Electricity Ancillary Services Primer

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Executive Summary and Observations – Electricity Ancillary Services Primer (August 2017)

The electric power grid is a complex system. Operators of power grids use a set of tools collectively referred to as "ancillary services" to keep the system precisely in balance between supply and demand in real time. For example, one type of ancillary services is "operating reserve," which represents excess power generation that could be made available within a few seconds or minutes to correct any imbalance that may unexpectedly arise over the course of a day. Additionally, operators use other ancillary service mechanisms to support frequency and voltage at specific levels to stabilize the grid.

The New England grid operator, ISO New England (ISO-NE), makes use of several ancillary service products, including operating reserves at both the 10- and 30-minute levels and frequency response mechanisms. In 2016, the cost to consumers in the region for these reliability mechanisms[1] was in total about $131 million, or less than 2% of the total cost of the wholesale market that includes energy and capacity payments.

As the power system evolves to include more renewables in the supply mix, some stakeholders have questioned the potential impact that intermittent generation, such as solar and wind, might have on the reliability of the grid. Conventional generators that possess inherent reliability characteristics are retiring, and variations in short-term supply from intermittent resources will likely increase as more wind and solar is developed. Early concerns about the potential need to make significant changes in grid operations to maintain reliability as renewable generation was added may have been overstated. In the last decade, power systems around the world have deployed increasing amounts of variable generation without significant impact on the real-time reliability. Even so, at some point, reliability in a power system with a very large penetration of intermittent resources may need to be enhanced through changes to planning and operations, which could include the expansion of ancillary services.

Just as New England has seen its share of renewables increase as a proportion of total supply, other electricity systems have already experienced even greater penetration of variable generation, including California and Texas in the U.S., and Germany, Great Britain and Denmark in Europe. These systems are exploring changes to their ancillary service products along with other potential improvements, with an expectation that some enhancements may be required in the next five to ten years. These expectations are driven in part by carbon reduction policies that will likely result in even larger amounts of new variable generation added into many power systems.

The most common change to date related to ancillary service tools across power systems has been to increase by a relatively small amount the frequency-related reserves needed to maintain reliability. Many systems with significant amounts of renewables have not yet found the need to make other major adjustments to ancillary services, although a variety of modifications are under consideration, and some systems, such as California, are looking to make changes in the next five years.

Besides the growth of renewables, other drivers of change in the sector include technology improvements, both on the transmission side itself to improve grid reliability and by advances on the distribution side where resources may potentially contribute to reliability in the future. These measures are supplementing both the reliability services that conventional generation have traditionally provided

[1] The ISO-New England includes a temporary winter reliability program in its collection of ancillary service tools, and its cost, roughly $30 million, is included in the total.

to grid operators, along with improvements in hardware and software that also allow renewable generators to contribute to ancillary services.

In New England, ancillary services are likely to evolve as the power system continues to transform. While lessons from other systems suggest that modifications to ancillary services are not necessarily imminent, analysts have found that, for the power grid to remain reliable and flexible, new options will likely be needed over the next decade. These options could include things such as additional fast response reliability products, sophisticated weather forecasting, and coordinating and balancing systems over larger areas to take advantage of geographic diversity of resources sited in neighboring, interconnected systems. This paper is not intended to suggest specific changes to ancillary services in New England or to opine about the appropriate timing for any such changes that may be needed. Rather, it is intended to provide information to advance regional dialogue about the future grid.

Observations

- Ancillary services, such as operating reserves and frequency response, are necessary tools used by grid operators to ensure reliability and stability of the power system in the short term.
- In New England, the cost to consumers of the ISO-NE's ancillary services is less than 2% of total wholesale market costs, which is measurable but clearly a very small proportion of the total system cost.
- Power grids across the world are transforming as conventional generation retires and renewable energy increases. However, thus far, short-term reliability has not been difficult to maintain.
- Renewable generation can provide some ancillary services needed to ensure system stability. Other changes in the power sector also improve reliability, such as better weather forecasting and more sophisticated demand response products.
- In power systems where renewables make up a much larger proportion of the generation supply than in New England, some operational changes and additions to ancillary services are likely to be made within the next five years to ensure reliability. In the US, California is taking the lead in these efforts, while Texas explicitly declined to make significant changes to its ancillary service products in recent years, although future changes are still possible.
- The experience of Texas and California to date, as well as renewable-rich regions within Europe, implies that New England, with its relatively smaller amount of renewable generation, would likely have years of leeway before ISO-NE might need to significantly alter its ancillary service products.
- New England's share of renewable generation is expected to grow in the future. At some point in the next decade, enhancements to the current set of ancillary service products used by ISO-NE may become necessary.

Contents

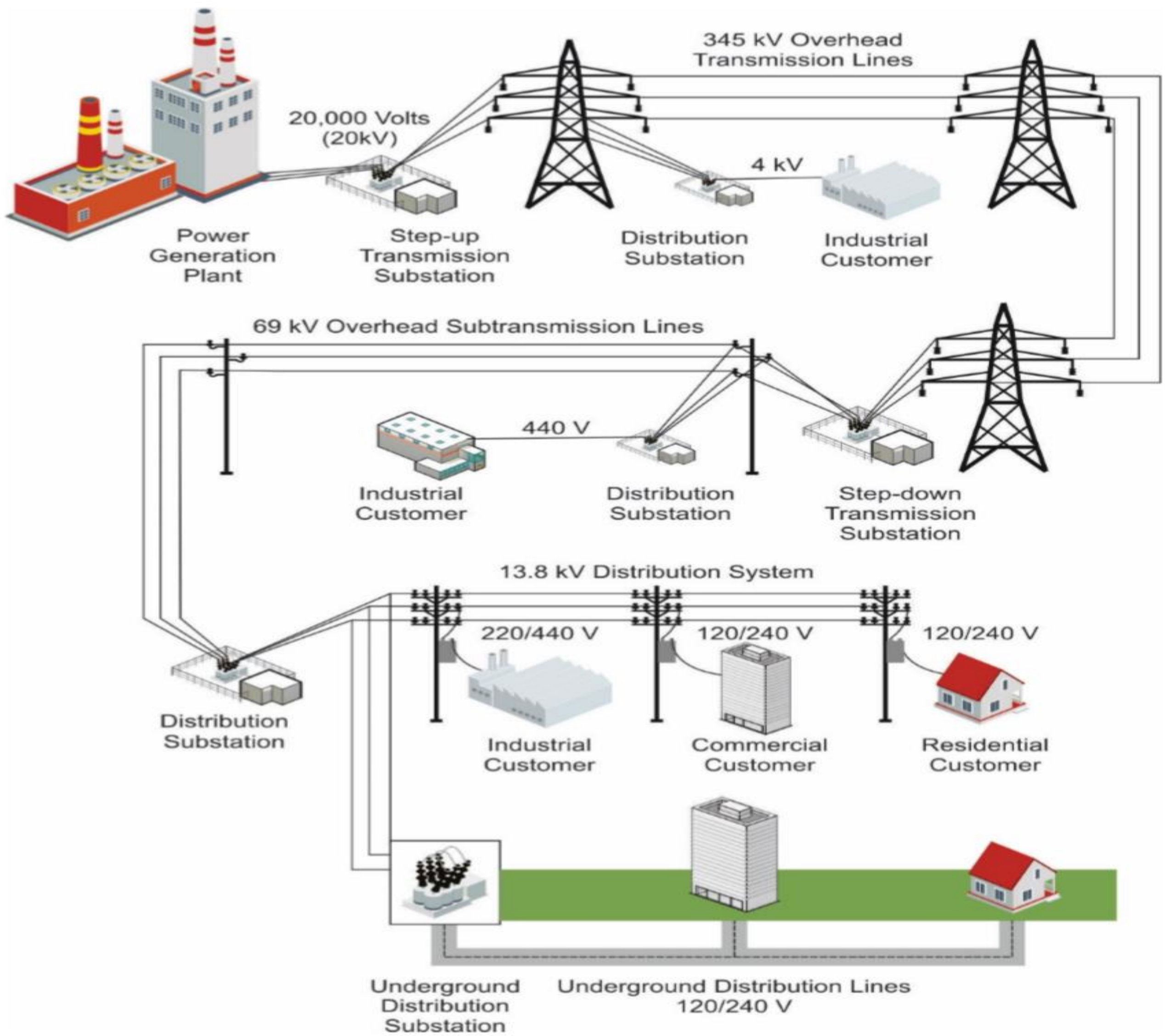
Introduction

This primer will explore, at a high-level, issues related to ancillary services, which are mechanisms that help maintain the reliability and stability of the electric grid. The first section will discuss and define what ancillary services are. In the second section, ancillary services products specific to the New England region will be described and then compared to those of other regional grids in the U.S. The section that follows will look to Europe, touching on those systems that already integrate a much higher proportion of renewables in their power supply mix. The evolution of ancillary services likely will come in response to several different drivers besides renewables growth, which will be briefly described in the fourth section. The last section will offer observations on the potential changes ahead in grid operations related to reliability. These observations will include both what is generally recommended by experts analyzing the power sector's ongoing transformation around the world and more specifically about what may lay ahead for the evolution of New England's ancillary services market, based on the experience of other systems. None of these observations, and in general nothing in this primer, should be interpreted as advocating for a particular form of ancillary service product, any market rule change, or views about the appropriate timing of any changes. This primer is intended to be informational only.

In addition, a broader discussion of reliability, such as that related to cyber security or physical attack, and of the resilience and assurance of fuel supply, while valid issues of interest, are well beyond the scope of this primer, and will not be addressed here. Likewise, this primer will not delve into distribution-level reliability, i.e., customer outages from storms or distribution equipment failure, but rather focus mainly on near real-time reliability issues related to the bulk transmission and generation system.

Finally, because issues associated with ancillary service reliability are complicated and this paper is necessarily limited in scope, those who wish to explore these issues in greater depth should review the annotated bibliography, attached as Appendix 1, for a guide to additional materials of potential interest. A glossary of terms is included in Appendix 2.

Figure 1: Representation of the electric grid



Source: DOE, *Managing Flexibility in the Modern Power System*, 2016

I. Ancillary Services

What are Electric Ancillary Services?

The electricity grid is a complex system. It is generally made up of generating plants connected by high voltage transmission lines that feed electricity through to the wires owned by distribution systems to meet the demand for power from the ultimate end-users (see Figure 1, above). The operators of the grid must reliably match the generation of power and the demand from consumers through the scheduling and dispatch of power supply to exactly meet load at all times. Unlike most other commodities, it is not easy or inexpensive to store electricity. Grid operators are therefore tasked with the job of transmitting electricity to the end users' premises in the instant it is consumed without interruption in real time in an efficient, cost-effective, and reliable manner.

Grid operators need tools and procedures that can keep the system operating in a reliable and stable manner over a scale of time that ranges from a fraction of a second to years into the future.

Electricity consumption fluctuates both naturally over the course of hours and days and in unexpected ways in real time. Further, unscheduled outages in generation, whether supplied by conventional fuel or by wind and solar, can occur at any time. For those reasons, grid operators need tools and procedures that can keep the system operating in a reliable and stable manner over a scale of time that ranges from a fraction of a second to years into the future. The necessity for the grid to be flexible and responsive to meet this challenge has existed long before intermittent[2] resources such as wind and solar began to be added in significant amounts to the generation mix on some systems. But, in recent years, various stakeholders have observed that an ever-larger proportion of variable energy resources could potentially increase the challenge of maintaining grid stability and reliability.

Ancillary services are defined as those functions that help grid operators maintain the reliability of the electricity system over very short periods of time up to one day, by providing flexibility to respond to variations in supply and demand, as well as maintaining frequency and voltage.

Ancillary services are an important piece of grid operations: they represent essential reliability services, albeit "ancillary" to the much larger and fundamental provision of energy and capacity from generators. Typically, ancillary services are defined as those functions that help grid operators maintain the reliability of the electricity system over very short periods of time up to one day. Ancillary services provide the flexibility needed to respond to variations in supply and demand, as well as maintaining frequency and voltage. See below, Figure 2, from the most recent installment of the US Department of Energy (DOE)'s Quadrennial Review.[3] This graphic illustrates the time-scale over which grid operations and planning typically function. The functions that occur on left side of the time scale, circled in red, are, broadly defined, the types of ancillary services that grid operators use to ensure reliability over the short-term.

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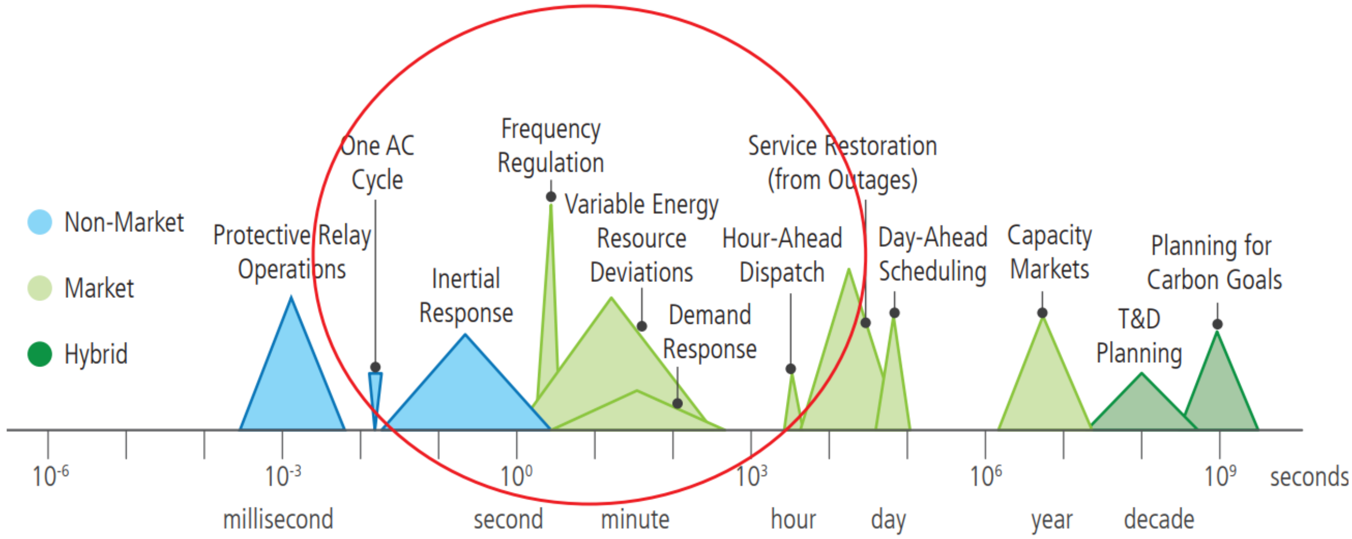
[2] Wind power is also referred to as asynchronous generation because its turbines are typically decoupled from the grid in terms of spinning. And solar photovoltaic energy is produced by a chemical process that also does not involve a spinning turbine. Although there can be made a technical distinction among asynchronous, variable, and intermittent, for the purposes of this primer, the terms are used interchangeably in describing wind and solar renewable energy, and readers will note from cited text that there is no universally accepted term of art to describe intermittent renewables (e.g., variable generation or "VG", variable renewable energy or "VRE"). In most cases, variable generation does exclude other forms of renewable energy that are considered more "dispatchable," such as biomass and hydro-electric.

[3] US Department of Energy's Quadrennial Energy Review, *Transforming the Nation's Electricity System: The Second Installment of the QER,* January 2017, Chapter IV, p. 4-8.

Figure 2 – Time-scale of Ancillary Services

Markets are used for grid operations in the order of seconds to minutes, such as frequency regulation and demand response (DR). Some essential



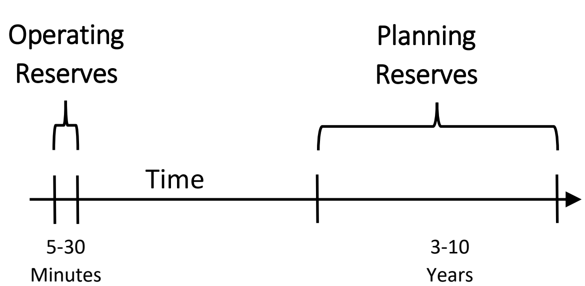
reliability capabilities, such as inertial response, occur faster than typical market signals. Acronyms: transmission and distribution (T&D), alternating current (AC).

Source: US DOE Quadrennial Energy Review, Second Installment, January 2017

Reliability depends on both long-term and short-term reserves

Although this primer will focus on ancillary services that typically operate on a time scale of a day or less, it is important to understand that other mechanisms exist to ensure that there is excess supply relative to forecasted demand over longer time periods. Such an excess is usually referred to as the planning reserve margin, which in the U.S. averages around 15%. That is, grid operators over the longer term acquire excess capacity that is at least 15% larger than the highest forecasted demand of electricity consumed.

Although both are essential to reliability, it's thus helpful to distinguish between operating reserves and planning reserves. Operating reserves, a cushion of excess power on a given day, will be explored in more depth throughout this primer as one of the fundamental aspects of ancillary services. Planning reserves, sometimes referred to as resource adequacy, relate to actions used to ensure that excess power plants will be available in the future as needed. See also, for example, the activities listed on the right side of the time spectrum in Figure 2, above, related to longer-term planning tools. In electrically restructured states, new generation is generally acquired through market mechanisms such as capacity market auctions. In regions without competitive wholesale markets, utilities that still own and operate generation typically plan over the long-run to self-build new generation or sign bilateral contracts to be certain that excess capacity will be available in the future.



The concepts however are inter-connected: without engaging in resource adequacy efforts over the longer run, the operators of grids, be they Regional Transmission Organizations (RTOs) or vertically-integrated utilities, would likely lack the reserve options they need to keep the system in balance in the shorter run.

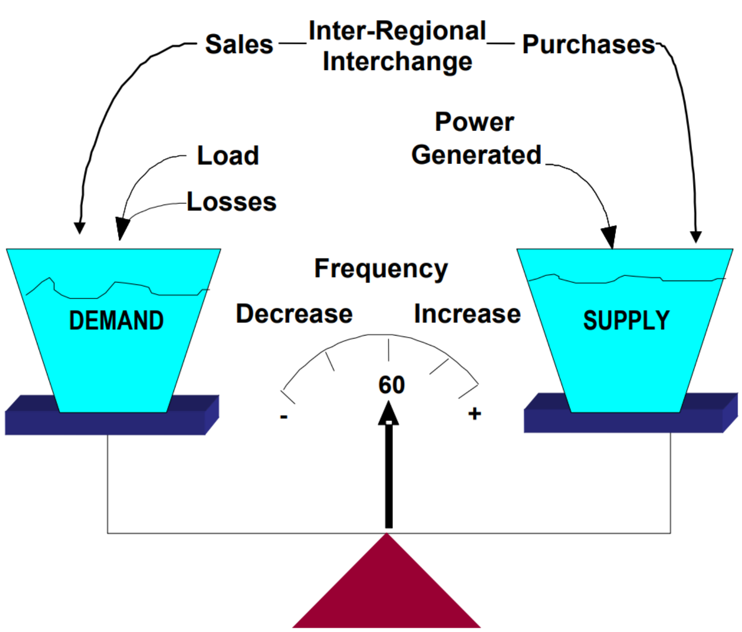
Ancillary services provide flexibility, frequency control, and voltage support

In the short term, operating reserve requirements are tools used by the operators of grids to assure that additional power generation will be ready and available to meet unanticipated changes in supply or demand at short or virtually no notice during a given hour or day. Thus, one important category of ancillary services is operating reserves, to provide flexibility to the system.

In the even shorter term, another category of ancillary service tools is necessary for grid operators, be they RTOs or utilities in non-wholesale market regions, to manage the precise pairing of supply and demand on a moment to moment basis. These mechanisms relate to real-time stability. Bear in mind that a power grid must balance a continuous supply of electricity that exactly meets the kWh needs of the users at any given moment, and also must continuously provide two specific forms of electric stability: frequency and voltage. Electric stability can be provided through a mix of market actions and grid protocols in RTOs, and through operating procedures by utilities in non-restructured regions.

Frequency of electricity refers to the level at which electric current alternates in steady state; in the U.S., it is set at 60 times per second, i.e., 60 Hertz. Frequency will drop or exceed the set point whenever supply and demand doesn't exactly match in real time. Mechanisms to maintain frequency are often referred to "regulating" tools.

Figure 3: Supply and demand must remain in balance



Electrical devices such as home appliances and industrial motors depend on the stability of both frequency and voltage to stay within certain very narrow limits, to avoid damage to equipment. Likewise, the grid must operate within those limits to avoid generators themselves from shutting off, which could lead to a collapse of the grid, potentially resulting in blackouts.

Source: NERC *Balancing & Frequency Control*, January 2011

Voltage can be thought of as the electric pressure between two points in the system, as measured in volts. Unlike frequency, which must stay constant throughout the system, voltage is intentionally maintained at a different level along different points on the grid. Generating plants typically produce power at 10-25 kV. This is transformed and transmitted across long distances at even higher voltage, e.g. along 115 kV or 345 kV bulk transmission lines. It is then stepped back down by transformers to be distributed locally along 34.5 kV distribution lines to consumers at much lower voltage levels, typically delivered to the premise at 120 V or 240 V. Electrical devices such as home appliances and industrial motors depend on the stability of both frequency and voltage to stay within certain very narrow limits. If either frequency or voltage fall outside those limits, electrical equipment can be damaged. Likewise, the grid needs to operate within those limits to avoid generators themselves from automatically shutting down to protect its equipment. If electric stability is not maintained in real time, a collapse of the power grid is possible, potentially resulting in blackouts.[4]

The Federal Energy Regulatory Commission (FERC) has broadly defined those ancillary services, through its Orders 888 and 890. Accordingly, RTOs like ISO-NE must reflect ancillary services in their open access transmission tariffs. Additional FERC actions taken since issuing those seminal orders have reshaped and modernized ancillary services to a certain extent. Similarly, in its role as the officially designated Electric Reliability Organization, the North American Electric Reliability Corporation (NERC) is responsible for setting rules that utilities and RTOs must comply with related to electric reliability. Some of the NERC rules focus specifically on the provision of ancillary services. Many recent directives by NERC have explicitly addressed how changing power system conditions may affect “essential reliability services.” Interested readers should look at Appendix 1, which offers cites to additional FERC and NERC resources as well as a rough chronology of FERC actions over the last 10-15 years related to ancillary service developments.

Types of ancillary services tools

While no single definition is universally used across power grids, it is possible to categorize the reliability tools related to ancillary services into providing three essential actions over the short term: (1) assure flexibility to meet load, (2) maintain steady frequency, and (3) provide voltage support.

