CHAPTER 23
APPLICATIONS AND GRID SERVICES

Tu Nguyen, Raymond Byrne, Rodrigo Trevizan, Alvaro Bastos, Felipe Wilches-Bernal, Sandia National Laboratories; Ricky Concepcion, L3HARRIS Technologies; Reinaldo Tonkoski, South Dakota State University; Alex Headley, The University of Memphis

Abstract

Energy storage is a unique grid asset capable of providing a variety of applications. As the electric power grid evolves toward a smarter and more reliable grid, with increased amounts of variable renewable generation, the need for energy storage will only increase. On the grid side, energy storage systems (ESSs) can participate in electricity markets by providing services such as energy arbitrage, frequency regulation, and spinning reserves. On the customer side, ESSs can provide a wide range of applications from on-site back-up power, storage for renewable systems to solutions for load shifting, and peak shaving for commercial/industrial businesses. As the application space for ESSs grows very quickly, it is essential to understand the characteristics as well as the requirements of each application. Therefore, this chapter aims to provide an overview of energy storage applications and their classifications.

Key Terms

energy storage applications, ancillary services, behind-the-meter (BTM), demand charge, duck curve, front-of-the-meter (FTM), Global Energy Storage Database (GESDB), QuESt

1. Introduction

Energy storage applications are often classified based on their durations. The short-duration applications, often referred to as *power applications,* involve the injection of real or reactive power over short time scales (e.g., seconds to minutes) to maintain the stability of the power grid. For example, frequency regulation is the second-by-second adjustment of output power to maintain the nominal grid frequency. Other examples include voltage support, small signal stability, virtual inertia, and renewable capacity firming. On the other hand, long-duration applications, often called *energy applications*, typically involve long discharge/charge cycles lasting more than several hours. In many cases, these applications require a high energy capacity (MWh) rating of the storage device to enable the long discharge times at maximum power. One popular example of energy application is arbitrage that involves buying energy from energy markets at low prices and selling that energy at higher prices to make profit, or using the charged energy later to avoid charges that are associated with high peak demand. Renewable energy time shift (i.e., shifting the available renewable energy to match the load) is another energy application that is growing very quickly with increased penetrations of photovoltaic (PV) generation in places like California. Transmission and distribution (T&D) upgrade deferral is also among the energy applications that can provide a very large potential benefit for energy storage systems (ESS). All of the above applications are described in further detail in the following sections.

Energy storage applications can also be categorized based on location. The terms front-of-meter (FTM) and behind-the-meter (BTM) are often used to specify the system location. BTM refers to a system that is situated at the customer's site (e.g., homes, commercial, and industrial facilities).

BTM systems are usually owned by the customer and operated for the customer's benefit, while FTM systems are often owned by the utility and provide grid services. BTM systems are subject to the rate structure from the local utility or load-serving entity, while FTM systems often participate in electricity markets or interface with utilities at the wholesale level via a power purchase agreement.

Another way of classifying energy storage applications is based on their purposes. Table 1 below represents five main groups of services: general energy, ancillary services, transmission services, distribution services, and end-user services. To make it easier to follow, the rest of this chapter presents the applications in the order that is shown in this table.

Table 1. Summary of energy storage applications

Applications	Power or Energy?	FTM or BTM?	Grid-connected or Off-grid?
General Energy Applications			
Energy Arbitrage in Electricity Markets	Energy	FTM	Grid-connected
Renewable Energy Time-shift (Renewable smoothing and firming)	Energy	FTM and BTM	Grid-connected and Off-grid
Ancillary Services			
Frequency Regulation	Power	FTM	Grid-connected
Operating Reserve (spinning, non-spinning, supplementary)	Energy	FTM	Grid-connected
Frequency Response and Virtual Inertia	Power	FTM	Grid-connected
Voltage support	Power	FTM	Grid-connected
Ramp support	Power	FTM and BTM	Grid-connected
Black Start	Power	FTM	Grid-connected
Transmission Services			
Transmission Upgrade Deferral	Energy	FTM	Grid-connected
Transmission Congestion Relief	Energy	FTM	Grid-connected
Stability Damping Control	Power	FTM	Grid-connected
Distribution Services			
Peak shaving and Upgrade Deferral	Energy	FTM and BTM	Grid-connected
Voltage regulation	Power	FTM and BTM	Grid-connected
Reliability and Resilience	Energy and Power	FTM and BTM	Grid-connected
End-user Services			
Time-of-use, demand charge and net-metering management	Energy	BTM	Grid-connected
Power Quality	Power	BTM	Grid-connected
Resilience (Back-up power)	Energy	BTM	Grid-connected and Off-grid

2. General Energy Applications

General energy applications include energy arbitrage and renewable energy time shift.

Energy arbitrage in electricity markets

In electricity markets, the energy price in a period usually indicates the relation between supply and demand in that period. For example, during a high demand period, the energy price is often higher because expensive generation units such as gas peakers must be committed to balance the load. Energy arbitrage refers to the market activity of buying electricity when the price is low and selling it at another time when the price is high. The variability in electricity prices is illustrated in Figure 1. This market activity is achieved through charging and discharging the ESS. The potential revenue depends on the shape of the price curve, as well as the round-trip efficiency of the ESS. The maximum revenue from arbitrage can be estimated from market data by solving a mathematical optimization such as a Linear Program (LP) [1].

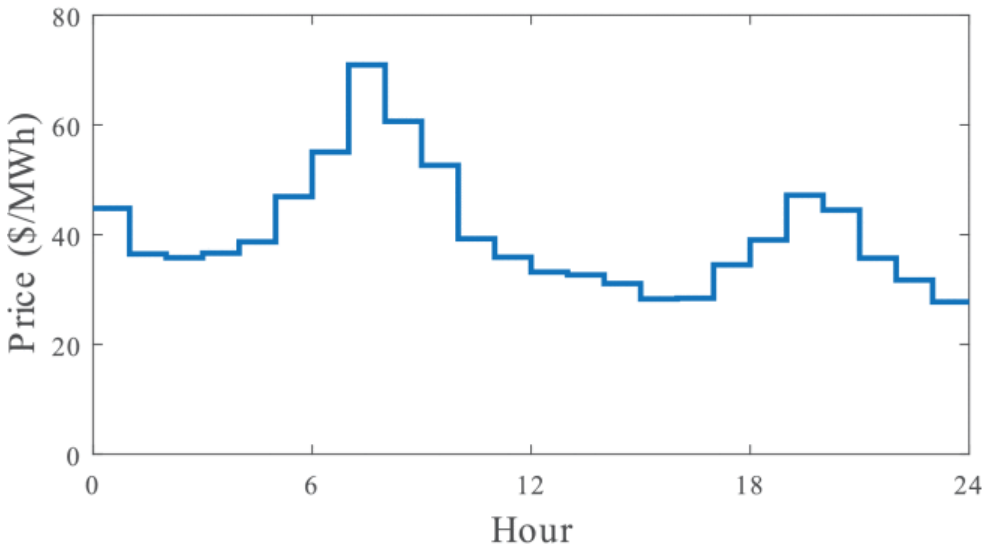


Figure 1. Day ahead local marginal price (LMP) on March 23, 2017 for ISO-NE's node D.STERLING13.8

In a vertically integrated utility, savings can be achieved by more efficient operation of the generation fleet (e.g., flattening of the demand curve with energy storage and reducing operation reserve). Generally, a production cost analysis is performed to minimize the overall operation cost of the utility.

