulty with this strategy is that demand response, although flexible, is generally tied to specific end-uses. Since the summer peak load is the typical target of DR programs, air-conditioning and refrigeration loads are the most common end-use application.

To reliably address the upward ramping problem for a wind-rich generation portfolio, demand response would need to be available year-round. Simple, mass-market air-conditioning cycling or curtailment programs would not be helpful. However, aggregators of automated demand response in the commercial and industrial sectors can harness year-round cooling and other loads that, even in the winter, may be able to deliver ramping to balance wind variations.

Finally, ramping downward tends to peak either during summer and autumn evenings, when load decreases rapidly as wind accelerates and, perhaps surprisingly, during winter and spring mornings, when load decreases somewhat as the solar resource increases (Lew, et al, 2009; Lew, et al, 2010). Like over-generation, ramping downward can be handled by demand-side thermal storage, but probably not as readily by demand response, if it is based on HVAC loads. For the case of wind ramping in the warmer months, thermal storage would appear to be helpful, if charging of the storage battery begins as the ramp occurs. It is unclear, however, if large numbers of thermal storage devices can be aggregated and dispatched fast and precisely enough to provide adequate ramping services.

Summary of Potential for Variable Renewable Power Integration

Based on this initial review of the match (or mismatch) between demand-side resources and renewable power balancing "problems," the potential for DSM to support the integration of variable renewable generation appears mixed. As noted earlier, the type of balancing needed varies across different time horizon horizons.

In the relatively long time frame of resource planning and load forecasting, energy efficiency for peak-coincident end-uses, particularly air conditioning, can contribute to balancing renewable under-generation, when net load would otherwise be elevated. The key limitation to the benefit provided by efficiency is that it can only reduce the load that would be active at a given time, i.e., when the under-generation is occurring. Therefore, the forecasted net load reduction from efficiency must account for the diversity of the affected load, as well as the degree of coincidence between that load, other loads and the renewable resource.

The most promising application of DSM to renewable power integration is in the relatively slow, predictable delivery of load following and ramping. Dispatchable DSM programs involving demand response or thermal storage are capable of balancing under-generation, which is driven by high coincident loads. Depending on whether the renewable generation portfolio is mostly wind or solar, the timing of deployment of DR or thermal storage would vary.

The main limitation of DR programs in this application is that the frequency of under-generation might exceed the limits of customer acceptance of the DR program, in which case only the most extreme under-generation events could be covered. Thermal storage is not subject to such customer-related constraints and could be applied to under-generation without a frequency limit.

As explained above, neither efficiency nor conventional DR are likely to be helpful in balancing over-generation, which is driven by relatively low coincident loads and the need to increase load by shifting it in time. An exception would be situations where a building's thermal mass could be used by the demand control technology, but this approach would require advanced building controls and integration with grid operations.

Thermal storage, on the other hand, is rather well suited to balancing over-generation, as the charging of the storage battery can increase load with flexibility in terms of its timing. The main limitation of this application is that the HVAC end-use must at least be active during the day of the event, although the timing need not coincide with the over-generation event.

Ramping, the rapid change of net load, appears to be more difficult for DSM resources to deliver. Ramping upward would be especially difficult for most demand-side resources to provide, because the resource may be needed year-round, including in the seasons when curtailment or shifting of heating or cooling loads is less feasible. There is potential for DR delivered by aggregators of large commercial and light industrial customers that have year-round cooling and other loads. Ramping downward would be difficult for conventional DR, but ramping in the warmer months could be handled by thermal storage, if charging of the storage battery can be controlled to begin as the ramp occurs.

Uncertainty in renewable power production can lead to sudden ramping events that are similar to the events for which contingency reserves are maintained by grid operators. If one assumes that load following and ramping capacity is provided to balance variable renewable sources, it is unclear if there will be much additional need for contingency reserves, beyond that needed to balance load variation. If so, these resources would have similar requirements as described above with regard to upward ramping, which would be difficult for DSM resources to deliver, with the possible exception of DR by aggregators of large commercial and light industrial customers.

Variable renewables are not expected to increase substantially the demand for fast frequency regulation services (Milligan & Kirby, 2007). Renewable technology vendors are working to embed the ability to deliver regulation in their products, and existing ancillary service markets have adequate regulation supply. In some power markets, such as the PJM (originally Pennsylvania-Jersey-Maryland, now expanded across the Midwest), allow demand response providers to bid into ancillary services markets. This can be an attractive market for aggregators of commercial- and industrial-sector curtailment services, where the aggregator can diversify across a large number of customers to maintain the contracted curtailment for the required duration.

Conclusion

There is clearly potential for DSM resources to contribute to integration of renewable power, especially in the slower-acting services involving annual resource planning and daily load following and ramping. Peak-coincident energy efficiency can help balance under-generation during periods of peak loads. Demand response has good potential to balance under-generation, subject to limits on event frequency, duration, and recovery, and possibly with upward ramping, where year-round participation is feasible. Thermal storage is more flexible, and it could provide a dispatchable resource throughout the year (as long as some HVAC load exists), balancing both under- and over-generation, and possibly contributing to downward ramping.