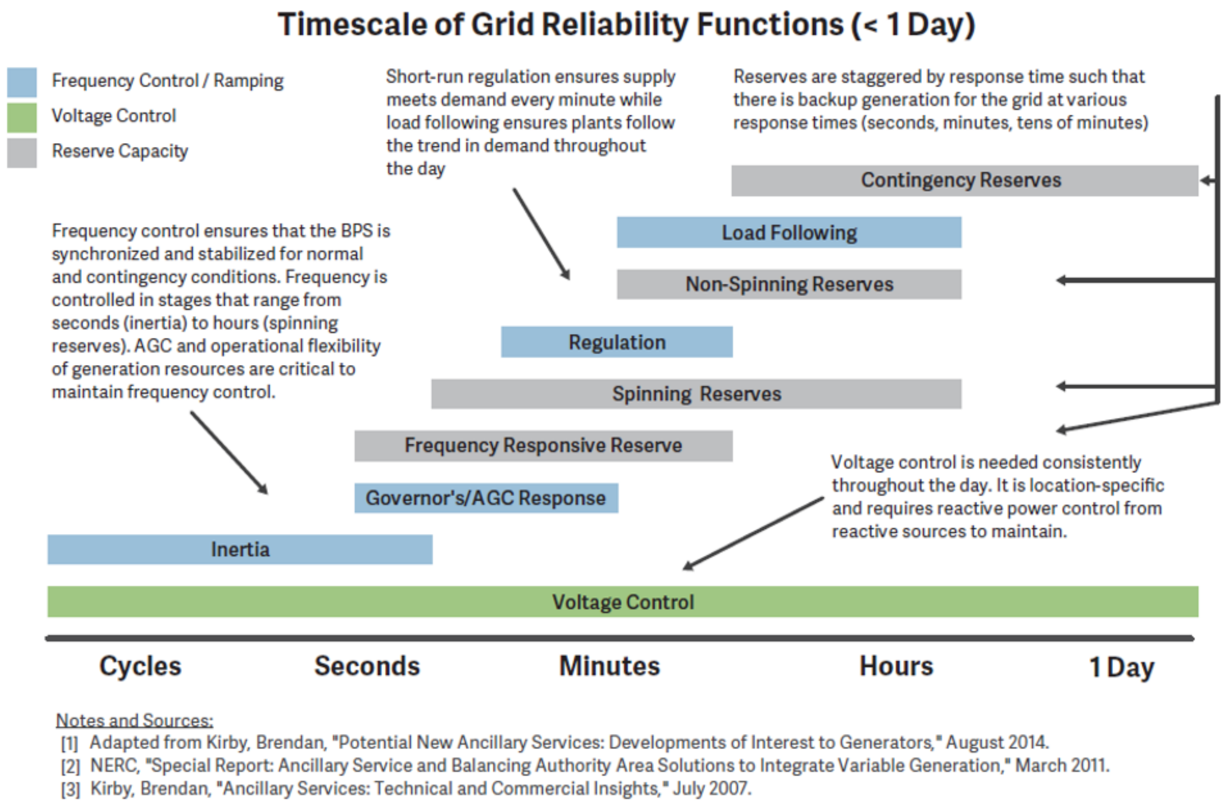
Three broad categories of ancillary services:

- Flexibility to balance supply and demand is provided by *operating reserves*
- Regulating reserves are used to maintain *frequency* at a constant 60 Hz
- *Voltage* controls are used across the system for stability

Before examining each in depth, it may be helpful to visualize how the various reliability mechanisms stack up over time. Figure 4 [next page], for example, offers a clear illustration of how the services related to reserves, frequency and voltage provide reliability along a timescale, from single oscillation in a fraction of a second to services that operate over hours in a day (from left to right).

[4] The largest blackout in United States history, the August 14, 2003 eastern blackout, was the result of unintended decaying voltage in the transmission system in Ohio, resulting in a cascade of uncontrolled outages. See NERC’s report, *Final Blackout Report July 13, 2004* for a detailed discussion of the underlying causes of the 2003 blackout.

Figure 4: Timescale of grid functions



Source: Analysis Group, *Advancing Past "Baseload" to a Flexible Grid,* June 2017

Flexibility related:

- Ramping or load following are generic terms for an essential grid operation, sometimes although not always defined as ancillary services. The terms relate to the vital task of bringing online, or taking offline, power plants typically over the course of a few seconds or minutes to several hours to meet changing load or supply conditions. Such activity has long been a part of daily grid operations, particularly to meet expected changes in demand throughout the day. Demand for power commonly fluctuates sub-hourly, hourly, daily and seasonally. Natural gas plants, for example, have the flexibility to quickly ramp up or down their energy output as system conditions change throughout a given day.

More recently, supply-side fluctuations have increased as variable generation like wind and solar has been added to the mix. The intermittency of these resources caused some stakeholders and others initial concern regarding the grid's ability to physically compensate quickly enough for short-term changes in wind or solar conditions. Although this point will be explored further in this paper, it is worth noting that early concerns about how difficult integrating renewables might be in terms of managing this additional need for flexibility were largely overstated, as power systems around the world have since easily accommodated much higher amounts of renewables than first anticipated.

Early concerns about how difficult integrating renewables might be in terms of managing this additional need for flexibility were largely overstated, as power systems around the world have since easily accommodated much higher amounts of renewables than first anticipated.

For example, VP of Operations Bruce Rew of the RTO Southwest Power Pool recently stated, "[t]en years ago, we thought hitting even a 25 percent wind-penetration level would be extremely challenging, and any more than that would pose serious threats to reliability… Since then, we've gained experience and implemented new policies and procedures. Now we have the ability to reliably manage greater than 50 percent wind penetration. It's not even our ceiling. We continue to study even higher levels of renewable, variable generation as part of our plans to maintain a reliable and economic grid of the future."[5]

Both operating reserves and the daily energy markets are typically used to provide ramping capability.

- Operating reserves are ancillary services that explicitly provide the ability to quickly fill in new energy supply when needed because of unexpected changes in the supply/demand balance, as well as supporting voltage and frequency. Most systems rely on two types of operating reserves: (1) contingency *spinning* (or synchronous) reserves that usually can respond very quickly, within ten to fifteen minutes, and (2) *non-spinning* (or supplemental) reserves that typically have response times on the order of ten to 30 minutes or more.

  Spinning reserves are provided by generation units that are actively generating (and whose turbines are "spinning") and thus can quickly increase or decrease their output when called upon within the required time. Non-spinning or non-synchronized reserves are provided by generation resources that are not actively generating, but are ready and able to start up quickly and begin providing energy to the grid within a specified timeframe. In some regions, these non-spinning reserves are referred to as fast-start resources.

  If a generating plant is producing electricity but not operating at its maximum, the amount of "spinning reserve" it could provide is essentially the difference in capacity between what it is actually producing at that time and the maximum amount of energy it could physically produce. If that difference is held in reserve as an ancillary service, then that amount is not available to be used by the plant owners to generate electricity in the energy market.

[5] SPP news release, February 17, 2017. https://www.spp.org/about-us/newsroom/spp-sets-north-american-record-for-wind-power/

Generating plants are typically compensated for offering spinning reserves, because otherwise that set-aside amount of energy could be sold instead in the daily market for electricity.

Spinning or contingency reserves can also be provided by resources that do not actually generate energy or "spin". For example, in systems where demand response is authorized to provide such services, then the "spinning" reserve would equal the amount of reduced consumption that resource could reach within 10 minutes after receiving a dispatch instruction from the grid operator.

Frequency related:

- Regulating reserves are actions that can be taken to respond in mere seconds to grid fluctuations or emergencies to stabilize frequency and to rebalance supply with demand. Often, but not always, regulating reserves are separated into two types:
  - As described by NERC, *primary* frequency response is an automatic process, when "[i]n the seconds-to-minutes timeframe, bulk power system reliability is almost entirely controlled by automatic equipment and control systems such as Automatic Generation Control (AGC) systems, generator governor and excitation systems, power system stabilizers, automatic voltage regulators (AVRs), protective relaying and special protection and remedial action schemes, and fault ride-through capability of the generation resources."[6] NERC suggests thinking of these automatic devices such as governors on generators as "similar to cruise control on your car. They sense a change in speed and adjust the energy input..."[7] of generators in a seamless manner, without human intervention, in seconds.
  - *Secondary* frequency response relates to both automatic as well as manual changes that can be made by plant operators in response to directives from the grid operator, generally within a period ranging from 30 seconds to five minutes. Secondary response can be provided by both spinning and non-spinning operating reserves through AGC systems that respond to automated signals as well as by actions taken by operators on-site. Frequency and balancing are interconnected concepts: because of the physics that underlies the power system, changing the balance of the system by adding or decreasing a small amount of supply also changes the frequency of the system.

Notably, frequency response is no longer necessarily limited to conventional generators. The DOE states that "[w]ith sensors and controls that monitor grid frequency, VG [variable generation] generators can change output as needed to provide active power control. Wind turbines can draw stored energy from the rotor to help arrest a frequency decline or can be operated at reduced output during periods of high VG penetration to provide 'synthetic' inertia and primary frequency response. For wind and solar to increase output and respond to a grid fault, they typically must be operated at less than full capacity."[8] A few systems, including California, are looking more closely at how to potentially incentivize wind

[6]NERC, *Accommodating High Levels of Variable Generation*, April 2009, p. 6.
[7]NERC *Balancing & Frequency Control,* January 2011, p. 12.

[8] DOE, *Maintaining Reliability in the Modern Power System* (December 2016), p. 26.

resources to provide this frequency service, by assigning a value to the wind capacity that is held back in certain critical hours.

This is a key point to emphasize, because some of the initial apprehension related to how grids might reliably integrate more renewables typically didn't necessarily count on renewables themselves contributing to stability. But synthetic reserves can be provided by wind and other inverter based technology that lack the massive turbines of conventional generation, through software solutions. As the American Wind Energy Association points out, "[w]ind turbines and solar plants have power electronics and output controls that enable fast and accurate voltage and frequency control, in many cases an order of magnitude faster than conventional power plants." NERC has stated that "Modern wind turbine generators can meet equivalent technical performance requirements provided by conventional generation technologies with proper control strategies, system design, and implementation." Regarding reliability concerns, NERC has noted that "This issue does not exist for utility-scale wind energy, which offers ride through capabilities and other essential reliability services."[9]

According to NERC, "modern wind turbine generators can meet equivalent technical performance requirements provided by conventional generation technologies with proper control strategies, system design, and implementation." Regarding reliability concerns, NERC has noted that "This issue does not exist for utility-scale wind energy, which offers essential reliability services."

Voltage related

- Voltage control is managed by injecting or absorbing "reactive power" at the local site of generation, transmission, and distribution to maintain the appropriate level of voltage at a given location. Reactive power (measured in kvar) is a phenomenon that is an integral part of the physics of generating alternating current, along with active (or real) power; the latter is what most laypersons would refer to as electricity, measured in kW. Reactive power in the right amount must be available locally to transfer active power across the network. In other words, to get and maintain the desired voltage at a given location, a precise amount of reactive power must be present. This is done by:
  - Monitoring local reactive power at power plants when generators are spinning and making minor adjustments on site that will maintain steady voltage.
  - Using devices along the transmission system (and distribution system as needed) to control voltage levels as well as installing power electronics equipment that actively injects or absorbs reactive power.

Voltage control is a tool not limited to conventional generators. The DOE notes that:

> (a]s with frequency control, advanced power electronics can give variable generation resources like wind and solar the ability to control reactive power and voltage. FERC has recently issued an order requiring this capability on larger variable generation units. Many types of storage can also use this sort of power electronics. In addition, synchronous condensers can be used to provide reactive power. Lastly, there is a class of relative inexpensive electronic devices called Flexible AC Transmission Systems

[9]AWEA report, *Renewable Energy Builds a More Reliable and Resilient Electricity Mix*, May 2017, p 31.

> (FACTS) that have existed for a while but are becoming less expensive and more widely deployed and can solve many voltage control problems that historically would have required larger and more costly generators, transmission lines or electromechanical devices. …Using the power electronics that already exist in VG [variable generation, such as wind and solar] resources to control voltage often involves little more than software changes.[10]

In most RTOs, voltage control is considered an ancillary service, but not one that necessarily is acquired and paid for through a market mechanism, in the way that operating reserves and frequency reserves typically are. Many conventional generators inherently provide reactive power, and as the DOE explained above, variable generators can also provide it. Methods of compensation for voltage control vary across systems. In most cases, providing voltage support is simply part of the overall requirement for interconnection to the grid, and considered good utility practice. In other circumstances, some financial incentives are offered to provide reactive power if doing so requires a generator to otherwise reduce active power while providing additional reactive power when called upon.

How are ancillary services used to prevent blackouts?

To appreciate how these ancillary services tools are used in practice, consider what happens when a large power plant unexpectedly goes offline and thus instantly stops delivering electricity into the grid:

> When a 1,000 MW generator trips off line there is an immediate generation/load imbalance with load exceeding generation by 1,000 MW. This results in all the synchronized generators throughout the interconnection slowing down and frequency dropping below 60 Hz as shown in Figure [5, below]. The interconnection would collapse instantaneously were it not for the inertia of the generators and motor loads. Inertia cannot support frequency but it does slow the frequency decline. As frequency drops and generators slow down the energy stored in the rotating mass of the turbine-generators is delivered to the power system.
>
> Next, other generators increase their output to make up for the generation that was lost and to reestablish the generation/load balance. Generator governor response is first with generators themselves detecting the power system frequency drop and autonomously increasing their output. The power system operator also detects both the generator failure and the frequency drop and directs generators that were kept in reserve to increase their output.
>
> Once reserve generation has replaced the full 1,000 MW that was lost when the failed generator tripped, the load and generation are again in balance and the power system 60 Hz frequency is restored. Normal economic operations resume when energy markets adjust supply to relieve the reserve generators, allowing them to return to reserve status in anticipation of the next contingency event.[11]

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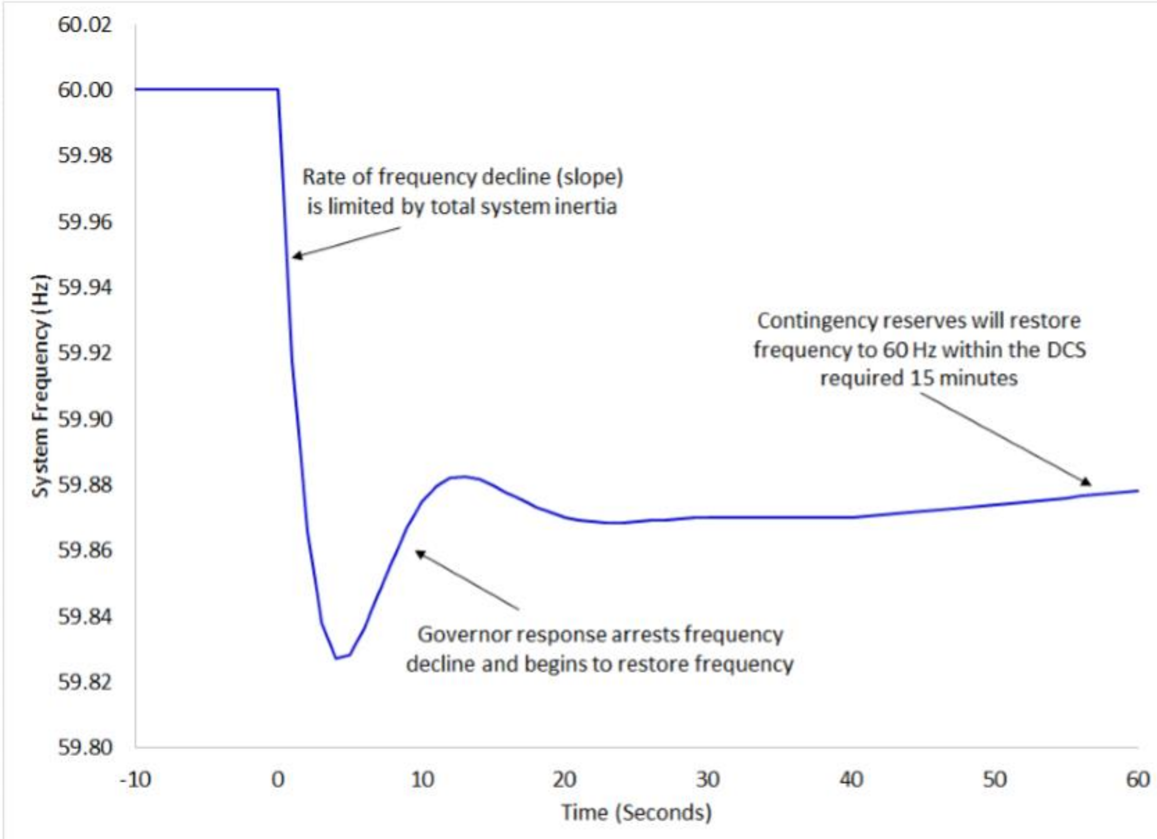
[10] DOE, *Maintaining Reliability in the Modern Power System* (December 2016), p. 30.
[11] Kirby, *Potential New Ancillary Services: Developments of Interest to Generators* (2015), p. 2.

Figure 5: Typical response in a contingency event



Source: Kirby, *Potential New Ancillary Services: Developments of Interest to Generators,* 2015

How large are ancillary services products in a typical power system?

This primer will explore in more detail how ancillary services may evolve or expand in the future, particularly as the amount of variable generation increases. However, as a starting point, it may be helpful to remain mindful of the fact that to date only a small amount of reserves, both frequency and operating, has been necessary to maintain the reliability of a power grid. As the DOE affirms,

> …while reserves are an important part of reliable system operation, the amount of reserves needed is relatively small compared to the total capacity requirements. [Figure 6, below,] summarizes the regulating and spinning contingency reserve requirements held by different operators and demonstrates that larger areas can typically carry fewer reserves on a relative basis due to the fact that a greater aggregation of supply and demand reduces overall variability.[12]

[12] DOE, *Managing Flexibility in the Modern Power System*, December 2016, p. 23.

The DOE's graphic shows the amounts in MWs of regulating (frequency) and contingency (operating) reserves required in various wholesale market regions in a recent year. The ISO-NE and its requirements are listed in the fifth row of the chart.

Figure 6 – Size of reserve requirements in US wholesale markets

Region	Regulating Reserve	Spinning Contingency Reserve	2013 Demand
CAISO	average (varies): ~338 MW up, ~325 MW down	~850 MW (average)	peak: 45,097 MW average: 26,461 MW
ERCOT	average (varies): ~300 MW down, ~500 MW up range: 400–900 MW	2,800 MW (maximum of 50% from load)	peak: 67,245 MW average: 37,900 MW
MISO	range: 300–500 MW	1,000 MW (2,000 MW total and 1,000 MW of spin)	peak: 98,576 MW average: 52,809 MW
PJM	average: 753 MW in 2013[e]	1,375 MW (Tier 2; maximum of 33% from DR)[f]	peak: 157,508 MW average: 89,560 MW
ISO-NE	average 60 MW range 30–150 MW	10-minute reserve: 1,750 MW 30-minute reserve: 2,430 MW	peak: 27,400 MW average: 14,900 MW
NYISO	150–250 MW	10-minute spin: (330 east zone, 655 MW NY control area 10-minute total 1,310 MW	peak: 33,956 MW average: 18,700 MW
SPP	average: ~300 MW up, ~320 MW down	545 MW	peak: 45.256 MW average: 26,360 MW

Source: Denholm et al. 2015

Source: DOE *Managing Flexibility in the Modern Power System*, 2016

Note that the amount of regulation (frequency) reserves and contingency (10-minute and 30-minute operating) reserves required by ISO-NE, as measured in megawatts, is indeed quite small in comparison to its system peak load, or roughly 0.2%, 6%, and 9% of peak, respectively. Larger systems have proportionately even smaller reserve amounts, including those with significantly greater proportion of wind and solar in their supply mix. For example, in Texas, ERCOT's operating reserves are only 4% of its peak load, and California's average contingency represents less than 2% of its system peak. The larger proportion of variable generation in those two systems has not yet required a proportionate increase in the amount of required operating reserves.

Recall that the amount of contingency (operating) reserves required in a system is related to the number of megawatts that might be quickly called upon to replace a supply shortfall if the largest generator in that system unexpected shut off. The amount of reserves needed to cover for a generator outage is not necessarily larger in larger systems. This is because the largest single source of power providing electricity at a given time, such a central generator within the system or an import of energy across a large transmission line from a neighboring system, is not necessarily any larger in power systems of varied sizes. The proportion or percentage of reserves relative to total capacity in larger systems is thus less than that found in smaller systems like ISO-NE. In addition, as the DOE noted above, larger systems are inherently more diverse geographically, which has been shown to smooth out the variability of local supply and demand fluctuations.

Impact of renewables on operating and regulating reserve requirements

The addition of more renewable generation in the supply mix of US power systems has had, at best, a limited impact on ancillary services requirements thus far. For the most part, grid operators have not yet increased their ramping requirements, i.e. operating reserves, to accommodate the growing levels of intermittent renewables. The DOE notes that despite rapid increases of renewables in the power mix over the last decade, the amount of operating reserves in most power systems today is currently sufficient to accommodate the variations in supply that such intermittent resources themselves may cause. Furthermore, detailed studies that estimate the impact of even larger amounts of renewables on power systems have not shown a need to increase operating reserves:

> Recent analysis has demonstrated that the current fleet of installed generation can typically provide sufficient system flexibility to accommodate significant increases in wind and solar generation. These studies of systems with up to 35% VG [variable generation] demonstrate that existing resources that are “backed down” to accommodate VG can typically ramp rapidly enough to provide load following at 5-minute dispatch time scales. The implication of this finding is that, while VG can increase ramping requirements, the existing generation fleet is largely adequate to meet this requirement. The average age of the gas combined-cycle fleet and combustion turbine fleet in the United States is 12 and 16 years respectively, so this capacity can provide grid flexibility services for the foreseeable future.[13]

With respect to regulation and frequency, the DOE explains how displacing conventional generation with variable generation (VG) can negatively impact ancillary services:

> VG impacts reserve requirements in several ways. First, it reduces generation from conventional generators, and the inertia in generators that are not operating is thus removed from the system. VG such as wind and solar uses power electronics (inverters) rather than synchronous generators to connect to the grid, so it does not replace the physical inertia from conventional generators. As a result, replacing conventional generation with VG typically reduces real inertia and traditional frequency response.[14]

However, as previously discussed, the same DOE report explains that when renewable resources are “loosely coupled” to the grid, these inverter-based generators can still provide support grid stability.[15]

The U.S. National Renewable Energy Laboratory (NREL) also performed studies on frequency response in the Eastern and Western Interconnections for scenarios with high wind energy penetration, in which it

[13] Ibid., p. 17.
[14] Ibid., p. 24.
[15] Ibid., p. 26.

found that adding wind generation is unlikely to significantly reduce frequency response and could potentially improve it.[16]

In reality, the impact of adding renewables to date on regulating reserves has been mixed. In certain systems, the average amount of frequency-related reserves that grid operators require has increased somewhat to adjust for the additional uncertainty that comes with incorporating intermittent wind and solar resources into a system. The DOE has looked closely at several power systems to determine how much more regulating reserves were required as the amount of variable generation grew. The table, Figure 7, below summarizes one of its findings, which indicates that in some cases, but not all, frequency-related reserves did increase. However, with exception of California, the increase was not as large as many might have expected, and the DOE explains why:

As renewable generation has been added to power systems, only minor adjustments to ancillary services have been needed thus far. In some cases, frequency reserves have been slightly increased, but operating reserves have remained largely unchanged.

> Several studies and real-world experience of power system operators indicate that increasing the amount of VG on the system slightly increases reserve requirements to maintain frequency stability. VG increases variability of the net load on various timescales, including very short time scales… These studies demonstrate a modest increase in regulating reserve requirements. Furthermore, recent experience has demonstrated little need for additional regulating reserves. As an example, MISO found that the addition of 12 GW of wind resulted in no need for additional regulating reserves. While this result may be surprising, it highlights the timeframe of the variability of wind. The output from wind does not change drastically over seconds or even a few minutes, and thus the need for additional regulating reserves is limited. Furthermore, over longer time scales, improved wind forecasting has decreased the need for operating reserves needed to address wind uncertainty.
>
> Despite rapid growth in recent years, the penetration of PV is still quite low, and, as a result, the impact of PV on reserve requirements has yet to be determined. While the output of a single PV system can change rapidly due to passing clouds, over large regions the aggregated output of many PV systems is much smoother and easier to predict. Variability in PV output is thus driven by longer-term weather impacting output over periods of many minutes to hours… VG also does not add to the need for contingency spinning reserves (those used to address the largest single point of failure in the system) unless a single wind or solar plant (or a transmission line collecting multiple wind/solar generators) becomes the single-largest contingency (point of failure).[17]

[16] See numerous reports from NREL listed in Appendix 1 regarding high renewable penetration studies which draw this conclusion.
[17] DOE, *Maintaining Reliability in Modern Power Systems*, December 2016, p. 25.