Renewable Energy Time-shift

The main goal of renewable energy time-shift is to shift renewable energy generation from off-peak to on-peak hours. A classic example is the California "duck curve," illustrated in Figure 2, which has been caused by a large increase in solar photovoltaic (PV) generation. The belly of the duck curve is a result of the reduced generation required at mid-day because of the increased PV generation. As the sun sets in the afternoon, PV generation starts declining while load starts climbing up to the afternoon peak. This creates a rapid increase in required generation forming up the duck's neck in late afternoon. Energy storage can be used to shift the peak solar energy from mid-day to late afternoon. This activity requires energy storage to charge when renewable energy generation is high, and to discharge when the load is high. In some market areas like the California

Independent System Operator (CAISO), there are market products to address the duck curve (e.g., the ramping product). In other market areas energy arbitrage is the only compensation mechanism for performing renewable energy time shift.

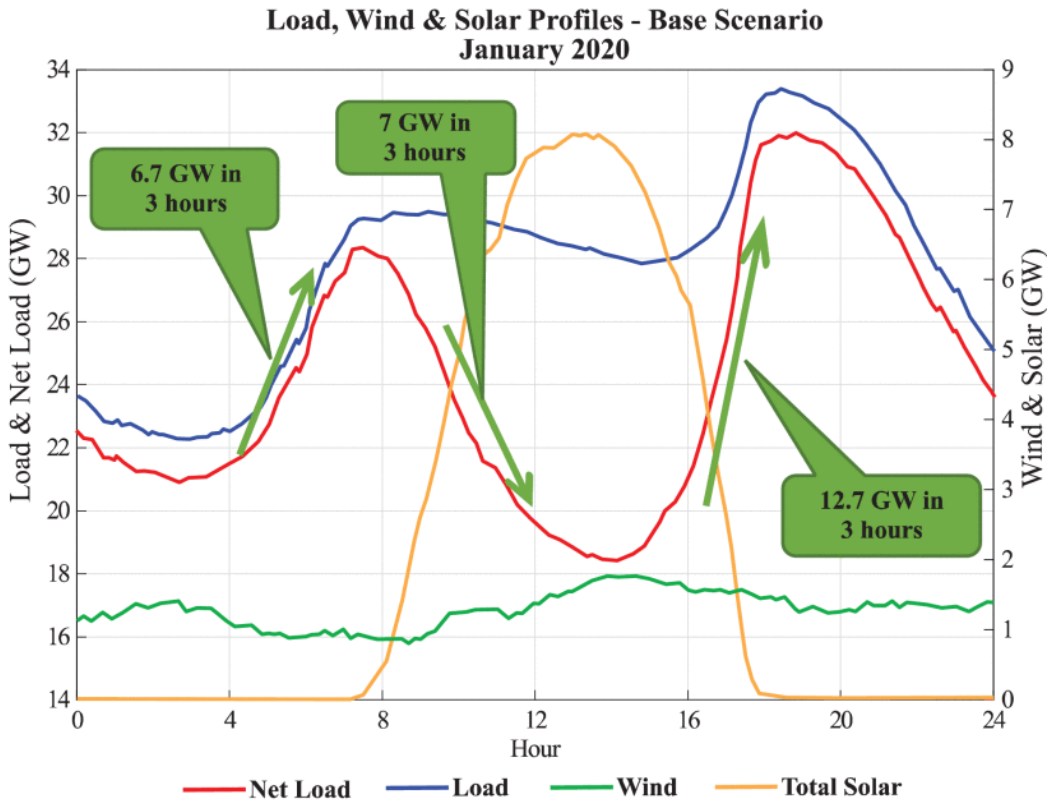


Figure 2. The North American Electric Reliability Corporation (NERC) assessment of California 2020 load, wind, and solar profile

3. Ancillary Services

Ancillary services refer to services that are required to maintain grid stability and security. They often include frequency regulation, frequency response, operating reserves, voltage support, ramping product, and black start.

Frequency Regulation

Frequency regulation is the second-by-second adjustment of generation to maintain grid frequency. In North America, balancing authorities send control signals to perform the second-by-second adjustment. In market areas, the independent system operator serves as the balancing authority and identifies the quantity of regulation reserves required, procures the reserves in the market, and sends a control signal to each generator providing frequency regulation. In a vertically integrated utility, the utility serves as the balancing authority and performs these functions.

The control signal sent to generators is referred to as the automatic generation control (AGC) signal, which is a function of the local frequency error, tie line flows, schedule exchanges, and grid characteristics, as illustrated in Figure 3. Most ISOs transmit an updated AGC signal every two to four seconds. Some ISOs have developed a separate signal for fast-responding resources

like energy storage, for example, the PJM RegD signal, as shown in Figure 4. Regulation Up refers to the increase in output power that increases grid frequency. Regulation Down refers to the decrease in output power that reduces grid frequency. In some market areas, like PJM (Pennsylvania, Jersey, Maryland Power Pool), frequency regulation is bidirectional. Other market areas, like CAISO and Electric Reliability Council of Texas (ERCOT), deploy regulation up and regulation down signals.

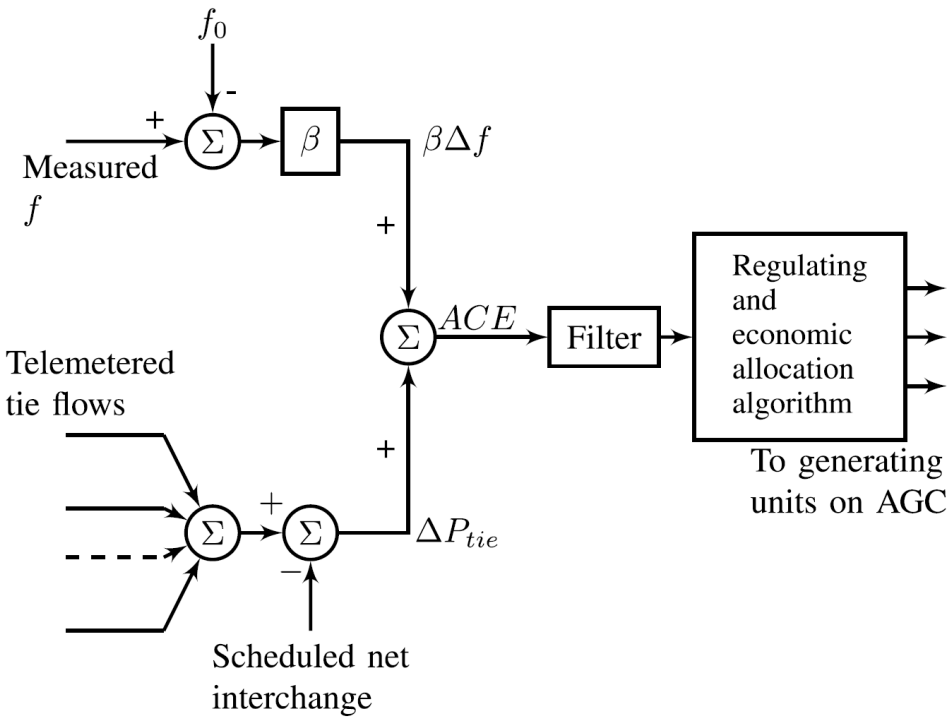


Figure 3. Typical AGC control logic for a balancing area [2]

Mandated by FERC Order No. 755 [3], frequency regulation resources must be compensated for the actual regulation service they provide. Typically, the compensation for providing frequency regulation in Regional Transmission Organizations (RTO) and Independent System Operators (ISO) markets consists of a capacity payment for the available capacity and a performance payment for the actual up and down movement (i.e., mileage), as well as the accuracy of the service (i.e., performance) based on how accurately the AGC signal is followed.