The potential for demand-side storage to complement DR in balancing renewable power seems significant. Although thermal storage can be expensive per kW of load shifted, compared to DR, it tends to be less expensive than supply-side storage (batteries, compressed air, etc.) and is more efficient. There are other demand-side storage resources that may contribute to future DSM resource portfolios. The potential to connect plug-in vehicles to the grid will add load, but it will also add a battery storage capacity that will be stationary (i.e., parked) 95% of the time. With smart control technology and incentives, this battery resource could also be harnessed to help balance variable renewable generation, as part of a so-called “Smart Garage” strategy (Swisher, Wang & Hansen, 2008).

These observations suggest that detailed modeling, which will be needed to explore the specifics of DSM balancing renewable power, also needs to consider the potential benefits and limitations of demand-side storage in detail. The timing of available HVAC loads for charging and discharging when needed, as well as the frequency and duration limits, need to be analyzed, all in the context of integration with a variable renewables-rich future generation fleet. And, of course, the relative economics of each resource portfolio must be evaluated and prioritized.

References

American Wind Energy Association (AWEA), 2012. http://www.awea.org/learnabout/industry_stats/index.cfm.

Brattle Group, Freeman, Sullivan & Co., Global Energy Partners, 2009. *A National Assessment of Demand Response Potential,* Federal Energy Regulatory Commission, Washington.

Cappers, P., et al, 2011. Mass Market Demand Response and Variable Generation Integration Issues: A Scoping Study, LBNL-5063E.

Ela, E. and B. Kirby, 2008. ERCOT Event on February 26, 2008. NREL/TP-500-43373. www.nrel.gov/docs/fy08osti/43373.pdf

Electric Power Research Institute (EPRI), 1985. *Commercial Cool Storage Design Guide*, EM-3981; and EPRI, 1993. *Space-Conditioning System Selection Guide*, TR-103329.

Energy and Environmental Economics (E3), 2009. National Time Dependent Valuation report, http://www.ethree.com/National_TDV.html

GE Energy, 2010. *Western Wind and Solar Integration Study*, NREL/SR-550-47781, at http://www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_final_report.pdf

Lew, D., et al, 2009. *How Do Wind and Solar Affect Grid Operations? The Western Wind and Solar Integration Study*, International Workshop on Large Scale Integration of Wind Power, http://www.nrel.gov/wind/systemsintegration/pdfs/2010/lew_wwsis_grid_impact.pdf

Lew, D., et al, 2010. Impact of High Solar Penetration in the Western Interconnection, NREL/TP-5500-49667, http://www.nrel.gov/wind/systemsintegration/pdfs/2010/lew_solar_impact_western.pdf.

Milligan, M and B. Kirby, 2007. Impact of Balancing Areas Size, Obligation Sharing, and Ramping Capability on Wind Integration, NREL/CP-500-41809, http://www.nrel.gov/docs/fy07osti/41809.pdf

Milligan, M., et al, 2009. Large-Scale Wind Integration Studies in the United States: Preliminary Results, International Workshop on Large Scale Integration of Wind Power.

North American Electric Reliability Corporation (NERC), 2009. Accommodating High Levels of Variable Generation http://www.nerc.com/docs/pc/ivgtf/IVGTF_Outline_Report_040708.pdf

Piette, M.A., D. Watson, N. Motegi, S. Kiliccote, E. Linkugel, 2006. *Participation through Automation: Fully Automated Critical Peak Pricing in Commercial Buildings*, ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA.

Swisher, J., K. Wang, and L. Hansen, 2008. Changing Course: Envisioning a New Electric Utility Paradigm, Power-Gen Renewable Energy & Fuels Conference, Las Vegas.

Swisher, J., K. Wang, S. Stewart, 2005. Evaluation of Automated Residential Demand Response with Flat and Dynamic Pricing, European Council for an Energy-efficiency Economy Summer Study.

Typical Meteorological Year (TMY), 2009. Data Version 3 available through the National Renewable Energy Laboratory available at http://rredc.nrel.gov/solar/old_data/nsrdb/.

Voosen, P., "As rooftop solar surges, states hit brakes," Greenwire, 12 December, 2011, http://www.eenews.net/greenwire/

Wiser, R. and G. Barbose, 2008. *Renewable Portfolio Standards in the U.S.*, Lawrence Berkeley National Laboratory, LBNL-154e, http://eetd.lbl.gov/EA/EMP/reports/lbnl-154e-revised.pdf.

Wiser, R., G. Barbose and E. Holt, 2010. *Supporting Solar Power in Renewables Portfolio Standards: Experience from the U.S.*, LBNL-3984e, http://eetd.lbl.gov/EA/EMP/reports/lbnl-3984e.pdf