Figure 7: Additional regulating reserve requirements due to addition of variable generation

Location	VG Added/ System Size	Increase in Regulating Reserves
New York	3,300 MW of wind on system with projected peak load of 33,000 MW	36 MW
Minnesota	5,700 MW of wind on system with peak load of 20,984 MW (providing 25% of total demand)	20 MW
Arizona	1,260 MW of wind providing 10% of annual demand	6.2 MW
Texas (ERCOT)	15,000 MW of wind	53 MW
California (CAISO)	6,700 MW of wind	Up to 230 MW

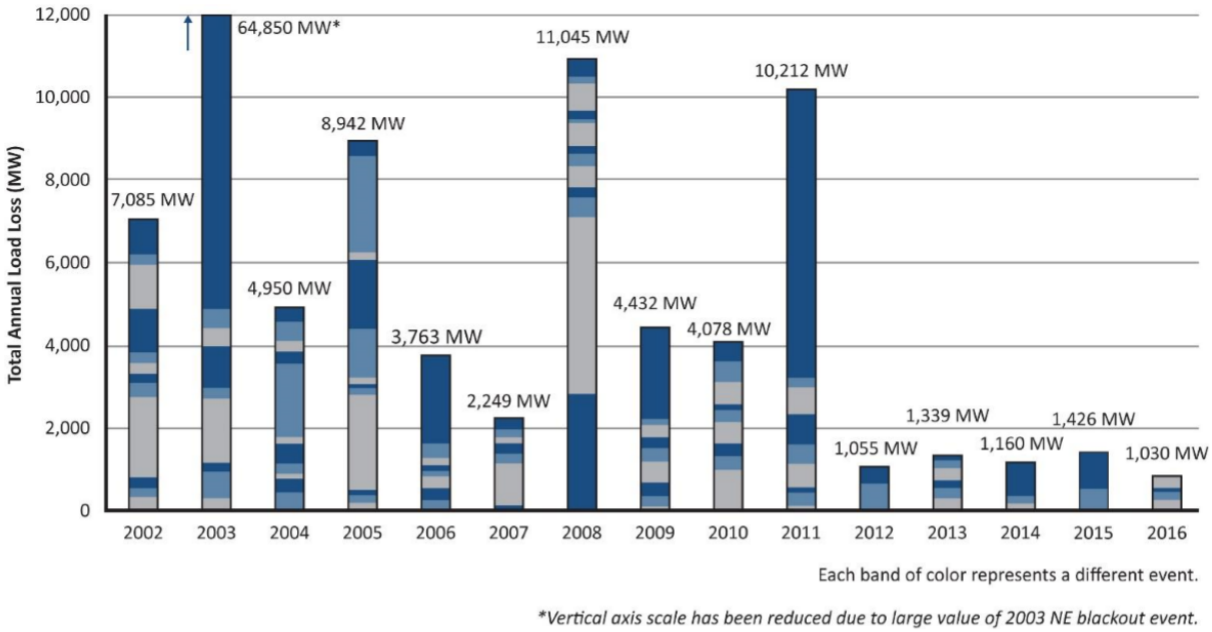
Source: Ela et al. 2011

Source: DOE, *Maintaining Reliability in Modern Power Systems*, December 2016

Finally, it is worth noting that the North American bulk electric power system has been by most measures a very reliable system, particularly in the most recent years, during a period when increasing amounts of variable generation have been added rapidly. This is illustrated in the NERC graphic, below, from its most recent annual reliability report.[18] The same report also found that all of NERC's interconnected systems had improved their frequency response performance over the prior year.

[18] NERC, *State of Reliability 2017*, June 2017, p. 29. Note that a single outage event accounted for two-thirds of the spike in 2011.

Figure 8 - Reliability of the North American bulk power system over time

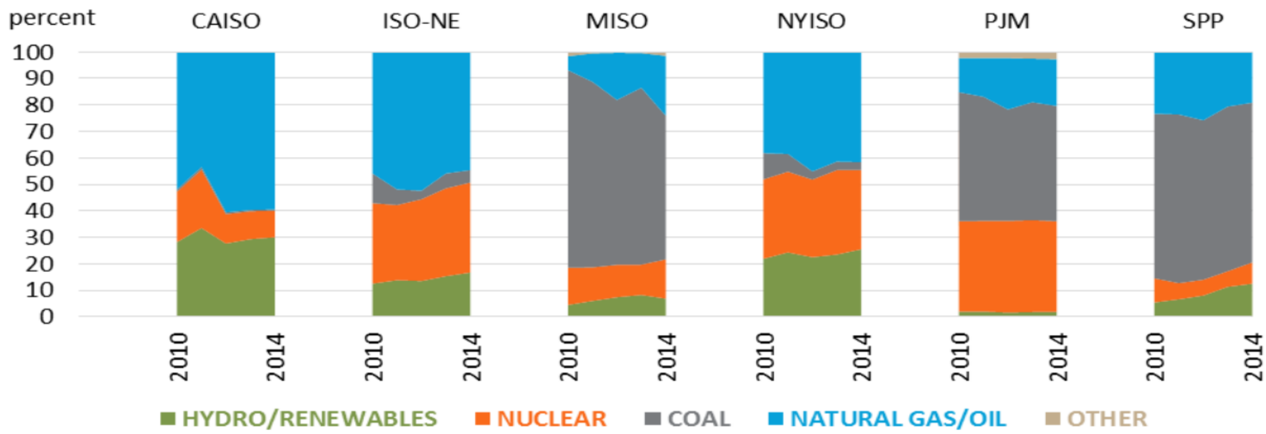


Source: NERC *State of Reliability 2017*, Figure 4.1: M-2 BPS Transmission Related Events Resulting in Load Loss

The power system is evolving

There is no doubt that across the U.S., including in New England, the power supply mix is changing. See Figure 9, below, which charts the changes in the share of generation over a recent five-year period among several wholesale markets in the U.S. In most regions, the proportion of energy coming from natural gas-fired plants as well as from wind and solar resources has quickly expanded while shares of coal-fired generation have decreased. In turn, many traditional aspects of transmission-level operations are drawing new scrutiny as the energy sector evolves. This evolution includes not only more variable renewables but also new forms of grid-scale energy storage, increased levels of demand response, and technology changes at the distribution level. The latter includes things such as accommodating distributed generation from solar PV and two-way flows of power.

Figure 9 – Proportion of total generation by fuel type[19]



Source: FERC Staff, *Common Metrics Report, Docket AD-14-15-000*, June 2016

Discussions around grid reliability, resilience and flexibility in the wake of these power system changes are intensifying. One such example, in the summer of 2017, is the debate in the U.S. focused on flexibility as it relates to the specific characteristics provided by different power supply options, particularly regarding concerns over coal plant retirements. This debate is perhaps epitomized by the April 2017 announcement from DOE Secretary Perry of the agency's 60-day review of "baseload" reliability. A brief review of the final report issued under that directive does not appear to indicate that variable generation necessarily implicates the need for additional ancillary services.[20]

> There is a growing body of evidence, however, that a substantial percentage of the total supply mix would need to be variable before this impact is noticeable enough to trigger significant modifications to ancillary services.

As the share of renewables in the supply mix increases, there has been debate regarding level of penetration at which variable wind and solar resources will necessitate an increase in ancillary services. Not everyone agrees on what that level is or what may necessarily be required in terms of changes. This issue is addressed in later sections. There is a growing body of evidence, however, that a substantial percentage of the total supply mix would need to be variable before this impact is noticeable enough to trigger significant modifications.[21] Even without universal agreement on how much more wind and solar could

[19] Note that this FERC-prepared chart of generation shares excludes the RTO ERCOT because its operations are not under the jurisdiction of FERC.

[20] The final report from the DOE's Staff 60-day review was released August 23, 2017, after the research of this primer was principally completed. Further review of the report, and reactions to the report by interested stakeholders, may be instructive in terms of implications of the evolution of the power sector on reliability. The final report can be downloaded at https://energy.gov/downloads/download-staff-report-secretary-electricity-markets-and-reliability.

[21] The IEA analysis introduced in this Primer on page 34 compares various grids with differing levels of renewable penetration and associated need to make operational changes.

be added without the need to enhance reliability services, it is fair to note that the amounts under consideration and being studied would be much larger than the proportion of intermittent resources that currently operates in New England.

Figure 10, below, prepared by the grid operator PJM, an RTO which manages generation and transmission assets in the mid-Atlantic, categorizes the features of different supply, energy storage, and demand resources. In the matrix chart, fossil-fueled and renewable generation exhibit both positive and negative attributes across the broader spectrum of reliability attributes, including ancillary services (labelled "essential reliability services" in the chart, following NERC terminology). In other words, all forms of generation possess both positive and negative attributes that affect the reliability and flexibility of the grid, as PJM's chart clearly shows.

Figure 10 – Attributes of power resource types

● = Exhibits Attribute
◓ = Partially Exhibits Attribute
○ = Does Not Exhibit Attribute

	Essential Reliability Services (Frequency, Voltage, Ramp Capability)					Fuel Assurance		Flexibility			Other		
	Frequency Response (Inertia & Primary)	Voltage Control	Ramp										
Resource Type			Regulation	Contingency Reserve	Load Following	Not Fuel Limited (> 72 hours at Eco. Max Output)	On-site Fuel Inventory	Cycle	Short Min. Run Time (< 2 hrs.)/ Multiple Starts Per Day	Startup/ Notification Time < 30 Minutes	Black Start Capable	No Environmental Restrictions (That Would Limit Run Hours)	Equivalent Availability Factor
Hydro	●	●	●	●	●	○	◓	●	●	●	●	◓	●
Natural Gas - Combustion Turbine	●	●	◓	●	◓	●	○	●	●	●	●	◓	◓
Oil -Steam	●	●	●	●	●	●	●	●	○	○	○	○	◓
Coal - Steam	●	●	●	●	●	●	●	◓	○	○	○	◓	◓
Natural Gas - Steam	●	●	●	●	●	●	○	●	○	○	●	◓	◓
Oil/ Diesel - Combustion Turbine	●	●	○	●	○	○	●	●	●	●	●	○	◓
Nuclear	◓	●	○	○	◓	●	●	○	○	○	○	◓	●
Battery/ Storage	◓	◓	●	●	○	○	○	●	●	●	◓	●	●
Demand Response	○	○	◓	◓	◓	◓	◓	●	●	◓	○	●	●
Solar	◓	◓	○	○	◓	○	○	●	●	●	○	●	●
Wind	◓	◓	○	○	◓	○	○	●	●	●	○	◓	●

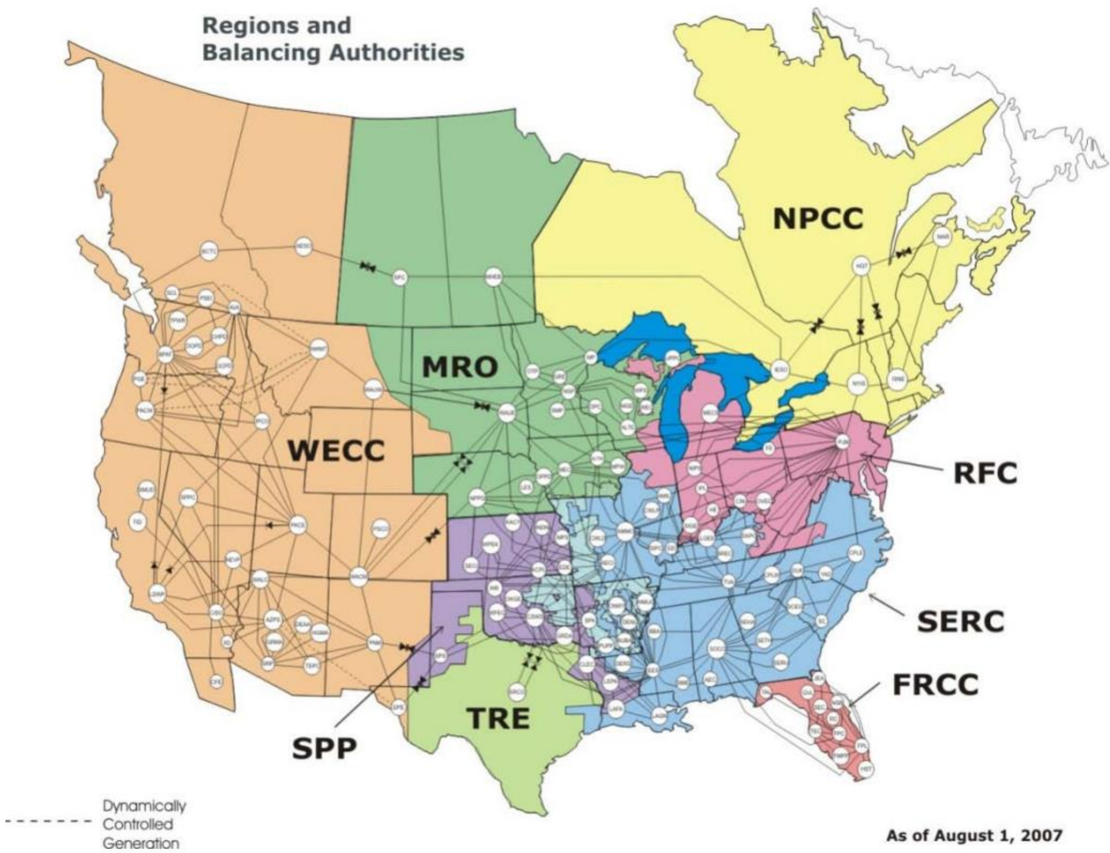
Source: *PJM's Evolving Resource Mix and System Reliability*, March 2017

In sum, ancillary services are a vital element in maintaining grid reliability. All sources of generation both create the need for and contribute to reliability and flexibility of the grid, to varying degrees. It is likely that traditional ancillary service products will evolve as the grid continues to transform.

II. Overview of Ancillary Services Markets in New England and other U.S. RTOs

In North America, there are eight regional reliability areas overseen by NERC, and over 100 balancing authorities within those regions which are interconnected through high voltage transmission tie lines that allow power to be imported and exported by grid operators. See Figure 11, below, for the regions and representations of the balancing authorities. ISO-NE operates under the mandatory rules and criteria issued by NERC and the Northeast Power Coordinating Council (NPCC). The New England ISO is intertied to both New York and to several neighboring Canadian balancing authorities within the NPCC through transmission lines.

Figure 11- Map of the North American bulk power reliability entities that make up NERC

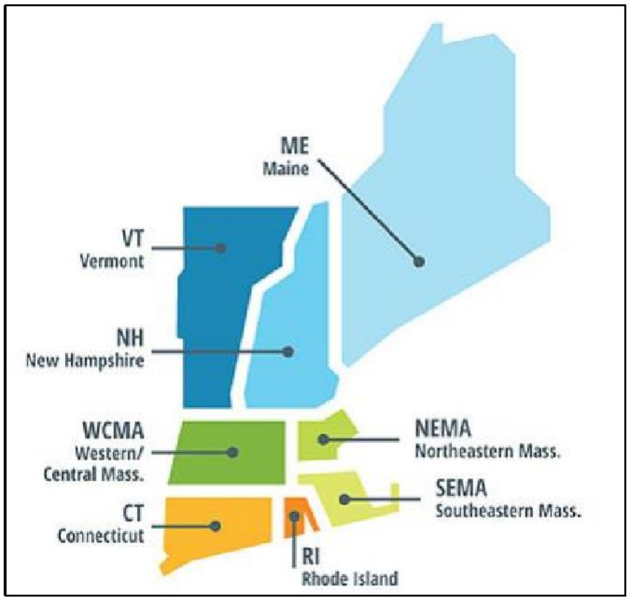


FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
SPP RE	Southwest Power Pool Regional Entity
Texas RE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Source: NERC *State of Reliability 2017*

ISO-NE serves the large majority of New England's consumers across the six states, except for a small portion of northern Maine that is electrically tied to New Brunswick.[22]

Figure 12 – The ISO-NE footprint



Ancillary service products in New England (ISO-NE):

- Operating reserves
  - 10 -Minute Spinning
  - 10-Minute Non-Spinning
  - 30-Minute Operating
- Forward reserve market
- Regulation service for frequency
- Temporary winter reliability program

Source: ISO-NE[23]

The following section describes the ancillary services products defined by ISO-NE to maintain reliability of the grid as well as their costs to the region's consumers. For greater detail, see the ISO-NE documents referenced in the bibliography at the end of this primer.[24]

ISO-NE currently offers the following broadly-defined ancillary services, each of which will be explored in more depth below:

---

[22] The Northern Maine ISA serves customers in Aroostook and Washington counties in Northern Maine with 130 MW of generation. It operates as part of the balancing authority overseen by the New Brunswick System Operator in Canada. Its ancillary service functions are defined in its tariff rules and are aligned with NBSO's protocols. Interested readers can find a description of the tariff rules at http://nmisa.com/docs/NMMR_11_18_2010.pdf

[23] Note that this map outlines the ISO-NE's energy zones, which many readers will recognize. For ancillary services, ISO-NE divides the region into four zones for reserve products: 1. Southwest Connecticut, 2. Connecticut, 3. Northeast Massachusetts and Boston. and 4. Rest of System (i.e. includes all territory not included in the other three zones).

[24] The ISO-NE provides a great deal of information on its operations and specifically ancillary services at varying degrees of technical detail through its website (www.iso-ne.com), which includes annual reports, periodic reviews by its market monitors, training materials prepared by ISO-NE personnel, tariff information, and pricing data (the latter is found at www.iso-ne.com/markets-operations/iso-express).

- **Real-time operating reserves** represent excess generating capacity that is available to respond to unexpected contingencies (such as the unexpected loss of a generator or transmission line) during the operation of the real-time energy market.
- **Forward reserves** represent the procurement of fast-response reserve capability from generators in advance of the delivery period; that is, the ability to start and ramp quickly in the event of system contingencies.
- **Regulation service** refers to generators that alter their energy output over very brief time intervals (minute-to-minute) to balance supply and demand and to maintain frequency in the real-time energy market. [25]

In addition, the ISO-NE's temporary **Winter Reliability Program** offers financial incentives "to certain generating resources to maintain adequate fuel supplies during winter months, intended to remedy fuel supply issues that can threaten reliability."[26] The Winter Reliability Program incentivizes fuel adequacy for the winters of 2013-2014 through 2017-2018, at which time reforms to the region's capacity market become effective. The Pay-for-Performance capacity market reforms, effective on June 1, 2018 are designed to closely link capacity payments to resource performance.

Operating Reserve Requirements

The grid operator's Internal Market Monitor (IMM) provides an excellent summary of the specific operating reserves that ISO-NE requires for reliable short-term operations. From its 2017 annual report, the IMM describes the specific products that contribute to the ISO's operating reserves:

> The ISO maintains a sufficient amount of reserves to be able to recover from the loss of the largest single system contingency (N-1) within 10 minutes. This requirement is referred to as the total 10-minute reserve requirement. Additionally, reserves must be available within 30 minutes to meet 50% of the second-largest system contingency (N-1-1). Adding this additional requirement to the total 10-minute reserve requirement comprises the system total reserve requirement.
>
> Operating reserves are provided by the unloaded capacity of generating resources, either online or offline, which can deliver energy within 10 or 30 minutes. Between 25% and 100% of the total 10-minute reserve requirement must be synchronized to the power system. The exact amount is determined by the system operators, and this amount is referred to as the 10-minute spinning reserve requirement [TMSR]. The rest of the total 10-minute reserve requirement can be met by 10-minute non-spinning reserve (TMNSR). The remainder of the total reserve requirement can be served by 30-minute operating reserves (TMOR).[27] Starting in October 2013, in addition to the total

[25] *ISO New England's Internal Market Monitor 2016 Annual Markets Report,* May 2017, p. 163.

[26] Ibid.

[27] According to the ISO-NE's external market monitor, Potomac Economics, in its *2016 ASSESSMENT OF THE ISO NEW ENGLAND ELECTRICITY MARKETS,* June 2017 report, p. 167, over the past ten auctions, the TMNSR purchase amount has represented the largest single potential contingency outage of the HQ Phase II Interconnection. The

reserve requirement, a replacement reserve requirement was added. The replacement reserve requirement adds 160 MW to the total reserve requirement in the summer and 180 MW to the requirement in the winter. [emphasis added]

In addition to the system-wide requirements, 30-minute reserves must be available to meet the local second contingency in import-constrained areas. Currently, local TMOR requirements exist for the region's three local reserve zones – Connecticut (CT), Southwest Connecticut (SWCT), and NEMA/Boston (NEMABSTN).

The system reserve requirement has been relatively constant over the past four years, with a total ten-minute reserve requirement of about 1,700 MW and total thirty-minute reserve requirement of about 2,500 MW in 2016.[28]

The forward reserve market (FRM) auction at ISO-NE

A forward market auction for reserve capacity[29] occurs twice per year in ISO-NE, prior to the beginning of each seasonal capability period, summer and winter. Forward reserve resources are assigned hourly schedules one day in advance of the operating day.

According to the internal market monitor:

> [t]he auctions award obligations for participants to provide pre-specified quantities of each reserve product. The FRM auction is intended to ensure adequate reserves to meet ten and thirty-minute reserve requirements. Some zones are constrained in terms of how much power they can import from other zones and can have different clearing prices. As a result, instead of having a single reserve requirement for all New England, the ISO identifies requirements at a regional level, as well as a system-wide requirement, for each reserve product procured in the auction.[30]

Regulation Requirements

As the external market monitor for ISO-NE explains:

> [t]he regulation market is the mechanism for selecting and paying resources needed to balance supply levels with the second-to-second variations in electric power demand and to assist in maintaining the frequency of the entire Eastern Interconnection. The

TMOR purchase amount has represented the expected single second contingency outage of either Mystic 8/9 or Seabrook.

[28] *ISO New England's Internal Market Monitor 2016 Annual Markets Report,* May 2017, p 17.
[29] As noted in section V of this primer, readers should be aware that the external market monitor has recommended that the FRM be eliminated soon.
[30] *ISO New England's Internal Market Monitor 2016 Annual Markets Report,* May 2017, p 172.

objective of the Regulation Market is to acquire adequate resources such that the ISO meets NERC's Real Power Balancing Control Performance Standard (BAL-001-2).[31]

Regulation reserves must be able to increase or decrease generation output in response to automated signals from ISO-NE that are received every four seconds. Compensation to each regulation reserve supplier is based on its ability to closely match the automatic generation control (AGC) signal, and is adjusted in proportion to its performance in each interval.

Winter Reliability Program

For the last few years, ISO-NE has run an additional, temporary program that it considers to be an ancillary service, the winter reliability program. The winter program is a seasonal measure designed to encourage certain generators to stockpile or contract for access to spare fuel (such as oil and LNG natural gas). The purpose is to have access to fuel in the event there is otherwise a constraint on natural gas commodity pipeline system in the New England. This constraint has occurred in winter when the combined sale of natural gas for both heating and electricity reaches its normal peak use. The winter program also authorized a supplemental demand response offering. The program is expected to expire after the end of the 2017/2018 winter season. The two offerings of the winter program are to be replaced in June 2018 with "Pay for Performance" modifications to the ISO's Forward Capacity Market. Its costs are currently included in the ISO-NE's calculation of ancillary services.