While frequency regulation is often the source of the greatest potential revenue from energy storage [4, 5, 6, 7, 8] the size of the frequency regulation market is typically small with respect to the size of the energy market. In most ISOs, the regulation market is 1-3% of the size of the energy market. This means that prices can fall quickly if there are many entrants to the market.

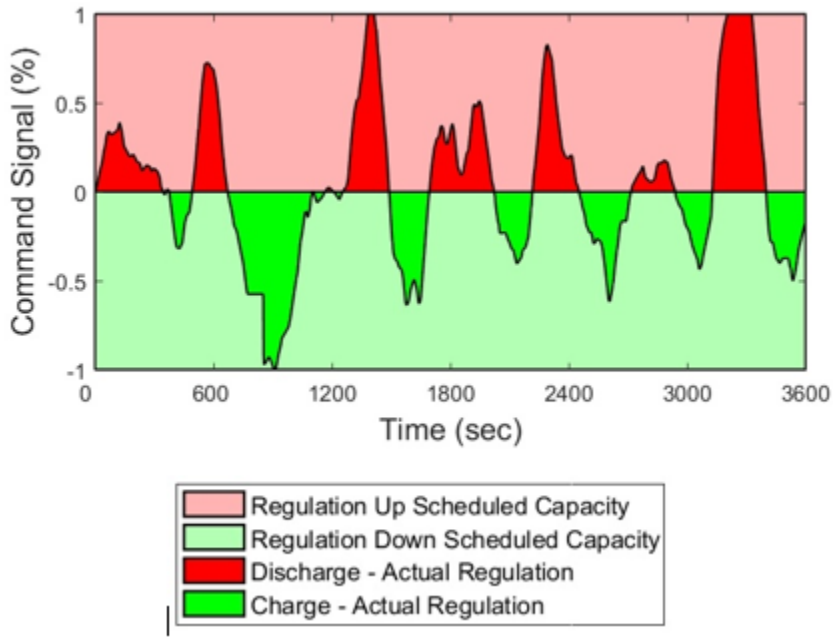


Figure 4. Representative regulation command signal (RegD signal from PJM) [9]

Operating Reserve (spinning, non-spinning, supplementary)

In a power system, the event (or contingency) operating reserve is the total amount of generating capacity that is available to the system operator to balance the load under contingency conditions (e.g., the loss of a large generator or transmission line). The event operating reserve often includes three main components:

- **Spinning reserve** – available from generators that are already synchronized to the grid and can change their output quickly. It is often the headroom between the generator's operating point and the maximum capacity of the unit. To comply with the North American Electric Reliability Corporation (NERC) Disturbance Control Standard, these units must be able to reach their full capacity within 10 minutes.
- **Non-spinning reserve** – available from off-line generators that can be brought online quickly or from online units with low ramp rate.
- **Replacement or Supplementary Reserve** – similar to spinning/non-spinning reserve but only needs to provide full capacity within 30-60 minutes. It is used to bring the spinning/non-spinning reserve units to pre-contingency conditions.

In the United States, each ISO/RTO has its own terminology and requirements for spinning and non-spinning reserve as summarized in Tables 2 and 3. The reserve products/services are often classified based on the frequency control types (as described below) that the reserve resources must provide to comply with NERC's standard.

- **Primary frequency control** is a local automatic control that rapidly (within seconds) adjusts generator output or load to offset large changes in frequency. The adjustment of generator output is termed governor response or frequency droop control.

- **Secondary frequency control** is a central automatic control that acts to adjust active power production to restore the frequency and power interchanges with other systems to their nominal levels following an imbalance. This automatic process, generally termed AGC in North America, acts on a time frame of several seconds to counteract frequency deviations.
- **Tertiary frequency control** consists of manual changes in scheduled unit commitment and dispatch levels in order to bring frequency and/or interchanges back to nominal values when secondary frequency control is unable to perform this task. Operating reserve is considered tertiary frequency control reserve.

Table 2. Operating reserve market terminology currently used by ISOs/RTOs [10]

<table>
<tr><th>ISO/RTO</th><th>Primary Frequency Control Reserve</th><th colspan="2">Secondary Frequency Control Reserve</th><th colspan="4">Tertiary Frequency Control Reserve</th></tr>
<tr><td rowspan="2">CAISO</td><td rowspan="2">No market</td><td colspan="2">Regulation Reserve</td><td rowspan="2">Spinning Reserve</td><td rowspan="2">Non-spinning Reserve</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Regulation Up</td><td>Regulation Down</td></tr>
<tr><td rowspan="2">ERCOT</td><td rowspan="2">No market</td><td colspan="2">Regulation Services</td><td rowspan="2">Responsive Reserve Service</td><td rowspan="2">Non-spninning Reserve Service</td><td rowspan="2">Replacement Reserve Service</td><td rowspan="2"></td></tr>
<tr><td>Reg Service-Up</td><td>Reg Service-Down</td></tr>
<tr><td>ISO-NE</td><td>No market</td><td colspan="2">Regulation</td><td>Ten-minute Spinning</td><td>Ten-minute Non-Spinning</td><td>Thirty-minute Operating</td><td></td></tr>
<tr><td rowspan="2">MISO</td><td rowspan="2">No market</td><td colspan="2" rowspan="2">Regulating Reserve</td><td colspan="2">Contingency Reserve</td><td></td><td></td></tr>
<tr><td>Spinning Reserve</td><td>Suplemental Reserve</td><td></td><td></td></tr>
<tr><td>NYISO</td><td>No Market</td><td colspan="2">Regulation</td><td>10-minute Spinning Reserve</td><td>10-minute Non-spinning Reserve</td><td>30-minute Spinning Reserve</td><td>30-minute Non-spinning Reserve</td></tr>
<tr><td rowspan="2">PJM</td><td rowspan="2">No market</td><td colspan="2" rowspan="2">Regulation</td><td colspan="2">Contingency Reserve</td><td colspan="2" rowspan="2">Supplemental Reserve</td></tr>
<tr><td>Synchronous Reserve</td><td>Quick-start Reserve</td></tr>
<tr><td rowspan="2">SPP</td><td rowspan="2">No market</td><td colspan="2">Regulation</td><td colspan="2">Contingency Reserve</td><td></td><td></td></tr>
<tr><td>Regulation Up</td><td>Regulation down</td><td>Spinning Reserve</td><td>Suplemental Reserve</td><td></td><td></td></tr>
</table>

Table 3. Selected characteristics of reserve markets in the United States [10]

Function	Product	Characteristics	CAISO	ERCOT	ISO-NE	MISO	NYISO	PJM	SPP
Primary Frequency Control Response	None								
Secondary Frequency Control Response	Regulation Reserve	Governor control necessary for participation?	No	Yes	No	Yes	No	No	No
		Separate markets for up/down regulation?	Yes	Yes	No	No	No	No	Yes
		AGC signal required?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
		Max time to deliver nominated capacity (min)	10-30	10	5	5	5	5	
		Min duration to maintain output (min)			60	60			60
		Min ramp rate (MW/min)			1				
		Min capacity offered (MW)		1				0.1	
Secondary Frequency Control Response	Spinning Reserve	Governor control necessary for participation?	No	Yes	No	No	No	No	No
		Max time to deliver nominated capacity (min)	10	10	10	10	10	10	10
		Min duration to maintain nominated output (min)	30		60	60			60
		Min capacity offered (MW)		1					
		Two-tiered market structure?	No	No	No	No	No	Yes	No
	Non-spinning Reserve	Max delay to be synchronized and at nominated capacity (min)	10	30	10	10	10	10	10
		Min duration to maintain nominated output (min)	30		60	60			60
		Min capacity offered (MW)		1					
	Supplemental Reserve	Separated into synchronized and non-synchronized reserve markets?		No	No		Yes	No	
		Max delay to be synchronized and at nominated capacity (min)		Agreed Upon	30		30	30	
		Min duration to maintain nominated output (min)		Agreed Upon					

As more and more variable renewable energy generation sources (e.g., wind and solar) are integrated into the grid, large contingencies can be caused by weather conditions that result in large ramping events. Therefore, the total required operating reserve will be a function of the expected variability of the renewable generation as well as the expected contingencies. Since an ESS can respond very quickly, it can provide all the above reserve types ranging from frequency regulation to spinning and non-spinning reserve. Although an ESS providing reserve capacity might only be called upon several times per year, it must have the capacity available at all times.

Frequency Response and Virtual Inertia

Electricity generation from renewables in the United States is projected to increase from 18% of the total energy produced in 2018 to 31% in 2050 [11]. In real terms, that represents an increase of 130% from 2018 levels, reaching around 11.7 trillion kWh. Most of that increase will come from PV, which is projected to represent 48% of renewable energy generated in 2050 and 15% of total electricity generation.

Displacing traditionally centralized, combustion-based generation with distributed renewable energy presents technical challenges. While matching electrical supply and demand has been achieved by controllable fossil fuel-based generators equaling forecasted load and power losses, renewable generation (e.g., from solar and wind power plants) is intermittent and has limited capability for power output control unless it is paired with energy storage or employs curtailment.

On smaller time scales, the power grid has relied on the kinetic energy stored in large rotating machines (e.g., traditional generation and large motor loads) to provide a short-term energy buffer to balance load and generation and to maintain synchronous operation. When there is a mismatch in electric supply and demand, the kinetic energy stored in the rotating machines, which is proportional to the moment of inertia of these machines, either increases or decreases to match the system load. This behavior results in reducing frequency deviations.

The physics of how grid-connected rotating electric machinery exchanges power with the grid governs the dynamics of grid power flows and frequency fluctuations. Converter-interfaced load and generation, such as motors and pumps controlled by inverters or PV and type 3 and 4 wind turbines, do not have the same intrinsic physical properties that couple load and generation mismatch with grid frequency deviations. Therefore, it is said that these systems do not provide inertia to the grid.

A decreased energy buffer to compensate for mismatches between load and generation raises concerns with respect to grid stability. Globally, reduced inertia harms the capacity of the power grid to withstand large power imbalances [12]. Larger frequency deviations stemming from generation loss have been recorded in places where there are large amounts of renewable energy generation from low-inertia sources [13]. Specifically, lower inertia leads to lower frequency nadir following a generator trip, higher frequency deviations and transient power exchanges during faults, which might trigger frequency-dependent protection mechanisms, such as under/over-frequency tripping of generators or disconnection of power lines [14]. The typical frequency response of a large power system after a loss of generation is illustrated in Figure 5. Grid inertia plays a crucial role in limiting the rate at which the power system frequency decreases, also known as rate of change of frequency (RoCoF). To halt frequency change, however, it is necessary to deploy frequency response, which will actuate generation to correct the power imbalances in the system.

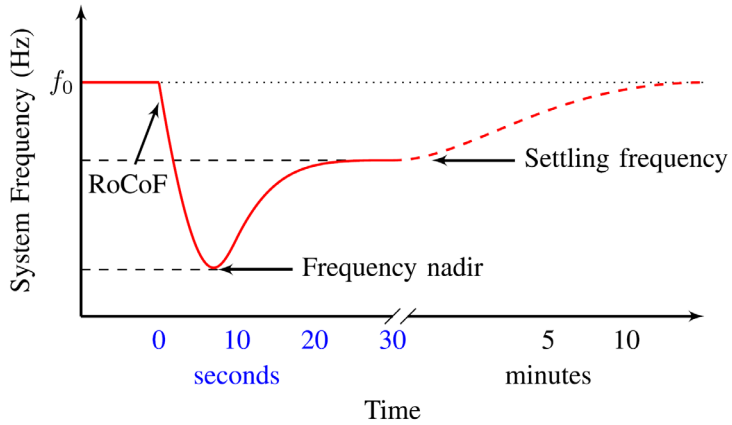


Figure 5. System frequency after a loss of generation [1]

Power systems operators have started to take action to mitigate the effects of low inertia. For example, ERCOT monitors system inertia in real time and deploys generation resources if estimated inertia falls below a critical inertia level [15]. Different settings for under-frequency load response relays can also be used to provide more reliability during loss of generator events. While large interconnected systems tend to be less dependent on inertia, small power systems such as insular grids have their performance particularly degraded by low inertia [16]. Irish transmission system operators (TSOs) have recently introduced new ancillary services to compensate synchronous inertial response, fast frequency response and post fault recovery [17]. Many energy market products have been proposed by Independent System Operators (ISOs) to facilitate the adoption of new technologies, especially energy storage systems. For example, Enhanced Frequency Response is a grid service developed in Great Britain for sub-second frequency response of energy storage assets using local measurements [18]. ESSs can also participate in Firm Frequency Response market [19].

On the research side, Virtual Inertia (also known as Synthetic, Digital or Emulated Inertia) was proposed to mitigate stability issues in low-inertia systems. Implementing virtual inertia is a way of making modern converter-integrated power generation compatible with legacy synchronous generator-dominated systems. It can be implemented by combining the flexibility and controllability of power converters with some kind of short-duration energy storage system to emulate the inertial response of a synchronous generator [20]. The first virtual synchronous generator model had the objective of emulating in detail the dynamics of the synchronous machines and operating similarly to the real system [21]. The concept was introduced early to the integration of doubly-fed induction generators (DFIG) into power systems operation [22]. Short-term energy storage could be implemented by leveraging the rotating masses of wind power generators and super-capacitors [23].