Cost of ancillary services to New England's consumers

For customers served by ISO-NE, the estimated wholesale cost of ancillary services (in $Billions) for the last five years has varied in large part because of the underlying cost of energy has varied. This has been driven by fluctuations in the price of input fuel to run generators. As Figure 13, below, indicates, ancillary services are a measurable but relatively small proportion of the total cost of the New England wholesale market over the last five years, compared to the amount paid by consumers for energy and capacity.

Figure 13– ISO-NE's wholesale market costs, including ancillary services payments, 2012-2016

Statistic	2012	2013	2014	2015	2016	% Change 2016 to 2015
Estimated Wholesale Costs ($ billions)						
Energy	5.2	8.0	9.1	5.9	4.1	-30%
Capacity	1.2	1.0	1.1	1.1	1.2	5%
Net Commitment Period Compensation	0.1	0.2	0.2	0.1	0.1	-38%
Ancillary Services	0.0	0.2	0.3	0.2	0.1	-30%
Regional Network Load Costs	1.5	1.8	1.8	2.0	2.1	6%
Total Wholesale Costs	**8.0**	**11.2**	**12.4**	**9.3**	**7.6**	**-18%**

Source: *ISO New England's Internal Market Monitor 2016 Annual Markets Report,* May 2017

[31] Potomac Economics, *2016 ASSESSMENT OF THE ISO NEW ENGLAND ELECTRICITY MARKETS,* June 2017, p. 178.

Over the last decade, in fact, that relationship has remained true. See the graphic, below, from the ISO's most recent annual report. The chart illustrates the relative size of the annual value of the region's energy (blue), capacity (green), and ancillary service (black) markets since 2007. The ISO's report notes that in 2016, ancillary services represented approximately 2% the total system costs, including the cost of operating reserve (real-time and forward markets) and regulation as well the costs associated with the out-of-market winter reliability program. The ISO further noted that total ancillary service costs have decreased by 30% from the prior year, in line with lower fuel input costs last year.[32]

Without the temporary winter reliability program, the cost to consumers for the ancillary services provided last year would have been approximately $100 million, or less than 1.5% of total system costs. The program will expire next spring.

> Ancillary services are a measurable but relatively quite small proportion of the total cost to consumers of the New England wholesale market over the last five years.

Figure 14 – Annual cost of the ISO-NE's wholesale market to consumers since 2007

Source: ISO-NE's *2017 Regional Electric Outlook*

[32] ISO-NE's *2017 Regional Electric Outlook*, p. 13.

How do ancillary services in ISO-NE compare to those in other RTOS?

As noted in the introductory section, while there is no single set of universally defined ancillary services, all U.S. RTOs comply with FERC and NERC reliability directives through similar although not identical ancillary services offerings. See the following chart, Figure 15, that categorizes operating reserves and regulation mechanisms relied upon in the various RTOs. While all have regulation, spinning and non-spinning reserves, some RTOs offer more granular products than others.

The discussion below looks more closely at the reliability issues or concerns that are being addressed in two states in the U.S. that currently are among the regions with the largest share of renewables in their respective power systems: Texas and California. Unlike the ISO-NE, both operate as a single-state RTO.

Figure 15 - Comparison of operating reserves and frequency regulation products across RTOs

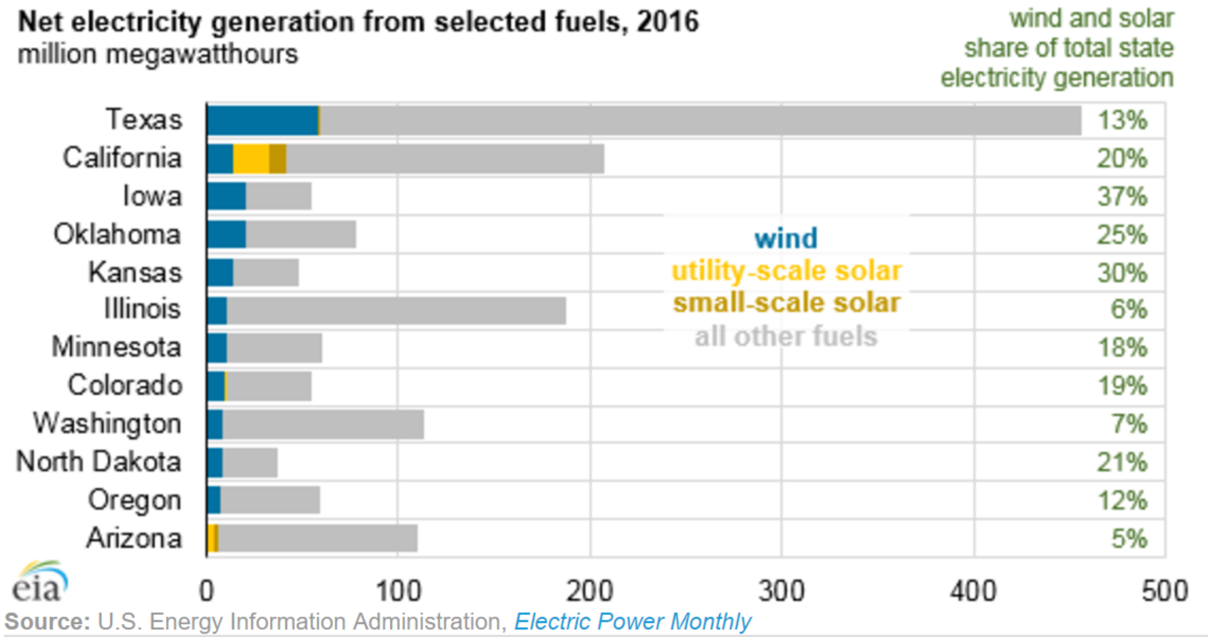
	Spinning Reserves	Non-spinning Reserves	Regulation
CAISO	Spinning	Non-spinning	Regulation-up Regulation-down Regulation Mileage-up Regulation Mileage-down
ERCOT	Responsive	Non-spinning	Regulation-up Regulation-down
ISO-NE	Ten-minute Synchronized	Ten-minute Non-synchronized Thirty-minute Operating	Regulation
MISO	Spinning	Supplemental	Regulation
NYISO	Ten-minute Spinning Thirty-minute Spinning	Ten-minute Non-synchronized Thirty-minute Non-synchronized	Regulation
PJM	Synchronized	Primary	Regulation
SPP	Spinning	Supplemental	Regulation-up Regulation-down

Source: Argonne, *Survey of U.S. Ancillary Services Markets,* 2016

Putting Texas, California, and New England into perspective

Texas and California are currently the two states with the greatest amount of electricity generated from wind and solar. Many US states have added significant amounts of renewables to their power supply mix in the last few years. As seen in Figure 16, below, a chart which ranks the leading states in the production of electricity from wind and solar generation, none of the six New England states currently rank in the top twelve states.

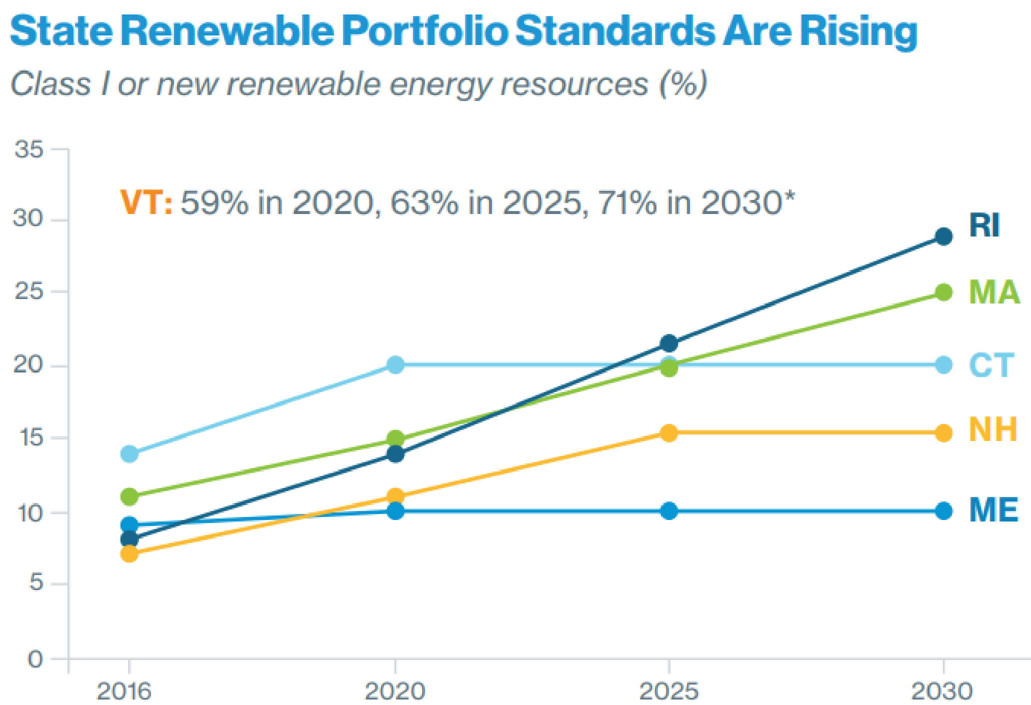
Figure 16 – US states ranked by the greatest amount of wind and solar generation



By comparison, New England's renewable targets currently range from 7-15 percent, although the penetration of renewables in the region will likely rise in response to both planned increases in RPS targets as well as other policy measures. The likely transformation of New England's power grid and implications for its ancillary services will be discussed later in this primer.

Renewable energy in New England will increase over the next decade, in part because of rising policy targets.

Figure 17: New England states' RPS goals



Source: ISO-NE 2017

However, for context it may be helpful to briefly examine how ancillary services are currently provided in two power grids that operate in the US states ranked highest in the largest deployment of renewables, that is Texas and California.

Texas (ERCOT)

The Electric Reliability Council of Texas (ERCOT), an independent system operator that geographically covers most of Texas (see map, below), has experienced significant growth in renewables, particularly large, land-based wind projects over the last decade. Renewable levels in ERCOT well exceed the proportion of renewables in New England. In recent years, ERCOT has been engaged in efforts to redesign its existing ancillary service market, particularly through a multi-year Future Ancillary Service (FAS) process.

Figure 18 – Geographic footprint of the ERCOT RTO

> Despite a significantly larger proportion of wind generation in Texas compared to New England, ERCOT has not yet made major changes to its ancillary services, although it has explored a variety of potential future actions.

Source: Argonne, *Survey of U.S. Ancillary Services Markets,* 2016

Like ISO-NE, the grid operators of ERCOT offer 1) regulation service based on 4-second automated generation control (AGC) signals, 2) a product that is akin to ten-minute spinning reserves called "responsive reserve service" and 3) a thirty-minute non-spinning reserve service, based on its traditional power system of large conventional generators. In ERCOT, each of these ancillary services are procured hourly.[33]

However, as the proportion of wind and natural gas plants grew in Texas, a set of stakeholders and ERCOT staff in 2013 formed the "Future Ancillary Services" Taskforce (FAST) to explore options for and propose changes to the services. The FAST also expressed interest in providing new opportunities for demand response and distributed generation to participate in ancillary services. See Figure 19 for a representation of current and proposed expanded ancillary services in ERCOT, as proposed by FAST.[34]

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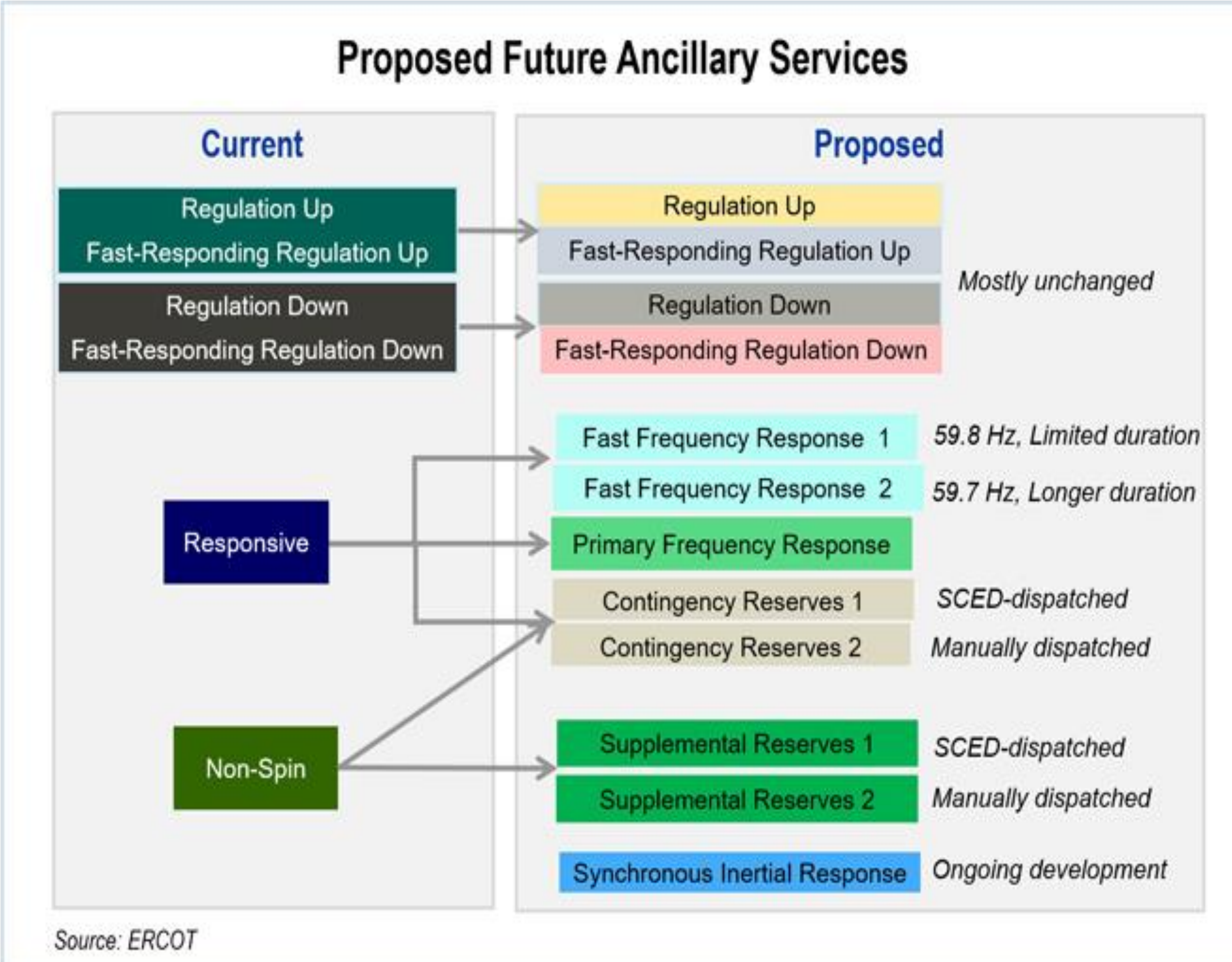
[33] There are, however, significant differences in many of the pricing and planning mechanisms between the two RTOs, including the lack of a capacity market in ERCOT. Additionally, in 2014, ERCOT adopted a demand curve for operating reserves (ORDC) to incentivize resources to produce both energy and reserves in times of shortage.

[34] Many documents related to ERCOT's taskforce activities can be found on its website, including the source of Figure 19, taken from the *FAST Two Pager April 2016 Final* document.

Figure 19 - ERCOT's current and proposed ancillary services of the FAST



One analyst described the rationale for and the proposed changes to ERCOT's current ancillary services in the following way:

> Declining synchronous inertia during high wind and low load conditions has resulted in higher rate of change of frequency than in the past. Differences in response characteristics of new technologies (combined cycle gas turbines with duct firing, demand response, storage, wind, etc.) change the historic relationship in the amounts of each service a resource supplies. The five minute energy market and the hourly reliability unit commitment have also reduced the need for the existing ancillary services.
>
> ERCOT is addressing these changes with the stated intent to base the ancillary service framework on fundamental system reliability needs rather than on the characteristics of the historic generators. Market based requirements are to be technology neutral and flexible enough to accommodate new technologies. Pay for performance will be

implemented where practical. ERCOT will leave regulation unchanged but will split Responsive Reserve into five distinct services. [35]

The proposed changes were in response to the ongoing evolution of the grid in Texas that included "increasing penetration of distributed and utility-scale intermittent generation resources, fast-acting storage devices, the evolution of sophisticated smart grid technologies, and increased use of demand response resources to support grid reliability."[36]

The taskforce proposed a revised framework that would expand ancillary services based on characteristics of different resources, such as unbundling the single frequency response product into five different reserve products, and offering a new fast operating reserve product for resources that could respond in less than a second. According to a review by the independent consulting firm the Brattle Group, if the FAST recommendations had been implemented, they would have created benefits of "about $19.4 million per year due to lower start-up costs, lower-cost procurement in the energy market, and opportunity cost savings in the real-time market."[37]

However, the FAS proposal failed to garner sufficient ERCOT stakeholder support after several years of study and the effort ended in 2016 due to lack of support over the need to move forward with such changes. New proposals to make modifications to reliability-related activities are now under consideration by ERCOT. These include opportunities to incorporate energy storage and expanded demand response into grid reliability operations.

Texas's experience is perhaps instructive to New England. Even after lengthy review of potential enhancements to its current set of ancillary service products, which are quite like ISO-NE's, ERCOT's stakeholders decided not to move forward in 2016 with significant changes. The decision not to make significant changes came even as its share of wind generation grew sharply over the same period. The experience in Texas implies that New England would likely have several more additional years of leeway, relative to ERCOT, before ISO-NE might need to significantly alter its ancillary service products.

California

California has one of the highest penetrations of renewables, both wind and solar, of any region in the U.S. Its ambitious economy-wide carbon policy goals will likely accelerate the penetration of variable generation in the future. As a result, California has been reviewing many reliability issues related to variable generation, to ensure flexibility and resilience of its grid as it increases its renewable penetration goals to 50% by 2030. Among the tools it intends to further incorporate are better integration of distributed solar assets, expanded use of demand response, a robust energy storage resource, and balancing energy over a larger geographic footprint.

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[35] Kirby, *Potential New Ancillary Services: Developments of Interest to Generators,* 2015, p. 8; note that original footnotes have been removed.

[36] *FAST Two Pager April 2016 Final.*

[37] Brattle Group, *Cost-Benefit Analysis of ERCOT's Future Ancillary Services (FAS) Proposal*, December 2015.

Figure 20 – Footprint of the California ISO (CAISO) RTO

California is focused on enhancing the flexibility of its power system to accommodate increasing amounts of renewable generation, through near term changes to operations and to expansion of ancillary services.

Source: Argonne, *Survey of U.S. Ancillary Services Markets,* 2016

NREL analysts, among others, have prepared many insightful reports on California's efforts in recent years to transform its energy sector. A 2016 report that summarizes California's current and prospective activities related specifically to reliable grid operations and renewables includes the following observation:

> Accommodating the changes in net load resulting from increased VG [variable generation] penetration requires enhancements to a power system's "flexibility," or the ability of the grid and generation fleet to balance supply and demand over multiple time scales. Numerous technologies and strategies for increasing flexibility have been implemented already, are being implemented today, or are being developed. These approaches allow VG to be used directly to offset demand and increase instantaneous VG penetration, or they improve the alignment of VG supply and demand.[38]

Among the points NREL calls attention to are changes to grid dispatch and scheduling. These do not require investment in innovative technologies and are considered in California to be a "least cost" option. Other ongoing changes include balancing supply and demand over larger areas, incorporating more demand response to reduce ramp rates, and allowing energy storage to provide reserves. The study used grid simulations to:

> [e]xamine the impact of 'near term' flexibility options in California, likely the first large region in the U.S. to experience significant impacts of PV on the transmission network; for this reason, California is a useful case study to examine how flexibility effects cost-

[38] NREL, *On the Path to SunShot: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System*, 2016, p. vii-viii.

> effective integration of solar resources. Lessons learned from this region may assist other regions in developing strategies to mitigate the impacts of variability and uncertainty of the solar resource.[39]

Although New England may not experience the same level of penetration of solar PV in the near future as California is experiencing now, it is still instructive to examine changes that the state's ISO is making to accommodate intermittent resources.

The DOE's Quadrennial Energy Review noted that the resilience and flexibility issues are under intense scrutiny in California. The QER explicitly suggests that California offers a good test case for other regions that may eventually see their own proportion of wind and solar renewable energy significantly increase. It points to a 2014 study, "Investigating a Higher Renewables Portfolio Standard in California," that identified emerging operations and planning issues, under a 50 percent renewable portfolio standard:

> Concerns in the study included over-generation as a critical management challenge that occurs when "must-run" generation— non-dispatchable renewables, combined-heat-and-power, nuclear generation, run-of-river hydro, and thermal generation that is needed for grid stability—is greater than loads plus exports. The principal mitigation for over-generation in many current systems is curtailing renewable resource contributions to the overall resource mix. Future systems may increase the role of storage, DR, and flexibility to manage over-generation. Second, renewable resources can change supply patterns suddenly, and as the sun sets, significant solar production disappears, requiring a need for fast ramping generation to fill in for lost solar resources. The study also found that a variety of integration solutions can reduce the cost of a high renewable scenario. Improvements in regional coordination—which address jurisdictional challenges when state regulation cannot reach beyond state borders, and Federal regulation cannot easily reach into distribution systems—could improve integration. DR, especially advanced practices that increase overall DR reliability, can support higher levels of VER integration.[40]

> In scenarios with more than 50% renewables, a critical management challenge occurs when "must-run" generation— non-dispatchable renewables, combined-heat-and-power, nuclear generation, run-of-river hydro, and thermal generation that is needed for grid stability—is greater than loads plus exports.

California also has early experience with the deployment of both utility-scale and distributed energy storage, that may be instructive to other regions where storage has not advanced as far. As the DOE QER pointed out,

> [u]tility-scale battery storage and distributed battery storage vary by scale and duration, but perform consistently at any scale from a grid management perspective. When

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[39] Ibid.

[40] USDOE Quadrennial Review, *Transforming the Nation's Electricity System: The Second Installment of the QER,* January 2017, p. 45-46.

> distributed storage is aggregated, it can offer local grid operators greater flexibility for managing system reliability and power quality than utility-scale resources. Aggregation can be scaled to fit specific local needs in distribution systems. An example of grid reliability applications of energy storage is seen in California, where the building of about 60 MW in new battery storage capacity is underway. These installations are being built to resolve reliability issues caused by the Aliso Canyon and the San Onofre Nuclear Generating Station outage, and they will help level out electricity supply in California by moving energy from the afternoon production of solar to the evening peak. While region-specific critical reliability requirements can drive storage deployment, additional incentives can help accelerate these benefits ahead of a major disruption.[41]

As California accommodates larger amounts of energy storage, the grid operator is not necessarily advocating significant modification of its ancillary service practices. Many operational changes on the grid, beyond those implicated in ancillary services, provide necessary flexibility and reliability. As a recent Brattle Group report observes,

> Many operational changes on the grid, beyond those implicated in ancillary services, provide necessary flexibility and reliability.

> With better understanding of system requirements, flexibility needs can be provided by a wide array of existing resources, and through advances in how those resources are operated. Depending on the region and the extent of renewable deployment, additional resources may be needed to provide certain types of operational flexibility. The California Independent System Operator's (CAISO) 2016 report on resource flexibility, for example, discusses how flexibility needs are increasingly involving shorter time scales. The study looked at three times scales: (1) seconds-to-minutes, (2) 5–10 minutes, and (3) multi-hour. CAISO found that the need for 3- hour ramping capacity increased significantly over the 2015–2017 timeframe. The study also described a wide range of existing resources that can provide the required flexibility, including existing natural gas-fired capacity, geothermal, hydroelectric and pumped storage, biomass, oil fired peaking units, solar, and demand response resources.[42]

Operational concerns over intermittent resources such as solar and wind can be eased by ancillary services and other changes to grid operations. This includes fully incorporating the attributes that all resources can provide and other changes to standard grid operations. For example, several analysts have noted that significant recent improvements in weather forecasting based on more sophisticated technology and data solutions have made renewables integration less difficult than it was believed it would have been a decade or more ago.