Research has suggested that operating energy storage devices as virtual synchronous generators can reduce grid frequency deviations following events [24]. Many types of virtual inertia systems exist, including algorithms based on synchronous generator models, swing equation, frequency-power response, droop control, virtual oscillator control, and inverters [25]. There have been efforts to include virtual inertia algorithms in converter-interfaced generators connected to the power grid. The standard IEEE 1547-2018 for interconnection and interoperability of distributed energy resources incorporates inertial response.

While inertia and virtual inertia can reduce the RoCoF observed following a large power imbalance, power grid operations rely on a three-tiered frequency control scheme for reestablishing load and generation balance and correcting system frequency deviations. Primary frequency response is the control scheme responsible for ramping up or down power output of controllable generation to correct imbalances between load and generation. In traditional generation, this control system is activated when local power measurements are outside of a deadband. Secondary frequency control (AGC) aims at returning system frequency to the nominal value and to reduce the difference between scheduled and measured tie-line power flows. The AGC signal is broadcasted to controllable generation assets inside of a control area that provide frequency regulation or load following services. Finally, tertiary control aims at redispatching generation assets to recover operational margins.

In 2018, FERC issued orders that allow an ESS to participate in electricity markets and to provide a number of grid services. Order 841 mandated that RTOs/ISOs should allow ESSs to participate in capacity, energy and ancillary service markets both as buyers as well as sellers of energy. These market participation rules should consider aspects unique to ESS [26].

FERC Order No. 842 determined that all new generation facilities should be capable of providing primary frequency response following settings defined by NERC guidelines [27]. This means that energy storage systems connected to the power grid through either a Large Generator Interconnection Agreement or Small Generator Interconnection Agreement will have to implement frequency response mechanisms such as droop control response to frequency deviation as shown in Figure 6.

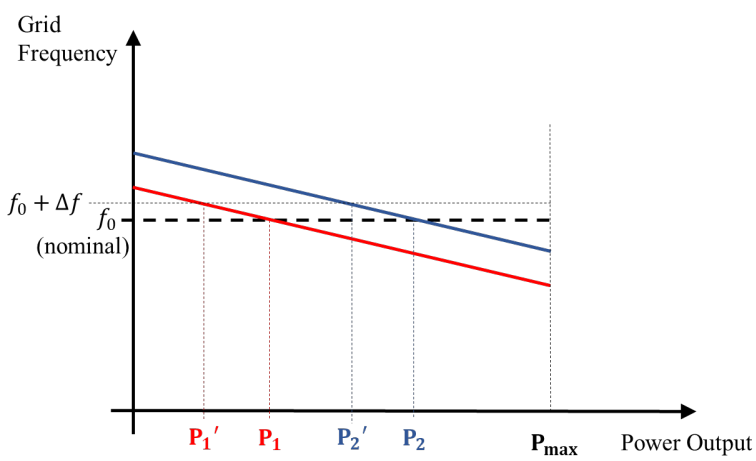


Figure 6. Droop control characteristic of a generator for two power output set-points and its response to a deviation in frequency

To limit the impact of primary frequency response to an ESS, FERC has issued special rules. These rules exempt an ESS from providing frequency response in cases where the normal operation of the device can be significantly impacted, or excessive wear-and-tear costs are possible. Those include situations where not enough state-of-charge is available, operating points that might degrade the unit if reached, or sustained service that could significantly discharge or charge the storage device.

Voltage support

Voltages at different nodes of the transmission system must be maintained within an acceptable range at all times. Generally, voltage regulation (support) is done through reactive power dispatch. The resources for voltage regulation like generators and reactive compensators (e.g., synchronous condensers, capacitor banks) can be compensated for their reactive power capability by the ISO/RTOs. The rules governing compensation for voltage support are usually defined in ISO/RTOs' Open Access Transmission Tariff.

An ESS can also provide voltage regulation by modulating real and reactive power of its inverter that interfaces with the grid. The amount of reactive power that an ESS can provide is limited by the characteristics of its power conversion system (PCS). This is often reflected in the power factor limit of the inverter. Most inverters specify an acceptable power factor (PF) range (see Figure 7). For example, if the power factor limit of an inverter is 0.7 (leading or lagging), the inverter can only provide as much reactive power as its real power rating.

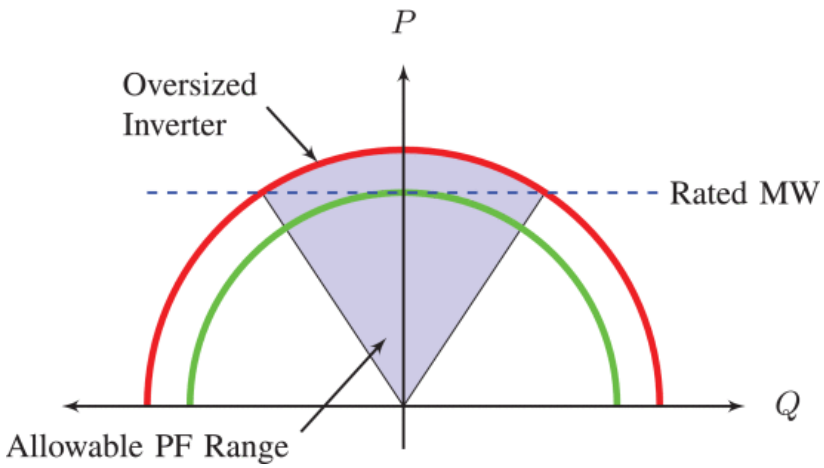


Figure 7. Power relationship for an oversized inverter

Ramp support

Inverter-based resources are, in many ways, incompatible with the current generation resources based on large spinning machines. The well-known example of the issues associated with daily ramping cycles of solar resources in particular is the Californian "duck curve" [28], which projects increasingly large swings in net power needs as renewable penetration increases.

This is a reality in many areas, and it can be a struggle for other generators connected to the network to ramp production up and down effectively in response. To date, this has been handled by installing flexible generation resources such as natural gas fired turbines (20%/ min ramp capability [29]) to manage these large swings in demand. However, this method is increasingly being eschewed in areas where zero-carbon alternatives are desired. Other traditional forms of generation such as hydroelectric power, geothermal, concentrated solar, and nuclear energy, are all less flexible than gas powered turbines though (15%, 6%, 5%, and 2% full load/min, respectively) [29].

Energy storage can fill this role by absorbing excess generation at midday and discharging during the evening ramp to reduce ramping requirements on the rest of the generation fleet. This is a similar concept to that of PV smoothing, however on a longer time scale that would require the use of much more substantial ESSs. Most energy storage technologies that are commercially

available or being developed are capable of easily ramping output at rates superior to natural gas turbines. ESSs could be particularly impactful in this capacity for areas transitioning to 100% renewable generation, where renewable resources and slow-ramping traditional generation will have to co-exist for decades.

Currently only a few areas are addressing ramping needs directly. For instance, in Puerto Rico, the Puerto Rico Electric Power Authority (PREPA) implemented a 10% nameplate per minute ramp-rate limit on all new renewable installations [30]. More recently, California posed a new load shifting product launched in November 2020 to address evening ramp concerns [31]. The new product is currently under review by FERC. This would give a direct value stream for energy storage systems to function in this capacity. As renewable penetration increases across the country, other states may follow suit.

Black Start and Power System Restoration

Frequency deviations due to load pick up in the power system restoration process are a major concern to DSOs and TSOs. Typically, conventional generation can only pick up loads within 5% (steam turbines) to 15% (hydro) of their capacity to ensure acceptable frequency dip [32]. Black start and grid-forming capabilities of ESSs will become of greater interest especially when the amount of wind and solar generation increases in the power system [33]. ESSs have the potential to significantly increase the speed and robustness of power system restoration [34]. After a blackout, standard black start procedures commence with power plants that can operate in island mode or with black start units that can initiate conventional thermal power plants. Since these conventional power plants need a minimum loading condition and have limited capability to pick up load, load must be systematically restored to reach this stable operation point until the main backbone of the power system is online. After the backbone is online, the remainder of the power system load can be restored [34]. Using the fast response time from ESSs to support cranking of bulk power plants can speed up the power system restoration process. ESSs can be operated as black-start units to crank regular-start units [33]. ESSs can also help reestablish the balance of load and generation during the load pick up process because of their bidirectional capability. This will require a redesign of the control architecture to include grid forming mode in ESSs and/or virtual inertia algorithms. In addition, this application might require oversizing the grid side converter because of the power intense nature of the restoration process.

The Imperial Irrigation District (IID) utility has successfully demonstrated the use of a 33MW/ 20MWh lithium-ion battery system to provide black start for a 44MW combined cycle natural gas turbine, located at El Centro Generating Station in Imperial Valley, California [35].

4. Transmission Services

Transmission Upgrade Deferral

When a component (e.g., a transmission line, a transformer) in a transmission network is reaching its capacity limit because of the increase in load (mostly the peak load) in a planning horizon, it requires an upgrade. In many cases, deploying energy storage can help defer this upgrade for some time since energy storage can flatten out the load shape by charging when demand is low and discharging during the hours of peak load. The required size of the energy storage is dependent on the expected load growth and the desired deferral time.

The economics of transmission deferral for a transmission line example are illustrated in Figure 9 (assuming continuous compounding). In the first scenario, the transmission upgrade occurs at year 0. In the second scenario, the upgrade occurs at the Kth year since energy storage enables a deferment of K years. When the net present value (NPV) of the deferral is greater than the NPV of the upgrade, there is a financial benefit to employing energy storage to defer the cost of the transmission upgrade. This benefit can be significant for a large deferral but is also highly location specific.

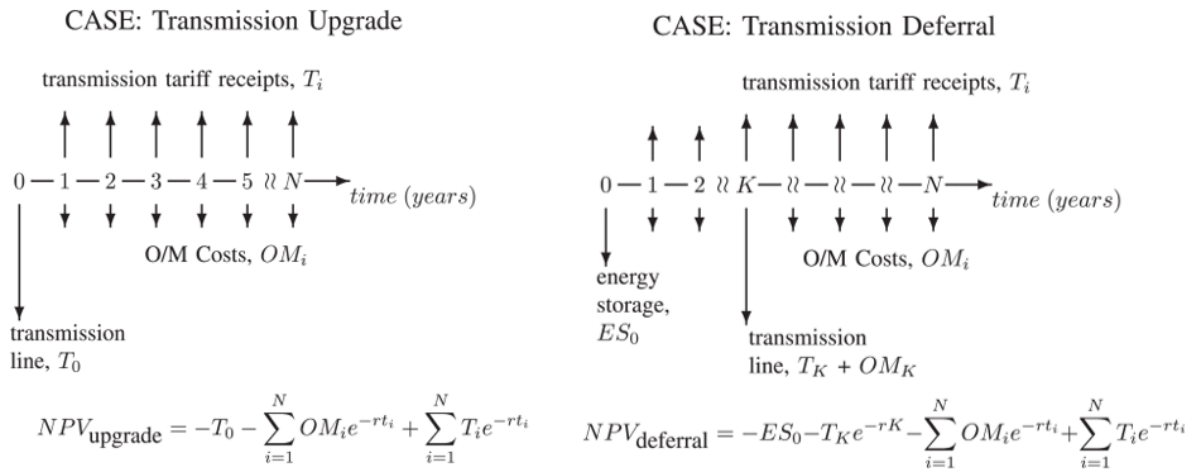


Figure 8. Transmission deferral example

Transmission Congestion Relief

Transmission congestions occur when transmission facilities are inadequate in delivering the available least-cost generated energy to the loads. For example, a congested interconnection line can prevent the delivery of available renewable energy from one system to its interconnected neighboring system during peak demand periods. In such situations, more expensive generators that are closer (or local) to the loads must increase their outputs to meet the demand, thereby increasing the energy cost.

Energy storage can be used in different ways to avoid congestion-related issues. In one way, an ESS can be deployed close to a large load center that often suffers from high congestion-related costs and charges. An ESS can store energy during low demand periods when there are no congestions, and discharge energy during peak demand periods. In another way, an ESS can be coupled with a renewable power plant (e.g., a solar or wind farm) that often must curtail its output during congestion times. The ESS can store what would have been curtailed energy for later dispatch. In this way, the renewable power plant can better utilize its rated capacity.

Stability Damping Control

All large geographically distributed electric power systems typically exhibit inter-area oscillations. These low frequency oscillations, typically in the 0.1-1.0 Hz range, are an electromechanical phenomenon where generators in one area oscillate against generators in another area. The proper damping of these oscillations is critical to the safe and secure operation of the system.

With appropriate control strategies, energy storage has been demonstrated to be able to provide damping to inter-area oscillations in power systems [36, 37, 38]. For this application, the active

power injections of multiple energy storage systems within the same power grid are modulated to destructively interfere with the inter-oscillations of the system. It is important to note that the energy storage systems considered for this application are those that interface with the grid through power electronics and hence their power injections can be easily controlled (see Chapter 13: Power Conversion Systems). The location and size of the energy storage systems as well as the available measurements to construct the control action are critical to determine the effectiveness of the controller. Generally, remote measurements of the local frequencies of the system, available from devices such as PMUs, are used in the design and implementation of the damping control strategy. Figure 9 shows the frequency difference of two generators in an example power system for the case with and without energy storage control. The two generators selected belong to the areas that oscillate against one another. The results in the figure show how effective a damping controller that uses energy storage as an actuator is at dampening inter-area oscillations.

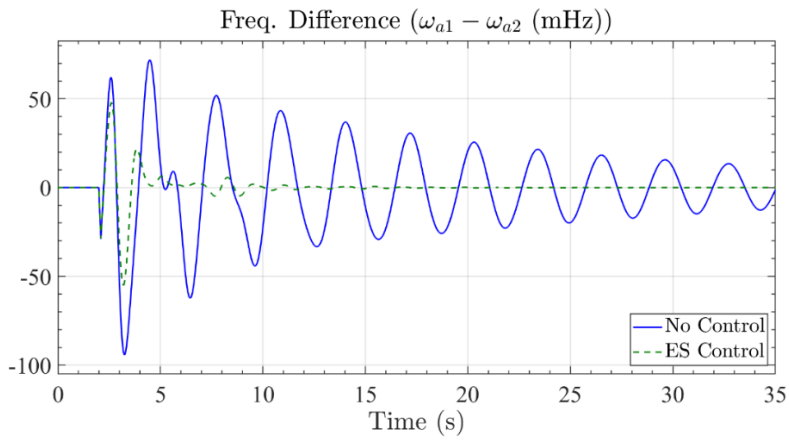


Figure 9. Frequency difference of an example power system with and without ES control

Distribution Services

Peak shaving and Upgrade Deferral

Like the transmission upgrade deferral mentioned in the previous section, load growth in distribution networks can often cause lines or transformers to exceed their ratings during peak periods. Energy storage can be deployed to mitigate the problem. The maximum benefit is achieved when there is slow load growth and a relatively small energy storage system can defer a large investment for a long period of time. In many cases, ESSs will only be required to discharge over several peak hours every year.