> Significant recent improvements in weather forecasting based on more sophisticated technology and data solutions have made renewables integration less difficult than it was believed it would have been a decade or more ago.

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[41] Ibid.

[42] Brattle Group*, Advancing Past "Baseload" to a Flexible Grid How Grid Planners and Power Markets Are Better Defining System Needs to Achieve a Cost-Effective and Reliable Supply Mix,* June 2017.

The California Public Utilities Commission (CPUC) Staff reviewed the needs for market reforms as California closes in on its 33% renewables target, and offered the following recommendations regarding ancillary services:

> CAISO currently operates ancillary services markets only for regulation (up and down separately) and for contingency reserves… CAISO is currently considering market frameworks for the provision of and compensation for reactive power (for voltage support), frequency response, and a flexible ramping product.
>
> [I]ncreasing penetration of wind and solar creates an increased need for ancillary services to respond to fluctuations and uncertainties. At the same time, wind and solar generators are less able to provide ancillary services than conventional generators, particularly under current designs and operations. Conventional sources will likely be needed to provide a substantial portion of ancillary services for the near future until new sources, such as advanced storage and [Distributed Energy Resources or] DERs (including controllable demand response, smart inverters, and PEV charging) can provide these services.[43]

The CPUC states that "Initiatives and programs aimed at providing greater supply-side flexibility are underway in five main categories: (i) flexible capacity; (ii) market mechanisms, (iii) regionalization of energy markets, (iv) renewables procurement and valuation; and (v) energy storage."[44] Other changes in grid and market operations on the distribution side are contributing to a "no-regrets" approach in which multiple efforts are underway simultaneously to enhance grid operations. These changes are well-understood by grid operators and the CPUC believes they should yield predictable, successful outcomes, such as improvements in next-day weather forecasting to improve wind and solar dispatch. Longer-term, the state is examining more dramatic improvements and changes. This includes Time-of-Use (TOU) and dynamic rates, enhanced electric vehicle-to-grid (VtoG) and demand response offerings, and new products such as flexible capacity that could better integrate advances in energy storage. The CPUC suggests these enhancements could take place by 2020 to 2025.[45]

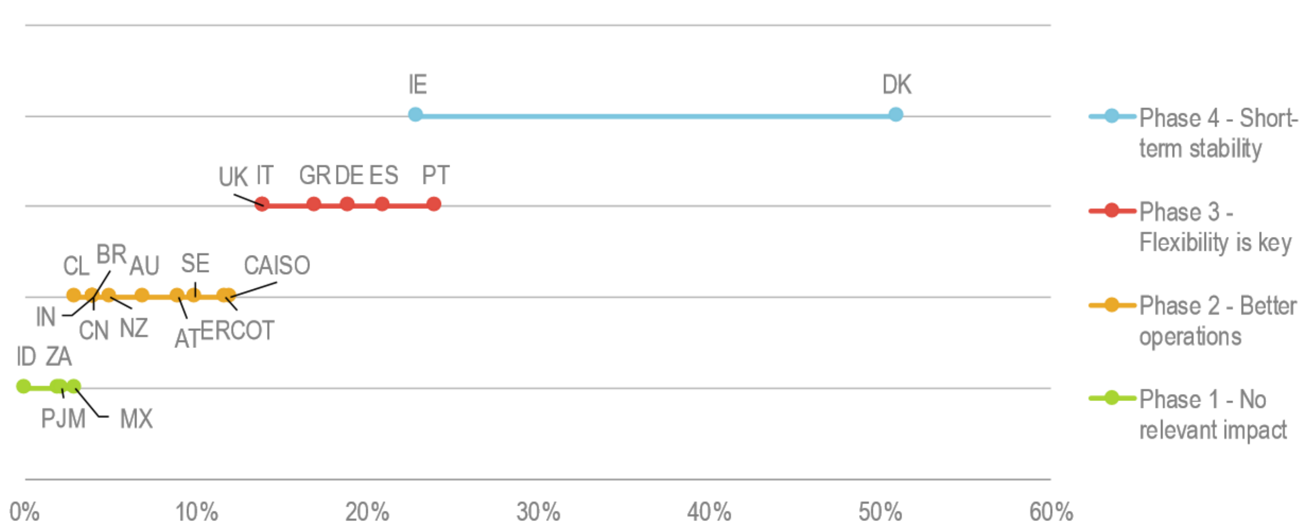
[43] *Beyond 33 Percent Renewables*, CA PUC Staff paper, November 2015, p. 17-18.
[44] Ibid., p. 20.
[45] Ibid*.,* p. 30-35.

III. Lessons from electric systems outside the U.S.

The issue of evolving grid operations to meet changing conditions is not limited to North America. The International Energy Agency (IEA), among many non-U.S. based institutions, has been exploring the broader question of grid transformation. IEA recently issued a paper on this topic, *Status of Power System Transformations 2017*. It identified four phases of evolution in grid operations, based on the amount of variable renewable energy (VRE) in the generation mix of different regions.[46] Its comparison chart, below, summarizes its finding of how various systems around the world are grouped into one of the IEA-ascribed phases.[47]

In the summary chart, observe that in Phase 1, where "VRE" or share of intermittent renewables is less than 5% of the capacity of the system, there is no noticeable impact on grid operations. Note that the ISO-NE, although not included in this mapping by IEA, currently has less than 5% share of variable (i.e., non-hydro) renewables in its mix.

Figure 22 – IEA's comparison of international power systems by share of variable generation and corresponding phase



Notes: AT = Austria; AU = Australia; BR = Brazil; CL = Chile; CN = China; DE = Germany; DK = Denmark; ES = Spain; GR = Greece; ID = Indonesia; IE = Ireland; IN = India; IT = Italy; MX = Mexico; NZ = New Zealand; PT = Portugal; SE = Sweden; UK = the United Kingdom; ZA = South Africa. PJM, CAISO and ERCOT are US energy markets.

Source: Adapted from IEA (2016), *Medium-Term Renewable Energy Market Report 2016*, OECD/IEA, Paris.

[46] In this primer, variable renewable energy (VRE) and variable generation (VG) are used interchangeably.
[47] International Energy Agency (IEA), *Status of Power System Transformations 2017*, p. 4.

In Phase 2, the amount of VRE is approximately 5-15% of the system. Its effects are noticeable to the grid operator but still considered manageable with existing protocols and at most requires modest updates to procedures; CAISO and ERCOT are found at the high end of this group.

At roughly 15%-25% penetration, or Phase 3, the amount of VRE requires the grid operator to potentially provide for additional flexibility on a timescale of several minutes to hours. This may include (but not necessarily require) significant modification or additions to ancillary services; Germany and the United Kingdom (UK or Great Britain) fall within this range.

Finally, in systems where VRE capacity makes up at least 25% or more of the total share of generation, identified by IEA as Phase 4, technology and improved grid operations are necessary to respond to potential disturbances of a few seconds or less. This would, as part of that response, likely require a sophisticated set of ancillary tools to ensure reliability. Only two national grids have been identified as Phase 4 systems, namely Ireland and Denmark.

The IEA report identifies both technical and economic measures, not limited solely to changes in ancillary services, that power systems can adopt as VRE increase to maintain reliability. It notes that integrated planning across both supply and demand resources is necessary, and points to:

> [f]ive broad market, policy and regulatory framework objectives [that] greatly enable the integration of larger shares of VRE in the context of power system transformation:
>
> • ensuring electricity security of supply, including measures to ensure that generator revenues reflect their full contribution to system security;
>
> • operating the power system efficiently at growing shares of variable and decentralised generation, including measures to unlock flexibility from all existing resources, improve dispatch practices by moving operational decisions closer to real time, and encouraging efficient energy price discovery through competitive frameworks;
>
> • providing sufficient investment certainty to attract low-cost financing for capital-intensive investment in clean power generation, including well-structured power purchase agreements (PPAs) for [Independent Power Producer] projects;
>
> • pricing of negative externalities, including measures to constrain carbon emissions and/or local air pollution when appropriate; and
>
> • fostering the integration and development of new sources of flexibility, including from thermal generators, grids, demand response resources and storage.[48]

The five objectives identified by IEA implicate ancillary services and grid operations specifically, and market structures more broadly, including advocating supportive policy mechanisms and better valuing newer flexible resources.

Three European systems with significant amounts of variable generation already deployed in their power systems, Great Britain, Germany, and Denmark, may also offer insight into how regions are adapting to higher levels of renewables. Each is examined in turn, below.

[48] Ibid.

Great Britain

Regulators and utilities in the electricity system in Great Britain have been actively addressing potential changes in reliability products in recent years. This is due to the large share of renewables it has already integrated into the grid and the expectation for further significant growth in its variable generation to meet the nation's carbon policy goals in the future.

According to one stakeholder report,

> [t]he future design of the ancillary services market will be essential to facilitating the transition to a low-carbon electricity system, in which variable renewables, storage and Demand Side Response (DSR) and other nascent technologies will play an increasingly significant role. As deployment increases, so will the need for flexibility to balance demand and supply whilst efficiently ensuring system security across all time horizons, from seconds, hours and days to seasons.[49]

At the request of the UK national regulator, Ofgem, National Grid in 2016 outlined potential changes in its "System Operability Framework" (SOF). The purpose was to address new system parameters and performance that are forecast because of the underlying changes in the generation mix, demand characteristics, modern technologies, and new market and industry governance arrangements. It used National Grid's Future Energy Scenarios to inform the analysis of different potential scenarios that could impact system operability. The SOF identified three key messages around (1) balancing and flexibility; (2) frequency and voltage management; and (3) co-ordination of the entire system. Incorporating ancillary services that reflect distributed generation, DSR, and newer technologies are part of the ongoing analysis.

Another National Grid report on the *Benefits of Interconnectors to GB Transmission System* noted that in the context of ancillary services, expanding the existing high-voltage direct current (HVDC) transmission lines that connect Great Britain to Ireland, France and the Netherlands could significantly improve system reliability as it seeks to meet its post-2020 green policy goals, if ancillary service products related to flows from the HVDC lines were available in the national market.

This primer does not delve deeply into the details of these planning efforts. Those interested in Great Britain's approach are urged to explore reports by Ofgem, National Grid and other stakeholders to appreciate the intensity of the discussions and analyses underway in the UK to address the quickly growing share of variable generation on its system.

Germany

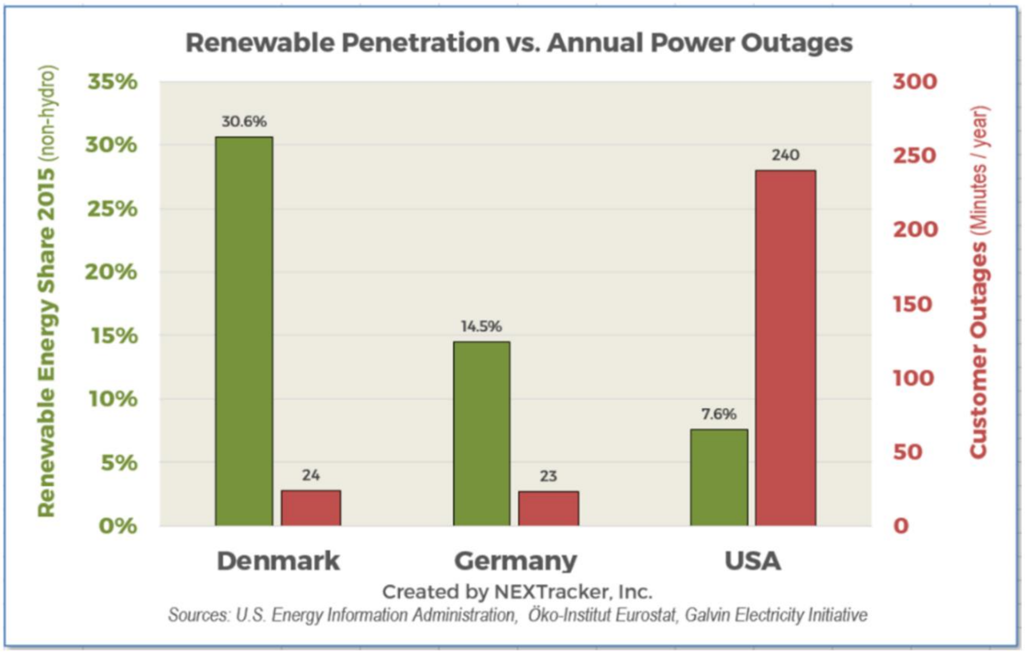
Germany has committed to transforming its economy by reducing its carbon emissions by 80% in 2050 (often referred to as "80x50" policies). This builds on initial efforts to reform the electricity sector

[49] Energy UK, *Ancillary Services Report 2017,* p. 10.

known in Germany as the Energiewende (energy turnaround). As such, Germany is examining many aspects of its power system, including potential changes to ancillary service offerings.

Germany's grid is already highly dependent on renewables. It has one of the lowest customer outage metrics in the developed world (see Figure 23, below). However, a very large proportion of Germany's transmission and distribution lines are underground. This likely contributes to its high reliability metric relative to the U.S., where weather-related outages, especially on distribution lines, are a major source of customer disruptions. In discussions about the impact of renewables on power sector reliability, Germany and Denmark are often cited for their reliable systems despite very high renewable penetration. A better comparison would require that distribution system effects be separated in such statistics.

Figure 23 – Comparison of US, Denmark, and Germany



Source: AWEA report, *Renewable Energy Builds a More Reliable and Resilient Electricity Mix*, May 2017

Nonetheless, Germany is an interesting case study, both for its current share of renewables and its aggressive policy stance to expand that share in the future. Regarding its current ancillary service market:

> [t]here are four transmission operators in Germany, which all share a combined market platform for the procurement of ancillary services. The market is broadly designed into three products – primary, secondary and tertiary control, which vary by required response time after an event that causes a net frequency imbalance. Primary and secondary control are used to provide both frequency response and balancing. Generation, DSR, and storage are able to bid into any/all of the three products.
>
> Primary Control – activated within 30 seconds, and operating for up to 15 minutes
>
> Secondary Control – for participants able to respond within five minutes.

Tertiary Control – activated within 15 minutes, for a period of up to an hour.[50]

Historically, the products are procured in very short-term markets compared to New England: secondary products are procured weekly and tertiary products are procured daily. Pre-qualification of resources is required, but the criteria are the same for all products. Aggregators can combine the bids of participants that would otherwise be too small to operate. Such an aggregation policy would suggest that new, smaller resources, such as energy storage assets and distributed energy resources, may have a better ability to contribute to ancillary services in Germany than in many other power systems that have not yet developed such a broad aggregation rule.

Looking ahead, German policymakers and grid operators are contemplating several potential changes. These include expanding the demand response market, investing in smart grid technology, and dramatically expanding its network of HVDC lines, to support new renewable sources offshore, that would include high performance power electronics for reliability.[51]

The German regulatory agency (DENA) has recently produced a study to suggest what ancillary service changes may be necessary by 2030, as renewable penetration increases to continue progress along the country's path toward its 80x50 goal. It contemplates a future in which conventional resources will not be able to provide all the reserves necessary, and makes recommendations across six dimensions of reliability to better incorporate the contributions of alternative resources including demand response, HVDC lines, and the distribution network. The following table, Figure 24, summarizes its recommendations:[52]

Among its recommendations, DENA is considering ways to potentially expand German wind operations to assist with frequency control (see far left of table) and to explicitly explore distribution system level options (see far right of table).

[50] Ibid., p. 20.
[51] IEEE Spectrum*, Germany's Grid: Renewables-Rich and Rock-Solid,* April 2013.
[52] DENA, *Ancillary Services Study 2030,* July 2014.

Figure 24 - Recommended changes in Germany's reliability measures

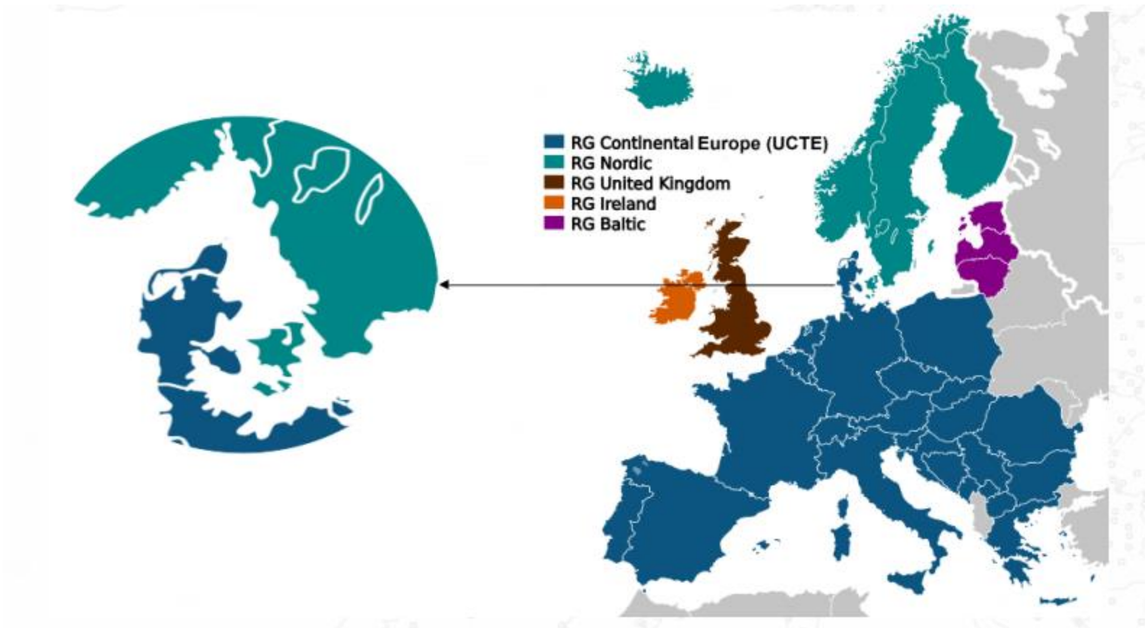
	Frequency control Instantaneous reserve	Frequency control Provision of balancing energy	Voltage control Provision of reactive power	Voltage control Provision of short circuit power	System restoration	System control
Requirements for 2030	▪ Significantly lower contribution by conventional power plants ▪ Without alternative providers, support from the European integrated grid would be required	▪ Demand for secondary balancing energy and minute reserve increases ▪ At times, conventional power plants will not be able to meet this demand	▪ The demand for reactive power in the transmission and distribution grids increases ▪ Increased demand for reactive power control in the distribution grid	▪ Bandwidth of the short circuit power available in future will hardly change ▪ Major time-dependent fluctuation at all grid levels due to decentralised energy units	▪ There are sufficient black start capable power plants to retain the central power supply re-establishment concept	▪ Increasing complexity ▪ Increased need for congestion and feed-in management ▪ Increased need for coordination between transmission and distribution system operators
Alternative providers	▪ Wind turbines ▪ Large-scale ground-mounted solar power plants ▪ Storage capacities	▪ There are alternative providers for all types of balancing energy, which can cover the future demand	▪ Reactive power compensators ▪ HVDC inverter stations ▪ Phase shifters ▪ Power plants in phase shift operation ▪ Provision from decentralised energy plants in the distribution grid	▪ Retooling the inverters in renewable energy plants to allow them to provide short circuit power even without feeding active power	▪ Decentralised system restoration is technically feasible but not macroeconomically efficient	▪ Conventional control technology is sufficient initially to utilise ancillary service potential ▪ Broad-based standardised ICT is required to utilise smaller potential Costs/benefits must be evaluated
Recommended action	▪ Use of the inertia of wind turbines ▪ Long-term: Review of the use of potential from throttling decentralised energy plants and storage facilities	▪ Adaptation of product characteristics and prequalification requirements ▪ Check implementation of adaptive demand calculation for balancing energy	▪ Develop coordinated balancing energy provision from decentralised energy plants in the distribution grid ▪ Check alternative use of reactive power from high voltage for extra high voltage in individual cases	▪ Option for distribution system operators to request short circuit power from decentralised energy plants without active power ▪ Effect on protection concepts must be evaluated in individual cases	▪ Weather and other generation-relevant forecasts must be incorporated in the future concept ▪ It must be possible to control RE systems during system restoration	▪ Esp. distribution system operators must be able to choose between grid expansion and optimised system control ▪ Rapid implementation of the "energy information network"

Source: DENA, *Ancillary Services Study 2030*, July 2014

Denmark

The power system in Denmark is dominated by wind energy, more so than any grid in the world. It has experienced multiple days in which 100% of its electricity has been provided by renewable energy. Denmark's long-term carbon policy goals for the power sector include moving to a fully 100% share of renewables by 2035. Denmark has large capacity interties to both Nordic Pool and Germany. This provides significant balancing benefits to the combined systems. Denmark also participates in the EU-wide "ENTSO-E" reliability framework.

Figure 25 - Denmark's power grid and surrounding grids



Denmark stands out for several innovations regarding its reliability measures, including incorporating a significant amount of distributed Combined Heat and Power (CHP) in the form of district heating. This offers necessary balancing through an active responsive demand program. The nation's utility, Energinet, which operates two distinct grids that reflect the underlying physical geography of the country, also employs sophisticated weather forecasting and an unusual fast ramping program for its coal facilities.

Regarding ancillary services markets, Energinet offers automated sub-30 second frequency regulation, and manual 15 minute and one-hour operating reserves. However, it may be difficult to draw direct lessons from the Danish experience to other regions such as New England. Denmark's extensive inter-European geographic balancing as well as the unique amount of district heating in the power system, rather than any specific feature of its ancillary services market, likely allows Denmark to flexibly operate one of the most renewable-intensive electricity system found today.[53]

[53] Danish Energy Agency, *Regulation and Planning of District Heating in Denmark*, 2016.