Voltage regulation

Voltage regulation issues are common to distribution networks. With increasing penetrations of distributed generation sources such as PV, voltage control concerns can limit further deployment of these sources. Current voltage control solutions include tap changing transformers and capacitors. Increased penetrations of variable renewable generation can cause tap changers to operate more frequently, significantly increasing maintenance costs. Energy storage can help regulate voltages in distribution networks via injections of real and reactive power. This benefit is highly location specific and there are currently no mechanisms for remuneration. In addition, other inverter-based assets like PV can also provide voltage support [39].

FERC Order No. 841 mandates that RTOs/ISOs allow distribution sited energy storage to participate in markets [26]. This opens a new opportunity for distributed ESSs to generate more revenue, however, this also creates challenges for the grid operators. These challenges are often associated with modeling and managing storage resources that span the transmission and distribution system.

Resilience

Resilience is "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event" [40]. Natural hazards and extreme weather conditions, equipment and network failures, and cyber/physical attacks have the potential to negatively impact grid resilience (see Chapter 18: Physical Security and Cybersecurity of Energy Storage Systems). These hazards and events, including high-impact low-probability events are commonly excluded from reliability calculations. Resilience improvement strategies must also consider options to improve grid flexibility and control [41]. ESSs can act as an effective power source for improved resilience through proper power system network placement and deployment, resilience-oriented optimal scheduling, and resilience market design. Thus, ESSs will have a major role in improving grid resilience. Future ESS resiliency services may include renewable curtailment minimization, black start support, and peaker replacement. The combination of services can increase the operational resilience of the grid.

Currently, there are no standard resilience metrics, which makes it difficult to quantify the benefits from different energy storage scenarios. Examples of proposed metrics are found in [42]. Location, size, and response time are critical factors that influence ESS performance and will impact the cost to benefit ratio of providing a resilience service.

To systematically assess the value of resilience enhancements with respect to critical events, a conceptual trapezoid is presented in [40]. The trapezoid, adapted for ESSs in Figure 10 [41], demonstrates the phases of a power system disturbance. The trapezoid includes the time sequence of these phases, and required recovery actions, enabling a dynamic, multi-phase resilience assessment with respect to operation and infrastructure. The improvement on power system resiliency with ESSs can be visualized by the dotted trapezoid in Figure 10. In Phase I, the ESS reduces the impact of initial events, and restores the grid to 100% resilient state. In case of an extreme event, ESSs provide an opportunity to improve the operational flexibility, thereby reducing the resilience degradation level without ESS resiliency services. In Phase II, while identifying the critical components for system recovery toward a resilient state, an alternate local grid can be formed by combining distributed generation with energy storage. Finally, in Phase III, ESSs can support power system restoration. Because ESSs can play a major role in reducing the time and impacts on each event phase, the total time to restore the system to the pre-event 100% resilient state can be significantly reduced.

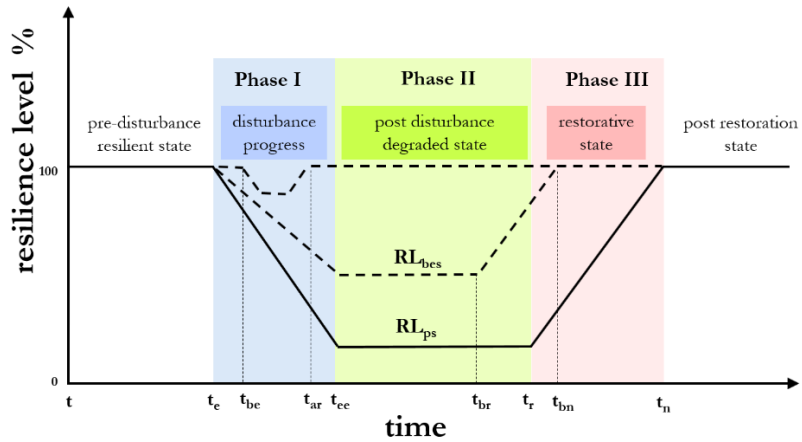


Figure 10. ESSs impact on the power system resilience trapezoid [41]

5. End-user Services

Time-of-use, demand charge and net-metering management

Time-of-use (TOU) pricing is a rate structure where energy prices change over time [43]. Rates can vary according to the time of day, season, and day type (weekday or weekend/holiday). TOU rates are often set in advance and do not adjust during a contract period. As more utilities provide TOU rate options, customers can reduce their bills by changing/shifting their electricity consumption. To maximize the benefit from TOU rate structures, the end-user must have the flexibility to change their total load patterns without interrupting their operations (commercial/industrial customers) or sacrificing their conveniences (residential customers). Energy storage can provide the needed flexibility to shift/shave loads to reduce/minimize the overall electric bill. This is like the arbitrage benefit in market areas.

A demand charge is a rate structure where the customer is charged based on their peak electricity consumption (kW) over some time period, e.g., the monthly billing cycle. Loads with high peaks, which include pumping and other industrial processes, can result in extremely high electricity bills when demand charges are in place. Energy storage can be deployed to smooth out these peaks, often resulting in significant savings.

Net energy metering (NEM) is a solar incentive that allows customers to sell excess energy back to the grid. In effect, this is using the grid as "storage" for the excess energy generated. The energy exported to the grid will be used to offset the customer's consumption during other periods of low solar generation. At the end of a billing period, the customer will be charged/credited for the net energy usage/surplus. NEM customers can better utilize the energy from their rooftop PV system by charging the ESS with excess energy when their loads are low and discharging that energy later when their loads are high. In this case, the customers can increase their savings by avoiding selling their renewable energy at low wholesale price and buying the energy later at much higher retail price.

Power Quality

Power quality generally refers to sags, surges, harmonics, and other flaws in an otherwise purely sinusoidal voltage or current. Power is still available to the process, but the power is of such poor quality as to be unusable. ESSs, through the advanced control of smart inverters, can protect critical loads, especially ones that require high-quality power (e.g., sensitive electronic devices and

microprocessor-based controls). ESSs are also able to mitigate power quality problems created by loads such as harmonics and low power factor [44]. It is very important to note that, even though smart inverters can be very flexible in terms of controlling their output power, their technical capabilities are limited within current codes and standards (e.g., IEEE1547, UL1741) that were often written for distributed energy resources. Therefore, there is an urgent need to update these standards that specifically address the issues associated with ESSs.