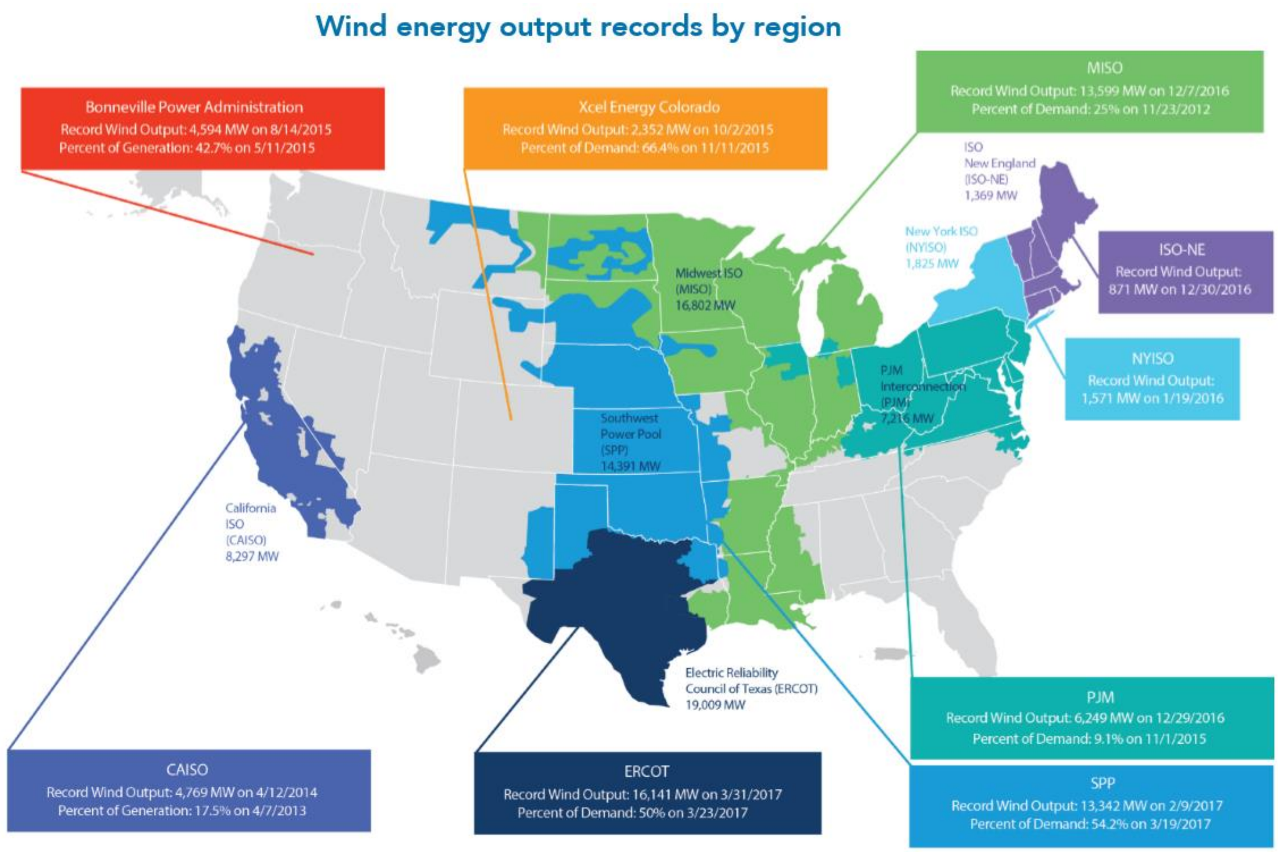
IV. Drivers for Enhanced Ancillary Services

This primer has focused extensively on the growth of renewable resources as a key driver underlying the transformation of power systems around the world. Grid operators and stakeholders are considering potential changes to system operations to be sure the grid can reliably integrate the expected continued growth in variable generation.

Other factors are also in play that may contribute to the energy sector's transformation and to its reliable function. This section will briefly identify drivers that will likely support continued renewables growth. It also mentions a few additional factors that may also influence the timing or specific changes necessary to maintain grid reliability in the future.

Several issues broadly related to reliability and power sector transformation have emerged in recent years. For example, many analysts have examined the potential over-reliance on natural gas fired generation and the possibility of supply constraints in some power systems that could negatively impact reliability. In regard to ancillary services, many stakeholders are looking closely at short term, i.e. hourly or daily, reliability issues that could result from the growing tide of renewables, especially wind. There is no doubt that in the last five years, wind has been added in significant quantities to the US power supply mix, including in New England. New records are being set for electricity produced by wind in many regions. Figure 26, below, shows the wind energy output records by RTO, as of spring 2017.

Figure 26 - Wind records set across the US in sprint 2017



Source: AWEA report, *Renewable Energy Builds a More Reliable and Resilient Electricity Mix*, May 2017

In New England, even though intermittent renewable resources have been increasingly placed in service, they are still a small portion of the total power supply in the region, especially relative to power systems like California or Texas. Natural gas plants have also been added in record numbers, and although supply constraints and lack of fuel diversity as gas displaces other forms of generation can both raise fair concerns about reliability, it is beyond the scope of this paper to delve into those topics, as noted in the introduction.

Renewable penetration is expected to continue to increase in the New England region. This is due to factors including the declining cost of renewable technologies as well as policy measures at the state level to promote carbon reductions. Various state actions include longstanding Renewable Portfolio Standard (RPS) targets, tax incentives for renewable investments, recent initiatives by southern New England states to acquire additional sources of clean energy through solicitations, continued participation in the Regional Greenhouse Gas Initiative (RGGI) carbon cap and trade program, and adoption of various long-term carbon policies e.g., reductions of carbon emissions by 80% from a previous baseline by 2050.

Other drivers of change are also reshaping the electricity sector and raising questions about the need for and/or timing of enhancements to grid operations. For example, NERC has weighed in extensively on the reliability impacts of rapidly growing distributed energy resources (DER). It issued a technical report in 2015 with several recommendations to enhance grid reliability. NERC observed that as two-way flows increase between grid and consumer, and as more devices reflect the advances that the phenomenon known as the “Internet of Things” will likely bring, grid operations may need to adapt to changing trends on the demand side.[54] As noted earlier, California and Germany are both explicitly examining potential changes to reliability tools because of increasing levels of DER.

There are also state efforts underway across the US to explore distribution grid modernization, including in New England and New York. The potential changes that may ultimately arise from the outcome of such efforts could impact the evolution of ancillary services on the bulk power system. However, it is still early in the evolution of the next potential phase of distribution operations, sometimes referred to as Utility 2.0. Outside of California and New York, few U.S. systems have yet reached the point where market rules have been established to accommodate those changes.

Still, regulatory reform at the distribution level could impact the future of ancillary services. Such distribution-level changes may include, for example, the dramatic expansion of two-way power flow resources like electric vehicles whose batteries could potentially be used to provide grid integration services. Many analysts are examining more broadly how such consumer-oriented electric technologies may evolve in the future. Once those technologies are more extensively developed and deployed, NERC expects that its rules will evolve to require that the regional transmission grids adapt to those changes, to maintain reliable daily operations. See Figure 27, below, illustrating how grid reliability may be influenced by the rise of more two-way interactions on the consumer or distribution side of the electric grid.

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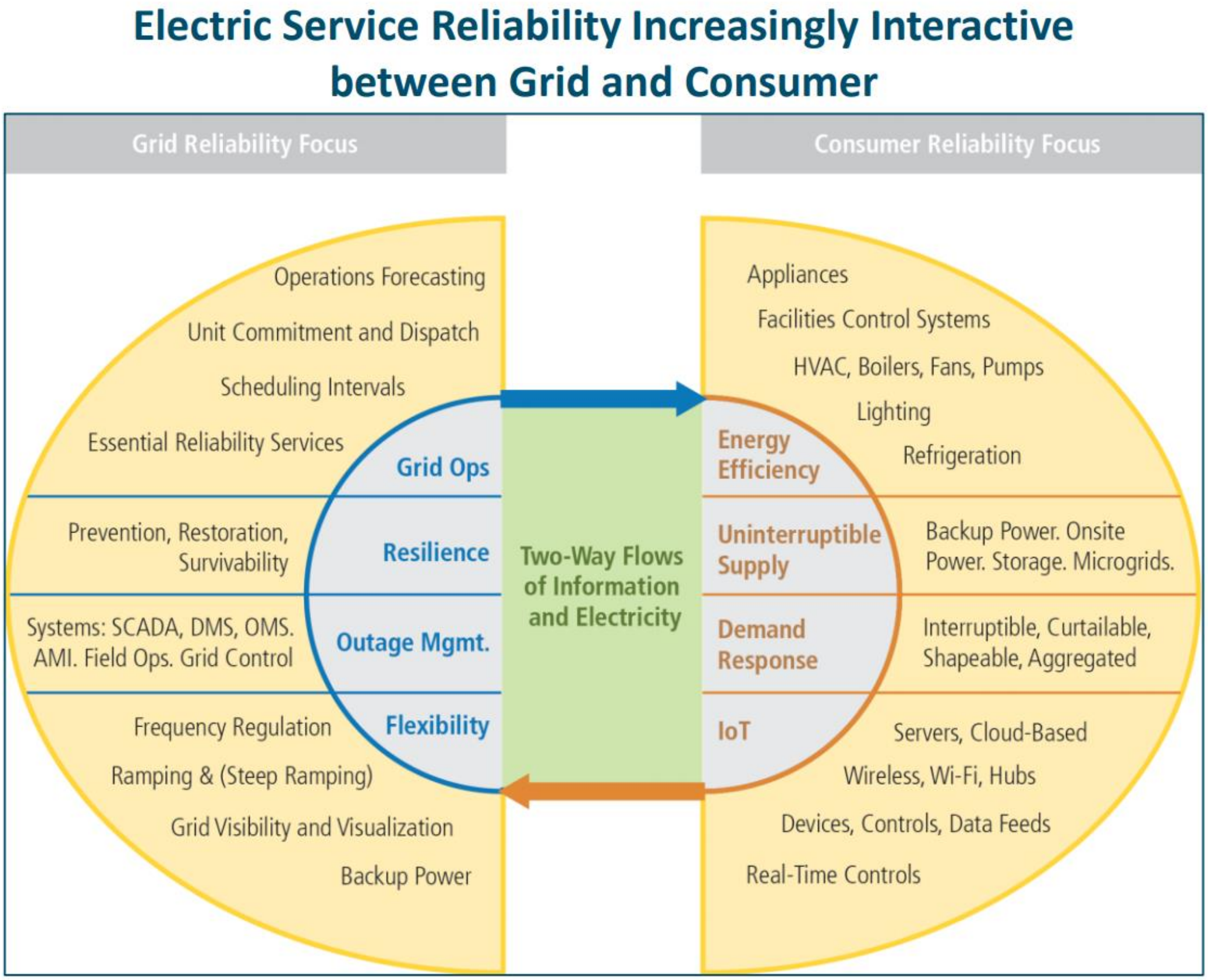
[54] NERC, *Essential Reliability Services Task Force Measures Framework (ERSTF) Report,* November 2015.

Figure 27 – Examples of how interactions between the grid and consumers may grow more complex



Source: Department of Energy, 2016

Another factor impacting the reliability of the power system has been enhancements on the transmission system. These have the potential to reduce the need to rely on increases in or modifications to ancillary services for certain aspects of grid reliability. The DOE notes, in its most recent installment of the Quadrennial Energy Review, that significant advances in phasor measurement units (PMUs) deployment can be interpreted as a first mover in the development of smarter transmission grids.[55] Indeed, the DOE suggests that upstream transmission systems are advancing more consistently and at a faster pace toward smart grid realization than local distribution systems, although recent rate cases and public utility budgets of larger investor-owned utilities and public power entities indicate that smart grid investments are accelerating at the distribution level as well.[56]

[55] DOE, *Quadrennial Energy Review: Second Installment,* January 2017, Chapter IV, p. 4-50.
[56] Ibid., p. 4-48.

In New England, the ISO-NE several years ago began rolled out a pilot project, Synchrophasor Infrastructure and Data Utilization (SIDU), to deploy PMUs across its system, which can make critical reliability measurements 30 times per second. According to ISO-NE, since implementing SIDU in 2013, "the high-speed synchrophasor data and advanced data analytics have been proven to provide valuable information on the regional power system by enabling the monitoring of system dynamics that was previously not possible; fast and accurate post-event analysis; and validating and improving power system models."[57] As the DOE notes, efforts such as these to enhance short-term reliability of the transmission grid directly through technology improvements are ongoing at the grid operator level and may defer or delay the need for other reliability reforms into the future.

[57] ISO-NE press release, July 9, 2015.

V. Potential Adjustments to Ancillary Services Markets

This section offers a view, based on the literature review prepared for this primer, on several related issues: when might changes to ancillary services be necessary, what types of adjustments have consistently been recommended elsewhere, and what that may imply for potential changes to the New England system in the years ahead.

Timing

There is no definitive answer to the question of when, if ever, existing ancillary services need to be modified to adapt to the transformation of the power sector. Over the last decade, many assessments have analyzed potential changes to grid reliability as the power supply shifts toward incorporating greater amounts of renewables. As has been discussed in previous sections, assessments have shown that a modest level of variable generation, such as the amount currently operating on the New England system, does not adversely impact grid operations and typically does not require significant enhancements to reliability measures. As more renewables are added to a power grid, for example to a level that IEA identified as Phase 3 when systems reach 15-25% variable generation, some modification may be necessary.

To date, only relatively modest changes have been made in the U.S. The effort in Texas to propose changes to ancillary services during a period when onshore wind was quickly being added failed to move forward, apparently without adverse impact to ERCOT's reliability. Even California, which has the highest penetration of renewables on its grid in the country except for Hawaii, has not yet made significant modifications to its basic ancillary service products. California is however contemplating a host of measures to do so, involving rule changes to encourage flexible ramping and operational modifications to accommodate a broader range of resources, such as energy storage.

Still, many systems at lower levels of renewables penetration are appropriately looking ahead to consider whether and when significant changes might be necessary as the energy sector continues to evolve, particularly in response to policy directives that will likely continue to encourage low-carbon supply and demand resources to be added in greater numbers to the bulk transmission and distribution systems. Studies recently conducted in both the eastern and western interconnections of the U.S. and in many regional systems suggest that these changes may be years in the making, depending on the pace of deployment of new renewables.

In Europe, where the proportion of variable generation is higher in most grids compared to the U.S., the council of transmission system operators (ENTSO) puts a high priority on making enhancements to ancillary services markets within five years, i.e., by 2022. ENTSO highlights that it is seeking to not only incorporate large utility-scale renewable resources but also allow for better integration of distribution side resources into the grid, with the goal of "…merging ancillary services from aggregated small-energy sources and demand response and management at the [Distribution System Operator] DSO level [to] provide extra means and system services for [Transmission System Operator] TSO operation. New modelling methods and tools for steady-state and dynamic analyses should also be developed."[58]

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[58] European Network of Transmission System Operators for Electricity (ENTSO), *Survey on Ancillary services procurement, Balancing market design 2016*, p. 48.

Likewise, NERC recommends that over time, before making significant changes to North American grids, the measurement of frequency response and voltage be enhanced on the transmission grids, to better quantify the effects from the changing resource mix. It notes that many system operators currently lack sufficient visibility and operational control of these resources. This is a crucial aspect of power system planning, forecasting, and modeling that requires adequate data and information exchanges across the transmission and distribution interface.[59]

Clearly, as grid operators look to measure, maintain and enhance reliability, the speed at which transformations occur on the traditional power system will in turn drive when potential modifications to ancillary services might be required. Given the analyses reviewed for this primer, these modifications will likely be needed gradually, typically over years. In the U.S., there often are lengthy processes in place for stakeholders to explore and assess the implications of such changes.

What changes might lay ahead for ancillary services?

Many studies have considered what changes may be necessary to ancillary services to maintain reliability as power systems evolve. These studies include both hypothetical systems to examine a future where much larger amounts of variable generation have been deployed, as well as studies assessing actual conditions in existing power systems. There is also growing interest in the potential for certain new and emerging technologies, such as the latest advances in renewables, storage, and demand response, to *contribute* to reliability rather than degrade it. For example, the DOE observes that:

> [w]hile one cannot know far in advance the output of any variable resource such as wind and solar, these resources can still play a role in meeting peak demand by taking into account the probabilistic aspects of their generation profile. Aggregation of these resources can reduce their overall variability. Demand response and smart grid technologies can be used to reduce peak load. Lastly, storage can be used to meet peak load by saving power (or thermal energy) from when it is cheaper to generate and using it when it is most valuable.[60]

In the same report, the DOE also points to potential curtailment of renewable resources as another option to contribute to system reliability in the future:

> [Variable generation or] VG itself can be used to mitigate ramp events via curtailment (reduction in output from a generator from what it could otherwise produce given available resources). Curtailment of VG incurs the cost of lost energy production and is typically avoided, but occasional curtailments can be effective for helping balance supply and demand, managing transmission overloads and maintaining system reliability. Specifically, curtailments can be less costly than shutting down and starting up a conventional power plant for a few hours during short periods of high VG output.[61]

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[59] NERC, *State of Reliability 2017*, p. 3.

[60] DOE *Maintaining Reliability in Modern Power Systems,* December 2016, p. 2.

[61] Ibid, p 18-19.

NREL has also provided significant general guidance about ancillary service changes to stakeholders, particularly through its Greening the Grid studies, based on analyses that examined various high renewable energy penetration scenarios. One recent report recommends that stakeholders consider adopting a set of ten measures. These measures include creating incentives and/or interconnection rules applicable to variable generation to take advantage of renewable resources' ability to provide load-following, voltage and frequency response, and to improve controls and communication for distributed energy resources and consumer demand response programs to be able to participate in reserve products.[62]

Developing short-term flexibility products appears to be a key change ahead for ancillary services. The DOE, in describing California's requirement to procure capacity that is flexible enough to address the largest predicted three-hour ramp rate in a given month, noted that:

> …regions throughout the United States are creating new incentives and standards for system flexibility. Proposed standards typically set a flexibility requirement and allow market participants to choose among existing or emerging technologies to meet the requirements…Other system operators are developing tools and practices to address shorter-duration ramps, particularly those created by solar and wind resource uncertainty, by requiring flexibility reserves…[in] response to forecasting errors associated with short-term variations in load or VG resources.[63]

Potential changes in the ISO-NE system

New England has also been examining potential changes in its system. ISO-NE, in its latest Regional Electricity Outlook report from summer 2017, observed that:

> New England's traditional power system is rapidly transforming into a more complex, less predictable hybrid grid where electricity needs are met with large generators and other power resources connected to the regional transmission system, in combination with thousands of small resources connected "behind the meter" directly to retail customer sites or local distribution utilities. In addition to significant amounts of carbon-free renewable energy, the regional generation fleet will need to include fast, flexible power plants ready to jump in and balance the variable output from wind and solar resources; these will likely be natural gas-fired generators in the near term because of their ability to turn on and off quickly. At the local level, rooftop solar systems and battery storage—along with energy-efficiency measures, electric vehicles, and smart meters—are changing how much electricity people draw from the regional power system, when they draw it, and what they add back to the grid.[64]

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[62] Sources cited by NREL on its Greening the Grid website page include *PJM 2012-2013, Cochran et al. 2012, NERC 2011, ICER 2012, and GE Consulting 2014.*

[63] DOE, *Reliability in Modern Power Systems*, December 2016, p. 19.

[64] ISO-NE, *Regional Electricity Outlook,* June 2017, p. 18.

Likewise, other more technical reports issued by ISO-NE show that near-term changes to enhance economic efficiency and maintain reliability are already underway. For example, the internal market monitor's recent annual report describes several design changes occurring this year in the energy and ancillary service products from the previous year. Most of the changes involve the energy market to provide better price formation to incentivize responsiveness to ISO-NE operational directives, that may affect short-duration reliability. Specifically:

Fast Start Pricing (implemented on March 1, 2017)

- On September 24, 2015, rule changes were filed to improve real-time price formation when fast-start resources are deployed. With these changes, a fast-start resource is able to set the real-time [Locational Marginal Price or] LMPs under a broader range of dispatch conditions than under the previous pricing method. In addition, real-time energy prices will better reflect the costs of operating fast-start resources when they are economically committed and dispatched thereby improving price transparency. Further, the changes are intended to improve market efficiency by strengthening performance incentives for all resources during operating conditions when performance tends to matter the most.

Sub-Hourly Settlement (implemented March 1, 2017)

- Under the revised settlement rules, all assets and transactions in the real-time energy and reserve market are settled on a 5-minute basis, rather than on hourly average prices and quantities. The rule changes align the settlement interval with the five-minute energy and reserve pricing intervals. They are intended to improve the incentive to follow price signals in the real-time energy market and to enhance the accuracy of real-time energy and reserve compensation. [65]

RTOs typically make minor changes to rules and procedures related to grid operations each year, and occasionally even major changes (such as adopting a capacity market mechanism). Near-term changes in ancillary services are also contemplated in New England. The ISO-NE's external market monitor (EMM) makes two specific recommendations for future modification to ancillary services in its most recent annual report:

- Introduce day ahead operating reserve markets that are co-optimized with the day-ahead energy market;
- Eliminate the forward reserve market.[66]

The report explains in some detail the EMM's concern about current inefficiencies and potentially extra costs that the proposed modifications might achieve in the near-term. It is beyond the scope of this paper to comment on the efficacy or need for these changes, but readers should be aware that modest changes to rules and markets, including ancillary services, are an ongoing aspect of ISO-NE's activities to maintain a well-functioning wholesale power market and grid.

[65] ISO-NE, *ISO New England's Internal Market Monitor 2016 Annual Markets Report,* May 30, 2017, p. 186.
[66] Potomac Economics, *2016 ASSESSMENT OF THE ISO NEW ENGLAND ELECTRICITY MARKETS,* June 2017, p. xiii.

Summarizing many of the enhancements that are likely to be implemented elsewhere as renewable shares grow, the following list includes possible modifications that the New England region may find itself exploring for adoption in the future:

- Increase awareness and visibility of the impact that all types of resources are having on grid operations, through hardware and software investments at the grid level, to monitor short term operations, frequency and voltage.
- Incorporate, possibly through aggregation products, customer demand response, distributed generation and other distribution level resources such as electric vehicles that can potentially provide reliability enhancements such as reduced ramp rates.
- Adopt rules or incentives to make best use of newer technology such as energy storage that can provide reliability benefits
- Implement software changes to grid dispatch and scheduling, which does not require investment in innovative technologies, to dispatch resources over shorter time periods
- Create additional fast response and flexibility products
- Make use of more sophisticated weather forecasting, and
- Coordinate and balance systems over larger areas to take advantage of geographic diversity of resources sited in neighboring, interconnected systems.

Looking ahead over the next few years, it is likely that the ISO-NE and its stakeholders will grapple with many of the same issues identified in grids around the world that are facing significant changes to the power supply mix. However, given the modest levels of variable generation currently in New England and its expected future growth levels, this issue has time to be further explored. The ISO-NE's ancillary service products are already relatively aligned with RTOs that are already experiencing higher levels of renewables. In the next five to ten years, the lessons that stakeholders in New England can learn from observing the success or failure of specific modifications or enhancements made to system reliability tools in other regions that move ahead first could be put to instructive use.

Appendix 1: Annotated bibliography for Ancillary Services Primer

(all URLS accessed between June - August 2017)

NERC

NERC has created several short, entertaining videos on the basics of grid reliability services.
https://vimeopro.com/nerclearning/erstf-1

For a more comprehensive examination of the evolving landscape for reliability services, see NERC's (November 2015) *Essential Reliability Services Task Force Measures Framework (ERSTF) Report*, which provides a detailed discussion of changes ongoing in the bulk system re reliability services and offers some guidance to the industry in the face of such changes.
http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Framework%20Report%20-%20Final.pdf

See also earlier ERSTF publications, including a concept paper that launched the discussion of Essential Reliability Services (ERS), NERC's *Essential Reliability Services Task Force: A Concept Paper on Essential Reliability Services that Characterizes Bulk Power System Reliability*, (October 2014) and the original announcement of the formation and planned scope of ERSTF (March 2014).
http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Concept%20Paper.pdf; and
http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/Scope_ERSTF_Final.pdf

Annual NERC reports highlight changes and evolution of bulk power markets from both a high-level perspective and in some technical detail. The most recent reports discuss changes in reliability with implications for ancillary services (AS):

- North American Electric Reliability Council, State of Reliability 2014, May 2014, http://www.nerc.com/11_pa/RAPA/PA/Performance_Analysis_DL/2014_SOR_Final.pdf
- North American Electric Reliability Council, State of Reliability 2015, May 2015 http://www.nerc.com/pa/RAPA/PA/Performance%20Analysis%20DL/2015%20State%20of%20Reliability.pdf
- North American Electric Reliability Council, State of Reliability 2016, February 2016 http://www.nerc.com/pa/RAPA/PA/Performance%20Analysis%20DL/2016_SOR_Report_Final_v1.pdf
- North American Electric Reliability Council, State of Reliability 2017, June 2017 http://www.nerc.com/pa/RAPA/PA/Performance%20Analysis%20DL/SOR_2017_MASTER_20170613.pdf

The Reliability Issues Steering Committee (RISC), an advisory committee to the NERC Board of Trustees, recently produced a helpful report (November 2016) meant to define and categorize key reliability risks to the bulk power system in the future, including issues related to ERS.
http://www.nerc.com/comm/RISC/Related%20Files%20DL/ERO_Reliability_Risk_Priorities_RISC_Recommendations_Board_Approved_Nov_2016.pdf

The NERC website offers a landing page that lists the various mandatory reliability rules it enforces as the designated Electricity Reliability Organization, which among other things form the basis for the ancillary services that various RTOs have implemented.
http://www.nerc.net/standardsreports/standardssummary.aspx

A now somewhat dated report (March 2011) from NERC, but still relevant in terms of exploring potential AS concerns at the time and to appreciate how AS has evolved in the intervening years, is *Ancillary Service and Balancing Authority Area Solutions to Integrate Variable Generation*. http://www.nerc.com/files/ivgtf2-3.pdf

Although not recent, NERC's excellent Special Report, *Accommodating High Levels of Variable Generation,* is a thorough discussion of how then current (April 2009) planning and operations could integrate much more substantial amounts of renewable resources. It includes useful technical reviews of intermittent resources contributions to AS and recommendations for future action to enhance reliability. http://www.nerc.com/files/ivgtf_report_041609.pdf

Also of interest is NERC's 2012 Special Assessment on *Interconnection Requirements of Variable Generation* that follows up from a larger initial effort in 2007 to identify and recommend changes to grid operations and rules to accommodate various forms of VG, especially solar. http://www.nerc.com/files/2012_ivgtf_task_1-3.pdf

For the more technically inclined, NERC's *Balancing and Frequency Control* report dives deeply into the nuts and bolts of primary and secondary frequency regulation, albeit in an accessible way. (January 2011). http://www.nerc.com/docs/oc/rs/NERC%20Balancing%20and%20Frequency%20Control%20040520111.pdf

Also, see NERC's analysis of the events leading up to the August 2003 Eastern Interconnect blackout, the cause of which was deemed to be a voltage event. http://www.nerc.com/docs/docs/blackout/NERC_Final_Blackout_Report_07_13_04.pdf

DOE & National Labs

The US Department of Energy (DOE) and its national labs have collectively published many excellent reports, some directly on AS topics and others that address broader issues related to the security and reliability of the grid.

An excellent recent DOE report, *Maintaining Reliability in the Modern Power System* (December 2016) discusses how reliability tools may evolve as the power system changes in the future. https://www.energy.gov/sites/prod/files/2017/01/f34/Maintaining%20Reliability%20in%20the%20Modern%20Power%20System.pdf

DOE's *2015 Wind Vison Stud*y outlined a pathway to greater renewable integration, with some high-level mention of the likely evolution of AS; see in particular Chapter 4. https://www.energy.gov/sites/prod/files/wv_chapter4_the_wind_vision_roadmap.pdf

The DOE's *Quadrennial Energy Review* provides a wealth of interesting analysis. See the landing page https://energy.gov/epsa/quadrennial-energy-review-qer for downloadable reports, including executive summaries. Of note, the January 2017 QER second installment report, Chapter IV, provides a useful discussion of the possible evolution of the grid to 2040 to accommodate future renewable energy and includes specific recommendations to ensure reliability and cost-effectiveness.

Of current interest is DOE Secretary Perry's April 2017 announcement of a 60-day grid reliability review, https://s3.amazonaws.com/dive_static/paychek/energy_memo.pdf The delayed final report, *Staff Report to the Secretary on Electricity Markets and Reliability,* was issued August 23, 2017 and can be downloaded at https://energy.gov/staff-report-secretary-electricity-markets-and-reliability.

National Renewable Energy Laboratory (NREL)

- *Greening the Grid* website maintained by NREL that provides basic info on AS. http://greeningthegrid.org/integration-in-depth/ancillary-services
- Cites of case studies from NREL's greening the grid home page; see, e.g., reports on Spain and India. http://greeningthegrid.org/integration-in-depth/ancillary-services#ReadingListAndCaseStudies
- Excellent recent analysis of potential impact on reliability of integrating more solar on the grid. Denholm et al, *On the Path to SunShot: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System*, (2016). http://www.nrel.gov/docs/fy16osti/65800.pdf
- The Eastern Integration Grid study was a major study encompassing multiple eastern US RTOs. Among its conclusions was that integrating more wind is feasible without significant grid design changes if coordinated over larger area, and ensuring proper incentives for reliability services, *Eastern Renewable Generation Integration Study,* (August 2016). https://www.nrel.gov/grid/ergis.html
- The massive Western grid integration study provides a similar level of insight and technical detail for Western RTOs and balancing authorities. Of note, *Western Wind Integration Study Phase 3 - Frequency Response and Transient Stability*, (December 2014). http://www.nrel.gov/docs/fy15osti/62906.pdf
- Jaquelin Cochran, Paul Denholm, Bethany Speer, and Mackay Miller, *Grid Integration and the Carrying Capacity of the U.S. Grid to Incorporate Variable Renewable Energy* (Golden, CO: National Renewable Energy Laboratory, 2015), NREL/TP-6A20-62607. https://energy.gov/epsa/downloads/grid-integration-and-carrying-capacity-us-grid-incorporate-variable-renewable-energy
- NREL's meta-study of various high-renewable studies offers useful summary of the analysis of several of the studies listed in this bibliography. *Relevant Studies for NERC's Analysis of EPA's Clean Power Plan 111(d) Compliance*, (June 2015). http://www.nrel.gov/docs/fy15osti/63979.pdf
- Report that suggests how technology improvements might give wind resources additional opportunity to contribute to AS, such as through synthetic frequency control. *Active Power Controls from Wind Power: Bridging the Gaps* (January 2014). http://www.nrel.gov/docs/fy14osti/60574.pdf
- Somewhat dated (April 2013) but in-depth presentation re need for ancillary services to evolve as renewable integration increases, including analysis that suggests advanced weather forecasting will solve some of the potential problems. http://www.nrel.gov/docs/fy13osti/58553.pdf

- A huge study first released in 2012, the NREL's *Renewable Energy Futures Study (RE Futures)* speculates on the possible pathways necessary to achieving 80x50 goals (i.e. 80% carbon reduction by 2050); Volume 4 includes a discussion of grid operations and needed flexibility in the future to accommodate massive amounts of renewables. See link to download sections of the 2012 study and related updates. http://www.nrel.gov/analysis/re_futures/
- A relatively early technical review of potential changes in AS was NREL's *Effective Ancillary Services Market Designs on High Wind Power Penetration Systems* (December 2011). http://www.nrel.gov/docs/fy12osti/53514.pdf
- Another early review reflecting expectations at the time was this NREL report that thoroughly discusses *Operating Reserves and Variable Generation*, (August 2011). http://www.nrel.gov/docs/fy11osti/51978.pdf
- Discussion of frequency response by GE Energy, *Eastern Frequency Response Study,* (May 2013), http://www.nrel.gov/docs/fy13osti/58077.pdf
- *DR Resources for Energy and Ancillary Services in the West -- EUCI: Western Energy Imbalance Market Demand Side and Transmission Solutions,* (August 2013) – NREL & LBNL joint publication http://www.nrel.gov/docs/fy14osti/60165.pdf
- For a synopsis of the concept of imbalance markets, using the western EIM as the example, see this two-page summary from NREL, http://www.nrel.gov/docs/fy12osti/56236.pdf
- Discussion of the basics of contingency reserves, Hummon, et al, *Fundamental Drivers of the Cost and Price of Operating Reserves*, (2013). http://www.nrel.gov/docs/fy13osti/58491.pdf

Lawrence Berkeley National Labs (LBNL)

- Useful as a marker of where ancillary services were 10 years ago and the related issues of concern at that time: Lawrence Berkeley Labs, *Loads Providing Ancillary Services: Review of International Experience,* (May 2007) https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/Loads_providing_Ancillary_Services_main_report_62701.pdf
- Interesting discussion of demand response as AS; while somewhat dated, it offers a useful snapshot in time (2013) of the state of AS in various RTOs. Cappers et al, *Market and Policy Barriers for Demand Response Providing Ancillary Services in U.S. Electricity Markets*. http://www.ourenergypolicy.org/wp-content/uploads/2013/08/lbnl-6155e.pdf
- Most current LBL wind market report (Aug 2015) provides aggregate statistics on wind penetration et al. https://emp.lbl.gov/publications/2015-wind-technologies-market-report

Argonne National Lab

- Argonne's excellent high-level survey of AS products in each of the US RTO markets and some comparison statistics, *Survey of U.S. Ancillary Services Markets,* (January 2016). http://www.ipd.anl.gov/anlpubs/2016/01/124217.pdf

Pacific Northwest National Lab

- Highly technical but interesting discussion of distributed assets/smart grid related technology's potential role in providing frequency control and related AS, *Distributed Smart Grid Asset Control Strategies for Providing Ancillary Services*, (Sept 2013). http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22875.pdf
- Another highly technical review, looking at distributed DR as a potential AS source, *Transactive Control and Coordination of Distributed Assets for Ancillary Services,* (Sept 2013). http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22942.pdf

ISO/RTO council

ISO/RTO Council's *Emerging Technologies Task Force, Emerging Technologies: How ISOs and RTOs can create a more nimble, robust bulk electricity system*, March 2017, available at http://www.isorto.org/Documents/NewsReleases/PUBLIC_IRC_Emerging_Technologies_Report.pdf

FERC

The Federal Energy Regulatory Agency (FERC) has jurisdiction over, among other things, the RTO market rules that provide for transparent pricing of ancillary services. Several proceedings in the last five years have dealt with an expansion of the transparency of and access to AS products as reflected by changes to RTO market rules approved by FERC. A rough chronology:

- Ancillary services were defined by the FERC in its seminal Order 888 (April 1996) and added to in Order 890 (February 2007), i.e. its Open Access Rules, where transmission providers were directed to include several types of ancillary services in their open access transmission tariff.
- In the wake of the massive August 2003 east coast blackout, which was caused by voltage collapse, the FERC Staff issued a very helpful report in February 2005 on the role of reactive power in maintaining grid reliability, *Principles for Efficient and Reliable Reactive Power Supply and Consumption*, Docket AD05-1-000, https://www.ferc.gov/CalendarFiles/20050310144430-02-04-05-reactive-power.pdf
- In 2005, FERC issued Order 661, which exempted large wind generators from having to provide reactive service, on the basis that it would be unduly expensive and could inhibit the growth of the wind industry. [Note that in 2016 this exemption was reversed by Order 827, in large part because the cost for wind generators to provide such service has fallen dramatically in the last decade.]
- After various inquiries and investigations, including https://www.ferc.gov/media/news-releases/2012/2012-2/06-21-12-E-2.asp, FERC issued Order 755 (2011) which created opportunities for flywheels and other fast responding resources to participate in RTO regulation markets. FERC Order 784, issued in 2013, expanded the access to frequency regulation from energy storage resources. https://www.ferc.gov/whats-new/comm-meet/2013/071813/E-22.pdf
- FERC inquiry AD14-14-000, Price Formation in Energy and Ancillary Services Markets Operated by Regional Transmission Organizations and Independent System Operators, in 2014 expanded earlier evaluations of issues regarding price formation in the energy and ancillary services

markets operated by RTOs/ISOs. https://www.ferc.gov/industries/electric/indus-act/rto/AD14-14-000.pdf

- FERC Staff report on *Paying for Reactive Power* (April 2014) provides useful background and technical discussion on the provision of reactive power and comparison across RTOs (e.g., see page 15 for a summary chart). https://www.ferc.gov/legal/staff-reports/2014/04-11-14-reactive-power.pdf
- In November 2015, the Commission issued an order (AD14-14-000) that directed each RTO/ISO to report on these five price formation topics: fast-start pricing; managing multiple contingencies; look-ahead modeling; uplift allocation; and transparency. https://www.ferc.gov/whats-new/comm-meet/2015/111915/E-2.pdf
    - See the ISO-NE's response (March 2016) to FERC's request for a report: https://www.iso-ne.com/static-assets/documents/2016/03/ad14-14-000.pdf
- November 2015 proposal to require all wind plants interconnecting with grids to possess reactive power capability. Final rule issued June 2016, https://www.ferc.gov/whats-new/comm-meet/2016/061616/E-1.pdf
- FERC issued Order 819, Docket RM15-2-000, (November 2015) to allow third parties to provide frequency response at market-based rates, https://www.ferc.gov/whats-new/comm-meet/2015/111915/E-1.pdf
- FERC issued Order 827 (June 2016) reversing the decade-long exemption on wind generators to provide reactive power. https://www.ferc.gov/whats-new/comm-meet/2016/061616/E-1.pdf
- FERC opened an inquiry (February 16, 2016), Docket No. RM16-6-000, *Essential Reliability Services and the Evolving Bulk-Power System—Primary Frequency Response*, aimed to examine provision and compensation of frequency responses as an "essential reliability service" as defined by NERC. Inquiry is ongoing; latest action (August 2017) is request for supplemental comments, https://www.ferc.gov/CalendarFiles/20170818171345-RM16-6-000.pdf
- FERC issued NOPR RM17-3-000 (December 2016), re Fast-Start Pricing in Markets Operated by Regional Transmission Organizations and Independent System Operators to examine whether all RTOs should adopt market rules regarding "fast start" resources. https://www.ferc.gov/whats-new/comm-meet/2016/121516/E-2.pdf

Much of FERC's actions over the last 15 years is summarized in an excellent document recently issued by FERC Staff, *FERC Reliability Primer 2016*, https://www.ferc.gov/legal/staff-reports/2016/reliability-primer.pdf

Also see FERC Staff document, *Common Metrics Report: Performance Metrics for Regional Transmission Organizations, Independent System Operators, and Individual Utilities for the 2010-2014 Reporting Period*, June 2016, which provides helpful comparisons of US RTOs across many measures. https://www.ferc.gov/legal/staff-reports/2016/08-09-common-metrics.pdf

ISO-New England

For a high-level understanding of ISO-NE operations, see the most recent annual Regional Electricity Outlook (REO) reports, which are clearly written and accessible to the lay reader.

- https://www.iso-ne.com/static-assets/documents/2017/02/2017_reo.pdf
- https://www.iso-ne.com/static-assets/documents/2016/03/2016_reo.pdf

ISO's "101" on energy and ancillary services (May 2014) is an excellent introduction to AS products in New England. https://www.iso-ne.com/static-assets/documents/2014/08/iso101-t3-mktcore.pdf

More detailed yet still high-level training materials prepared by ISO-NE on wholesale markets, including AS, for readers who wish to go deeper in understanding the New England reserve and regulation products:

- https://www.iso-ne.com/static-assets/documents/2017/04/20170403-02-wem101-bulk-power-overview.pdf
- https://www.iso-ne.com/static-assets/documents/2017/04/20170403-16-wem101-reserve-mkt-overview.pdf
- https://www.iso-ne.com/static-assets/documents/2017/04/20170403-17-wem101-reserve-mkt-settle.pdf

To review the ISO's technical document that underlies the markets for regulation and operating reserves (spinning and non-spinning), see ISO New England Operating Procedure No. 8: Operating Reserve and Regulation http://www.iso-ne.com/static-assets/documents/rules_proceds/operating/isone/op8/op8_rto_final.pdf

Internal Market Monitor (IMM) reports offer thorough discussions of market operations and suggestions for future modifications of market rules, including specific section discussing ancillary service products.

- IMM 2016 annual report (May 30, 2017) https://www.iso-ne.com/static-assets/documents/2017/05/annual_markets_report_2016.pdf
- IMM 2015 annual report (May 26, 2016) https://www.iso-ne.com/static-assets/documents/2016/05/20160526_amr15_release__final.pdf

External Market Monitor (EMM) reports also provide a thorough discussion and data points regarding ISO-NE market outcomes, including key statistics of price trends in the AS market.

- https://www.potomaceconomics.com/wp-content/uploads/2017/07/ISO-NE-2016-SOM-Report_Full-Report_Final.pdf (June 2017)
- EMM 2015 annual report (June 15, 2016) https://www.iso-ne.com/static-assets/documents/2016/06/isone_2015_emm_report_final_6_14_16.pdf
- EMM 214 annual report (June 15, 2015) https://www.iso-ne.com/static-assets/documents/2015/06/isone_2014_emm_report_6_16_2015_final.pdf

To find current real-time prices on the eight AS market products, among other pricing data, see ISO Express website: https://www.iso-ne.com/isoexpress/web/reports/pricing/-/tree/ancillary

Some helpful layman-level discussions of various aspects of ISO-NE operations can be found on the ISO's newswire website, including

- Description of 2015 changes to the regulation market http://isonewswire.com/updates/2015/4/7/redesigned-regulation-market-now-in-effect.html

- Discussion in 2016 of potential impact of energy storage on ISO operations http://isonewswire.com/updates/2016/6/22/new-energy-storage-options-emerging-in-new-england-iso-ne-pu.html

Another interesting discussion of the potential role of energy storage in ISO-NE, including graphics related to AS (2017). https://www.iso-ne.com/static-assets/documents/2017/04/20170411-webinar-energy-storage.pdf

Filing by ISO-NE at FERC: *Independent System Operator (ISO) New England, ISO New England Inc. and New England Power Pool, Market Rule 1 Revisions to Increase Resource Dispatchability; Docket No. ER17-68-000 (ISO New England, October 2016).* https://www.iso-ne.com/static-assets/documents/2016/10/er17-68-000.pdf

For an overview from 2011 of the structure of ISO markets at that time, including AS http://www.gridwiseac.org/pdfs/tew_2011/presentations/burkepres_tew11.pdf

Executive summary of study prepared by GE Energy, that examined what might happen if ISO-NE supply mix reached 24% variable generation by 2020, *Final Report: New England Wind Integration Study*, (2013). http://variablegen.org/wp-content/uploads/2013/01/newis_es.pdf

An overview of and links to the ISO-NE's smart transmission grid efforts involving sychrophasors can be found here: http://isonewswire.com/updates/2015/7/9/synchrophasor-technology-data-helping-to-ensure-grid-reliabi.html

Other RTOs/Wholesale Markets

PJM

- A good starting point is the discussion of AS markets in the external monitor's latest report: http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2016/2016q2-som-pjm-sec10.pdf
- An extensive report recently issued (March 2017) describes how the generation mix in PJM is changing and how specific generation attributes relate to reliability; this report was sparked in part by reliability concerns stemming from the region's polar vortex experience in 2014. http://www.pjm.com/~/media/library/reports-notices/special-reports/20170330-pjms-evolving-resource-mix-and-system-reliability.ashx

NYISO

- Long Island Power Authority, The Need for and Design of a Ramping Product, BPWG (May 2017) available at http://www.nyiso.com/public/webdocs/markets_operations/committees/mc_bpwg/meeting_material/2017-05-08/The%20Need%20for%20and%20Design%20of%20a%20Ramping%20Product.pdf

- NYISO Market Monitor reports provide commentary on ancillary service issues; see for example, *New York ISO Electricity Markets Second Quarter of 2016*, August, 2016, http://www.nyiso.com/public/webdocs/markets_operations/documents/Studies_and_Reports/ReportMMU_Quarterly_Reports/2016/NYISO%20Quarterly%20Report_2016-Q2_Final.pdf

California

- CAISO site for documents related to its current AS products, http://www.caiso.com/Documents/Section8_AncillaryServices_Jul1_2013.pdf
- See also the ISO's assessment of the region's current reliability, *California ISO 2016 Annual Report on Market Issues & Performance*, May 2017, available at https://caiso.com/Documents/2016AnnualReportonMarketIssuesandPerformance.pdf
- CPUC Staff's review of potential changes to the state's grid as renewable integration approaches 33% goal, November 2015, *Beyond 33 Percent Renewables,* http://www.cpuc.ca.gov/uploadedFiles/CPUC_Website/Content/Utilities_and_Industries/Energy/Reports_and_White_Papers/Beyond33PercentRenewables_GridIntegrationPolicy_Final.pdf
- Independent consultant's discussion of CA-ISO's DER reliability measures, http://www.scottmadden.com/insight/ferc-approves-aggregated-der-caisos-energy-ancillary-markets/
- J.H. Nelson and L.M. Wisland, 2015, *Achieving 50 Percent Renewable Electricity in California: The Role of Non-Fossil Flexibility in a Cleaner Electricity Grid*, Union of Concerned Scientists; http://www.ucsusa.org/sites/default/files/attach/2015/08/Achieving-50-Percent-Renewable-Electricity-In-California.pdf
- also: D. Lew, M. Schroder, N. Miller, and M. Lecar, 2015, *Integrating Higher Levels of Variable Energy Resources in California*, with GE Energy Consulting, http://www.largescalesolar.org/files/Final-CA-VER-Integration-6-15-15.pdf
- CAISO positive experiment with utility scale solar providing frequency response (January 2017 report) http://www.caiso.com/Documents/UsingRenewablesToOperateLowCarbonGrid-FAQ.pdf (see also a useful article from GTM discussing the experience: https://www.greentechmedia.com/articles/read/PV-Plants-Can-Rival-Frequency-Response-Services-From-Natural-Gas-Peakers)
- For some historical perspective, albeit highly technical, this national lab paper discusses the need for faster frequency control and other changes to the CA's market, circa 2008 "Assessing the Value of Regulation Resources Based on Their Time Response Characteristics" http://www.pnl.gov/main/publications/external/technical_reports/PNNL-17632.pdf
- CA is exploring a regional imbalance market through SB350 process; includes discussions of needs of future grid with substantially larger renewable penetration, noting that a larger balancing area will reduce need to procure more frequency https://www.caiso.com/Documents/Presentation-SB350RatepayerImpactsAnalysis-BrattleGroup.pdf
- NERC and CAISO (November 2013), *2013 Special Reliability Assessment: Maintaining Bulk Power System Reliability While Integrating Variable Energy Resources – CAISO Approach*,

http://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERCCAISO_VG_Assessment_Final.pdf

- Discussion of potential changes to voltage-related ancillary services in the CA-ISO, *Reactive Power Requirements and Financial Compensation, Revised Straw Proposal October 8, 2015*, https://www.caiso.com/Documents/RevisedStrawProposal_ReactivePowerRequirements_FinancialCompensation.pdf

Texas

- ERCOT formed a Future Ancillary Services Team (FAST) to explore AS issues starting in 2013. See large list of downloadable papers available at http://www.ercot.com/committee/fast, including *ERCOT, Future Ancillary Services in ERCOT, ERCOT Concept Paper, Draft Version 1.1,* November 2013 http://www.ercot.com/content/mktinfo/dam/kd/ERCOT%20Methodologies%20for%20Determining%20Ancillary%20Service.zip
- Samuel A. Newell, Rebecca Carroll, Pablo Ruiz, and Will Gorman, *Cost-Benefit Analysis of ERCOT's Future Ancillary Services (FAS) Proposal*, prepared for ERCOT, December 21, 2015, available at http://www.brattle.com/system/news/pdfs/000/000/982/original/Cost-Benefit_Analysis_of_ERCOT's_Future_Ancillary_Services_%28FAS%29_Proposal.pdf?1450901946
- Summary of the FAST efforts including the graphic used in primer, http://www.ercot.com/content/wcm/lists/89476/FAS_TwoPager_April2016_FINAL.pdf
- Description of the failure of the FAS taskforce, https://www.greentechmedia.com/squared/read/the-low-down-on-texass-efforts-to-bring-distributed-energy-to-grid-markets

Southwest Power Pool (SPP)

- Southwest Power Pool, 2016 Wind Integration Study, (January 2016), available at https://www.spp.org/documents/34200/2016%20wind%20integration%20study%20(wis)%20final.pdf

Ontario (IESO)

- Johannes Pfeifenberger, Kathleen Sees, Judy Chang, Mariko Geronimo Aydin, et al., The Future of Ontario's Electricity Market: A Benefits Case4 Assessment of the Market Renewal Project, prepared for IESO, April 20, 2017, available at http://brattle.com/system/news/pdfs/000/001/217/original/Benefits-Case-Assessment-MarketRenewal-Project-Clean-20170420.pdf?1493215752
- IESO report on HDVC Interties that touches on AS benefits, http://www.theimo.com/Documents/IntertieReport-20141014.pdf as does this recent report (May 2017) that examines the benefits of the interties specifically between Ontario and Quebec.

http://www.ieso.ca/-/media/files/ieso/document-library/power-data/supply/intertiereport-20170508.pdf?la=en

International

International Energy Agency (IEA) has for many years been issuing reports on renewable energy, including reports in its grid integration of variable renewable energy (GIVAR) program, under the Power of Transformation rubric.

- Particularly relevant is 2014's report that discuss fifteen country case studies. https://www.iea.org/publications/freepublications/publication/the-power-of-transformation---wind-sun-and-the-economics-of-flexible-power-systems.html and a related fact sheet of high-level insights https://www.iea.org/media/presentations/PowerOfTransformation_Factsheet.pdf
- The most recent iteration is the 2017 study; see the executive summary for policymakers here https://www.iea.org/publications/freepublications/publication/StatusofPowerSystemTransformation2017SummaryforPolicyMakers.pdf

For a broad discussion of European electricity issues, see this IRENA report on grid integration challenges, which includes a brief section on ancillary services (April 2015). http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP_Tech_Brief_Power_Grid_Integration_2015.pdf

For a comprehensive look at Europe's AS markets, see the ENTSOE's (March 2017) *Survey on Ancillary services procurement, Balancing market design 2016*, https://www.entsoe.eu/Documents/Publications/Market%20Committee%20publications/WGAS_Survey_final_10.03.2017.pdf

Also see ENTSOE's 10-year R&D plan, which anticipates exploring "enhanced" AS from 2022-2027. http://riroadmap.entsoe.eu/wp-content/uploads/2016/06/entsoe_ri_roadmap_2017-2026.pdf

Denmark

- The country's energy (power and gas) utility is Energinet. For information on its market rules, in English, see https://en.energinet.dk/Electricity/Rules-and-Regulations
- A helpful discussion of Denmark's unique reliance on district heating through CHP can be found in, Danish Energy Agency's *Regulation and Planning of District Heating in Denmark*, https://ens.dk/sites/ens.dk/files/Globalcooperation/regulation_and_planning_of_district_heating_in_denmark.pdf
- For informal discussion of innovations of the Danish power system, see http://www.martinot.info/renewables2050/how-is-denmark-integrating-and-balancing-renewable-energy-today and https://www.greentechmedia.com/articles/read/despite-denmarks-high-wind-penetration-ancillary-services-prices-remain-mod

France

- An analysis by French utility EdF shows that coordination of intermittent resources over larger geographic area solves many reliability concerns, Zulueta et al, Électricité de France R&D, Economic and Technical Analysis of the European System with a High RES Scenario (November 2015). https://energiforskmedia.blob.core.windows.net/media/21040/4_edf_lopez_botet_zulueta.pdf

Germany

- The German Energy Agency (DENA) has been exploring challenges to the necessary transition to a renewable-dependent grid by 2030. See, for example, its *Ancillary Services Study 2030,* July 2014, that lists recommendations and issues for further study related to specific ancillary services. https://www.dena.de/fileadmin/dena/Dokumente/Themen_und_Projekte/Energiesysteme/dena-Studie_Systemdienstleistungen_2030/dena_Ancillary_Services_Study_2030_-_summary.pdf
- The European network of transmission system operators for electricity transmission (ENTSO) provides several useful resources on AS activities, including Germany's. See https://www.entsoe.eu/about-entso-e/market/balancing-and-ancillary-services-markets/Pages/default.aspx
- For the English language translation of the German ancillary service network site, go to https://www.regelleistung.net/ext/?lang=en
- From the IEEE, helpful articles outlining the German plan to expand its HVDC system. http://spectrum.ieee.org/energy/renewables/germany-takes-the-lead-in-hvdc (April 2013) and other improvements contemplated as part of the energy turnaround (August 2014) http://spectrum.ieee.org/energywise/energy/the-smarter-grid/germanys-superstable-solarsoaked-grid

Great Britain

- See this report by the UK regulator (Ofgem) that discusses, in laymen's terms, the challenge and benefits of interconnecting HVDC lines from other European grids, to facilitate carbon-reduction goals by 2030; includes specific discussion of potential AS changes. https://www.ofgem.gov.uk/ofgem-publications/93802/ngetreporttoofgem-qualitativeinterconnectorbenefits-pdf
- Energy UK, *Ancillary Service Report 2017,* (April 2017) discusses concerns & potential changes to AS https://www.energy-uk.org.uk/publication.html?task=file.download&id=6138

independent analyses/general discussions of ancillary services & reliability

AWEA prepared a preemptive response to the DOE 60-day review in its informative *Renewable Energy Builds a More Reliable and Resilient Electricity Mix*, (May 2017), that can be downloaded from this page: http://www.aweablog.org/renewable-groups-products-boost-electric-grid-reliability-security-diversity/

See also AWEA's earlier report (2015) which makes a similar set of arguments. http://awea.files.cms-plus.com/AWEA%20Reliability%20White%20Paper%20-%202-12-15.pdf

Advanced Energy Economy (AEE) 's report, J. Weiss and B. Tsuchida, June 2015, *Integrating Renewable Energy into the Electricity Grid: Case studies showing how system operators are maintaining reliability,* was prepared by Brattle Group. It explores two case studies: ERCOT and Xcel in Colorado in integrating increasing amounts of renewables and offers specific discussion re how changes in ancillary services were necessary as penetration of renewables increased. http://info.aee.net/hubfs/EPA/AEEI-Renewables-Grid-Integration-Case-Studies.pdf?t=1480709130819

Rocky Mountain Institute (RMI) has recently issued a series of news articles and commentaries by Amory Lovins et al that address reliability and AS under the general rubric of "The grid needs a symphony, not a shouting match" (summer 2017 in anticipation of the outcome of the DOE baseload review) https://www.rmi.org/news/grid-needs-symphony-not-shouting-match/

- Also see an interesting review by RMI of the role of energy storage in AS (referred to as "RTO/ISO services") via several case studies, including CA & NY in the paper by Fitzgerald, Garrett, James Mandel, Jesse Morris, and Hervé Touati, "The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid." Rocky Mountain Institute, September 2015. http://energytransition.umn.edu/wp-content/uploads/2016/04/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf

The Brattle Group issued a useful report by Judy Chang et al, for NRDC (June 2017), *Advancing Past "Baseload" to a Flexible Grid How Grid Planners and Power Markets Are Better Defining System Needs to Achieve a Cost-Effective and Reliable Supply Mix* that argues reliability is achievable with significant amounts of renewables in the supply mix.
http://www.brattle.com/system/publications/pdfs/000/005/456/original/Advancing_Past_Baseload_to_a_Flexible_Grid.pdf?1498246224

The Analysis Group also issued a report by Hibbard et al, *Electricity Markets, Reliability and the Evolving U.S. Power System* (June 2017) that discusses reliability and AS in the context of increasing penetration of renewables.
http://www.analysisgroup.com/uploadedfiles/content/insights/publishing/ag_markets_reliability_final_june_2017.pdf

There are many excellent discussions of the potential for electric vehicles (EVs) to provide reliability through Vehicle to Grid services, given that EV penetration is expected to increase dramatically in the next several decades. For example, see Efficiency Vermont's helpful assessment of this topic, "Electric Vehicles as Grid Resources in ISO-NE and Vermont" (May 2014). https://www.veic.org/documents/default-source/resources/reports/evt-rd-electric-vehicles-grid-resource-final-report.pdf

Independent consultant Brendan Kirby (former NREL researcher) has been writing about reliability for many years. His most recent work includes several papers related to ancillary service evolution:

- *Potential New Ancillary Services: Developments of Interest to Generators,* (2015) http://www.consultkirby.com/files/01B2_Kirby_Paper_-_Potential_New_Ancillary_Services.pdf
- M. Milligan et al (Nov-Dec 2015), *Alternative No More,* Power and Energy Magazine, IEEE (Volume 13, Issue 6), http://www.consultkirby.com/files/Alternative_No_More_-_Nov_2015.pdf

Appendix 2: Glossary of Terms

(The following glossary is a subset of power system acronyms and terms provided by the ISO-NE on its website, https://www.iso-ne.com/participate/support/glossary-acronyms)

10-minute nonspinning reserve (TMNSR): A form of operating reserve provided by off-line generation that can be electrically synchronized to the system and increase output within 10 minutes in response to a contingency; also called 10-minute non-synchronized reserve. On-line generation that can increase output within 10 minutes also may provide this service because spinning reserve is higher quality than nonspinning reserve due to the fact that the possibility of a failed start does not exist.

10-minute spinning reserve (TMSR): A form of operating reserve provided by on-line generation that can increase output within 10 minutes in response to a contingency.

30-minute operating reserve (TMOR): A form of operating reserve provided by on-line or off-line operating reserve generation that can either increase output within 30 minutes or be electrically synchronized to the system and increase output within 30 minutes in response to a contingency. (Also see spinning and nonspinning.)

ancillary services: Services that ensure the reliability of and support for the transmission of electricity to serve load, including regulation and frequency response (regulation or automatic generator control), spinning reserve, nonspinning reserve, replacement reserve, and reactive supply and voltage control.

area control error (ACE): The instantaneous difference between the net actual and scheduled interchange (i.e., transfer of electric energy between two control areas), accounting for the effects of frequency bias and correction for meter error.

automatic generation control (AGC): The automatic adjustment of a control area's generation to maintain its interchange schedule plus frequency bias.

Balancing authority (BA): For an area comprising a collection of generation, transmission, and loads within metered boundaries (defined by NERC to be a balancing authority area), the entity responsible for integrating resource plans for that area ahead of time, maintaining the area's load-resource balance, and supporting the area's interconnection frequency in real time. The ISO is registered with NERC as a BA and is responsible for complying with NERC standards applicable to BAs.

Balancing authority area: For compliance with NERC reliability standards, an area comprising a collection of generation, transmission, and loads within metered boundaries for which a responsible entity (defined by NERC to be a balancing authority) integrates resource plans for that area ahead of time, maintains the area's load-resource balance, and supports the area's interconnection frequency in real time. This term is used interchangeably with control area.

baseload generating unit: A generating unit used to satisfy all or part of the minimum load of the system and, as a consequence, produce electric energy continuously and at a constant rate. These units are usually economic to operate on a day-to-day basis.

bulk electric power grid, bulk electric power system, bulk electric system, bulk power grid, bulk power system:

- The interconnected electrical generating resources, transmission facilities, tie lines with neighboring systems, and associated equipment used to produce and transmit electric energy, generally operated at 100 kV or higher. (ISO Operations, FERC, NERC)
- An interconnected electrical system consisting of generation and transmission facilities on which faults (short circuits) or disturbances (severe oscillations or changes of current, voltage, or frequency) can have significant adverse impacts outside a local area. (NPCC and ISO System Planning)
- A system of synchronized power providers and consumers connected by transmission and distribution lines and operated by one or more control centers. (EIA)

capacity: The rated and continuous load-carrying ability, expressed in megawatts or megavolt-amperes, of generation, transmission, or other electrical equipment.

capacity market: A market where generators receive compensation for investing in generating capacity. Load-serving entities, the market participants that secure electric energy, transmission service, and related services to serve the demand of their customers, make capacity payments to generators to ensure the long-term availability of sufficient generation capacity for the reliable operation of the bulk power grid.

cascading outage: The uncontrolled successive loss of bulk electric system facilities triggered by an incident (or condition) at any location on the system, which results in the interruption of electric service that cannot be restrained from spreading beyond a predetermined area. (Also see interconnection-reliability operating limit.)

coincident peak load: The highest value of the sum of all loads at one specific time in a particular geographic area. It is sometimes measured instantaneously and other times as the highest integrated hourly value.

contingency: The unplanned disconnection of a power system element, such as a transmission facility or a generator, from the electricity grid.

control area: See balancing authority area.

demand: Load; the amount of electrical power used; the level of electricity consumption at a particular time measured in megawatts.

Demand resource, demand-side resource: A source of capacity whereby a customer reduces the demand for electricity from the bulk power system, such as by using energy-efficient equipment, shutting off equipment, and using electricity generated on site.

dispatch: When a control room operator issues electronic or verbal instructions to generators, transmission facilities, and other market participants to start up, shut down, raise or lower generation, change interchange schedules, or change the status of a dispatchable load in accordance with applicable contracts or demand bid parameters.

distributed generation (DG): Generation provided by relatively small installations directly connected to distribution facilities or retail customer facilities. A small (24 kilowatt) solar photovoltaic system installed by a retail customer is an example of distributed generation.

distribution: The delivery of electricity to end users via low-voltage electric power lines (typically <69 kV) (see transmission); the transfer of electricity from high-voltage lines to lower-voltage lines.

disturbance: An unplanned event that produces an abnormal system condition; any perturbation to the electric system. Also, the unexpected change in the area control error caused by the sudden failure of generation or an interruption of load.

DOE: Department of Energy

DSM: demand-side management

Eastern Interconnection: One of two major AC power grids in North America that spans from central Canada eastward to the Atlantic coast (excluding Quebec), south to Florida, and west to the foot of the Rocky Mountains (excluding most of Texas). The electric utilities within the Eastern Interconnection are electrically tied together during normal system conditions and operate at a synchronized frequency of 60 Hz average. The Eastern Interconnection is tied to the Western Interconnection, the Texas Interconnection, and the Quebec Interconnection, and other systems in Canada through numerous high-voltage DC transmission lines.

electric energy, electrical energy: The ability of an electric current to produce work (heat, light, another form of energy); the generation or use of electric power over a specified time, usually expressed in gigawatt-hours (GWh), megawatt-hours (MWh), or kilowatt-hours (kWh).

electric energy market, energy market: A system for purchasing and selling electric energy using supply and demand to set the price (see electricity market and wholesale electric energy market). The energy markets operated by ISO are the Day-Ahead Energy Market and the Real-Time Energy Market.

electricity market: A system for purchasing and selling electricity using supply and demand to set the price (see electric energy market and wholesale electric energy market). In general, electricity markets include electric energy markets, capacity markets, and ancillary services markets, a part of which are regulation markets and operating reserve markets.

electric power: The rate at which electric energy is transferred or used to do work, measured in kilowatts (or watts or megawatts).

energy: see electric energy, electrical energy

energy efficiency: A type of other demand resource that is an installed measure or a system on an end-use customer’s facility that reduces the total amount of electrical energy and capacity that otherwise would have been needed to deliver an equivalent or improved level of end-use service. Such measures or systems include the use of more efficient lighting, motors, refrigeration, HVAC equipment and control systems, and industrial process equipment.

energy market: See electric energy market and electricity market.

ERO: Electric Reliability Organization

FACTS: flexible alternating-current transmission system

fast-start resource: A generation unit that can start up and be at full load in less than 30 minutes, which helps with recovery from contingencies and assists in serving peak demand.

FERC: Federal Energy Regulatory Commission

first contingency: The largest impact on the system when a first power element (generation or transmission facility) of a system is lost. See N-1.

forward reserve: The 10-minute nonspinning reserves and 30-minute operating reserves the ISO purchases on a forward basis on behalf of market participants.

Forward Reserve Market (FRM): In New England, a market used for acquiring the generating resources needed to satisfy the requirements for 10-minute nonspinning reserves and 30-minute operating reserves.

frequency: The rate of oscillation (cycles/second) of the alternating current in an electrical power system, measured in hertz (Hz). In the United States, the rate is 60 Hz.

frequency bias: A control area’s response to an interconnection frequency error, typically expressed in megawatts per 0.1 Hz (MW/0.1 Hz).

generating resource, generating unit, generator: A facility that produces electric energy (see resource).

generation: The production of electric energy from other sources of energy, expressed in megawatts; supply.

grid: The network of the transmission lines, substations, and associated equipment of an electric power system.

HVDC: high-voltage direct current

Independent System Operator (ISO): An independent, federally regulated organization formed at the recommendation of FERC to impartially coordinate, control, and monitor the operation of a regional bulk electric power system, including the dispatch of electric energy over the system and the monitoring of the electricity markets, for ensuring the safety and reliability of the system.

interchange: Transfers of electric energy that cross Balancing Authority boundaries.

interchange schedule: The agreed-upon specifications for the transfer of electric energy between two control areas including, for example, the size of the transaction in megawatts, the start and end times, the beginning and ending ramp times, and the rate.

interconnection: The connection between two bulk electric power systems or control areas.

intertie: The circuit that connects two or more control areas or systems.

load: Demand; the amount of electrical power used; the level of electricity consumption at a particular time measured in megawatts.

load shedding: Controlled or scheduled power outages (controlled blackouts) to balance the demand for electricity with limited supply.

N-1: A first contingency; the largest impact on the system when a first power element (generation or transmission facility) of a system is lost.

N-1-1, N-2: A second contingency; the loss of the facility that would have the largest impact on the system after the first facility is lost.

nameplate capacity, nameplate: The rating of a generator and a measure of its ability to produce electricity.

NERC: North American Electric Reliability Council

NESCOE: New England States Committee on Electricity

nonspinning: Off-line generation not synchronized to the system.

nonspinning reserve, nonsynchronized reserve: Off-line generation that can quickly be electrically synchronized to the system and increase output to respond to a contingency and serve demand.

NOPR: Notice of Proposed Rulemaking

NPCC: Northeast Power Coordinating Council, Inc.

operating reserve: The megawatt capability of a power system greater than system demand, which is required for providing frequency regulation, correcting load forecasting errors, and handling forced outages, drawn from spinning and nonspinning sources of power. Also, the synchronized or nonsynchronized reserves that may be used to recover from a contingency.

outage: When a facility or piece of equipment goes off line. See forced outage planned outage, scheduled outage, and unplanned outage.

Planning Authority (PA): An entity responsible for coordinating and integrating transmission facility and service plans, resource plans, and protection systems. The ISO has registered with NERC as a PA and is responsible for complying with NERC standards applicable to a PA.

power market: The buying and selling of electricity. See electric energy market, electricity market, and wholesale electric energy market.

power system: The elements of an electrical system, including generation units, transmission lines, distribution lines, substations, and other equipment. See bulk power system.

PV: solar photovoltaic

real-time: The period in the current operating day for which the ISO dispatches resources to provide electric energy and regulation service and, if necessary, commits additional resources.

Real-Time Energy Market: a market that balances differences between the day-ahead scheduled amounts of electricity needed and the actual real-time load requirements (see Day-Ahead Energy Market and energy market).

real-time reserve market: An ISO market where resources capable of providing 10-minute and 30-minute reserves are designated in real time, for which they are paid the reserve market clearing price.

Regional Transmission Organization (RTO): An independent regional transmission operator and service provider established by FERC and that meets FERC's RTO criteria, including those related to independence and market size. The RTO controls and manages the high-voltage flow of electricity over an area generally larger than the typical power company's service territory for its distribution system.

regulation: The capability of specially equipped generating resources to increase or decrease their generation output every four seconds in response to signals they receive from the ISO to control slight changes on the system. This capability is necessary to balance supply levels with the second-to-second variations in demand.

regulation market: A market in which load-serving entities pay for regulation service on the basis of real-time load obligations and market participants satisfy regulation requirements by providing the service from their own resources, through internal bilateral transactions for regulation, or by purchasing regulation from the market.

reliability: The assurance that power is available even under adverse conditions, such as unplanned outages of generation or transmission lines.

reliability coordinator (RC): The entity with the highest level of authority for reliably operating the bulk electric system, including the authority to prevent or mitigate emergency operating situations in next-day and real-time operations. The ISO has registered with NERC as an RC and is responsible for complying with NERC standards applicable to an RC.

Reliability Coordinator Area: The collection of generation, transmission, and loads within the boundaries of the reliability coordinator. The boundaries of a Reliability Coordinator Area coincide with one or more Balancing Authority Areas.

Reliability Regions: A defined region of the New England Control Area that reflects the operating characteristics of, and the major transmission constraints on, the New England transmission system. These regions contain the load zones.

resource: Any source of electric energy that increases the availability of capacity (in megawatts), such as a dispatchable load, a demand-response resource, or an electricity import or external transaction. Also see generating resource.

resource adequacy: The ability of a bulk electric power system to supply the aggregate electrical demand and energy requirements (i.e., the electrical loads of all the customers at all times plus external transaction sales to other control areas), taking into account scheduled and reasonably expected unscheduled outages of system devices (e.g., generators, transformers, circuits, circuit breakers, or bus sections). Annual expected system resource adequacy is calculated in terms of system loss-of-load expectation, accounting for load forecast uncertainty caused by weather and resource availability and reflecting assumed forced and scheduled outages.

resource planner (RP): An entity that develops a long-term plan (generally one year and beyond) for the resource adequacy of specific loads within a Planning Authority area (i.e., the customer demand and energy requirements, including the electrical loads of all customers at all times plus external transaction sales to other control areas). The ISO has registered with NERC as an RP and is responsible for complying with NERC standards applicable to an RP.

seams: The interface between two control areas, systems, and markets (see seams issues).

seams issues: Trading barriers between adjoining wholesale electricity markets resulting from the use of different rules and procedures by the neighboring markets, which can obstruct the trading or sharing of electric capacity and energy between the two markets and affect the reliability of each system.

spinning: On-line capacity electrically synchronized to the system.

spinning reserve: The reserve capability that a generator can fully convert into electric energy within 10 minutes after receiving a request from ISO New England to do so.

step-down transformer: A transformer, usually located on the distribution system, that converts electricity from a higher to a lower voltage.

step-up transformers: A transformer, usually located at a generator site, that converts electricity from a lower to a higher voltage.

supply: Electricity delivered to the system; generation.

synchronous condenser: Either a combustion turbine or hydro resource that is synchronized to the New England transmission system and operates as a motor (i.e., it is consuming energy). Also, rotating equipment (or a generator with 0 MW output) that can provide dynamic voltage support, typically designed and operated as separate equipment from generating units.

synchronous generator: A typical type of generator connected to the network.

tie line: A transmission line that connects two control areas; an interconnection.

transfer capability: The amount of megawatts that interconnected electricity systems under specified conditions can reliably transfer from one system to the other over all transmission lines that connect the systems.

transmission: The transporting of electricity through high-voltage lines to distribution lines (see distribution).

transmission line: Any line with a voltage greater than or equal to 69 kV that carries bulk power over long distances. Typical industry voltages are 69 kV, 115 kV, 138 kV, 230 kV, and 345 kV.

transmission operator (TOP): An entity responsible for the reliability of its "local" transmission system and that operates or directs the operations of the transmission facilities. The ISO has registered with NERC as a TOP and is responsible for complying with NERC standards applicable to a TOP.

VAR: Voltage Amperes Reactive

wholesale electric energy market: The buying, selling, and reselling of the electric energy generated by a bulk power system to meet the system's demand for electric energy. New England's wholesale electric energy markets are the Day-Ahead or Real-Time Energy Market. (Also see energy market.)

wholesale electricity: Power that is bought and sold among generators, utilities, municipalities, and other wholesale entities (see market participants).

wholesale electricity markets, wholesale electric power market: The buying, selling and reselling of electric energy, ancillary services and capacity at the transmission level.