6. Stacking Services

Energy storage can provide many grid services. Value stacking refers to the case where an energy storage system provides multiple grid services to maximize revenue to the owner or to maximize grid benefit. There are two primary motivations for value stacking. First, energy storage is still relatively expensive, so value stacking can increase the likelihood that a project has a positive net benefit. Second, some applications like T&D deferral only require charging/discharging as little as a few hours per year to provide the required benefit. The system is then available for the rest of the year to provide other services which can further improve the project's net benefit.

The value provided by an energy storage system is contingent on charging/discharging at the correct times to provide the required benefit. Therefore, value stacking is easily formulated as an optimization problem [1]. Typically, a relatively simple energy flow model can be employed:

$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D$$

where S_t is the state of charge at time step t (MWh), γ_s is the storage efficiency (percent) used to model self-discharge, γ_c is the conversion efficiency (percentage) used to model conversion losses, q_t^R is the quantity of energy (MWh) recharged at time step t, and q_t^D is the quantity of energy (MWh) discharged at time step t. This model assumes a constant conversion efficiency which is a valid approximation for many technologies. However, for flow batteries the conversion efficiency varies significantly, and a different model should be considered [45].

The cost function for the optimization problem contains terms associated with the cost/revenue associated with charging/discharging for each of the proposed value streams. The results of a typical optimization are illustrated in Figure 11. In this example, the system is providing the following benefits: energy arbitrage; frequency regulation; reduction of the regional network services (RNS) obligation; and reduction of the forward capacity market obligation (FCM). The FCM and RNS benefits require discharging in specific hours to achieve the benefit. In this example, the optimum policy is to engage in frequency estimation with a 50% state of charge until it is time to charge up to 100% state of charge in anticipation of the discharge periods to reduce the RNS and FCM obligations. Afterword the system returns to providing frequency regulation. Energy arbitrage does not occur during this time period because the other grid services offer more potential revenue [6].

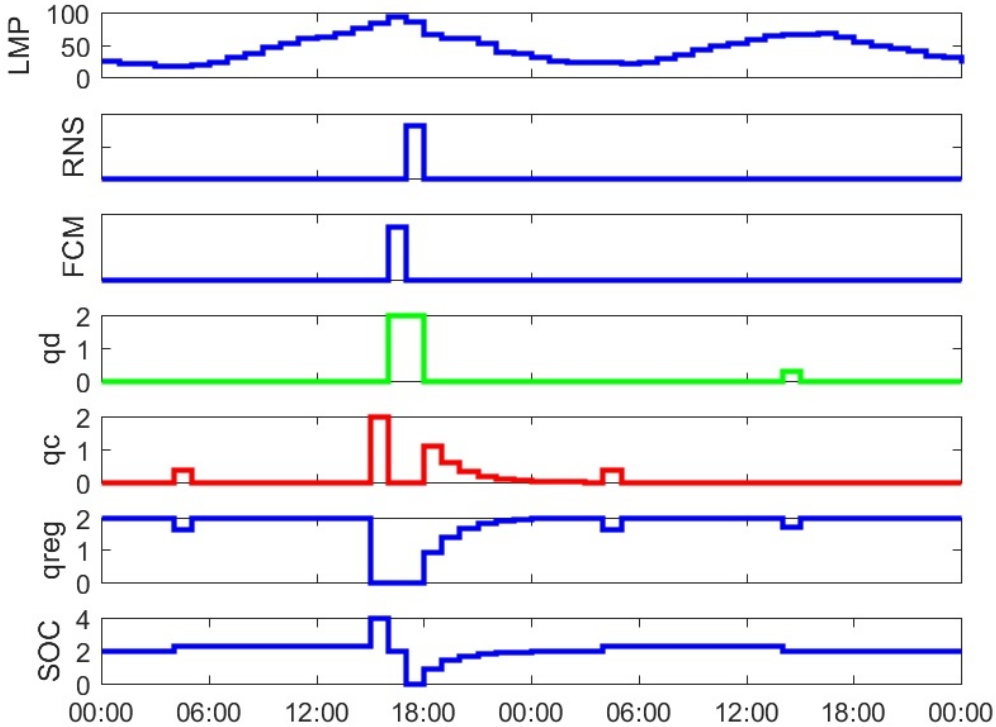


Figure 11. Optimization results for a system providing: energy arbitrage; frequency regulation; reduction of the regional network services (RNS) obligation; and reduction of the forward capacity market obligation (FCM)

The example in Figure 11 assumed perfect foresight to assess the maximum potential revenue from an energy storage system. In reality, the energy management system will have to rely on a forecast to identify the optimum charge/discharge times. This represents a challenge for value stacking. For example, if a demand charge reduction benefit requires discharging during a coincident peak load hour that is difficult to forecast, the probability of accruing the benefit can be low. A potential mitigation is to increase the capacity of the energy storage system and to discharge over multiple hours, but this increases the system cost. Often, reducing these types of demand charges can provide a significant amount of revenue, so the potential to miss opportunities creates revenue uncertainty/risk, which can impede project financing. Another consideration is the impact of various activities on the life of the energy storage system. Currently it is difficult to model the reduction in capacity or useful life from providing various grid services. Ideally, the optimization should also include this factor. This concern can be mitigated if there is a warranty with flexible terms.

7. Technology Selection and System Specifications

ESSs can operate either as dynamic generators or controllable loads depending on their control strategy and their location on the grid. This flexibility allows ESSs to offer multiple types of grid benefits, such as the applications described in the previous section. The technical requirements for these applications cover a wide range of values; for example, the frequency regulation application requires relatively short discharge duration (usually up to 1 hour) and possibly thousands of cycles per year, whereas energy arbitrage oftentimes requires longer discharge durations (usually up to 8 hours, depending on the tariff structure) and no more than one cycle per day. With regards to the

storage capacity, optimal benefits of distribution services and end-user services can be achieved through smaller ESS sizes when compared to general energy applications, ancillary services, and transmission services. These observations imply that some energy storage technologies might not be feasible options for a given set of grid applications.

The currently available portfolio of energy storage technologies contains systems with a wide range of capabilities, such as long vs. short discharge duration. Energy storage technologies can be divided into two broad groups based on their power-energy relationship. The first group is composed of technologies with long discharge durations (more than 10 hours), such as pumped hydro and compressed air energy storage (CAES) systems. Deployment of these technologies involves the construction of large facilities, such as dams and water storage reservoirs for pumped hydro systems or underground caverns – naturally occurring or man-made – and steel above-ground storage reservoirs for CAES systems. On the other side of the energy spectrum, the second group corresponds to technologies with shorter discharge durations (typically less than 4 hours), including electrochemical and flow batteries. Although rapid technological advances in recent years have allowed these storage technologies to reach higher powers and longer discharge times, this broad classification is still useful to provide initial insights on the selection of storage technologies for a given project.

Another convenient classification of energy storage technologies is based on whether they have an electric output during their discharging period. Most of the storage technologies have an output in electric form, however, some thermal storage technologies do not, which restrict their use only to grid applications that do not require an electric output. A common example is the use of ice and chilled water storage in commercial buildings to reduce HVAC loads throughout the day. This technology is effective for energy arbitrage and demand-side load management; ice or chilled water is made and stored in large tanks during the night (low price energy), which is then used to cool the building during daytime hours (high price energy) and reduce HVAC use. On the other hand, molten salt thermal storage technology does provide an electric output. This technology is based on the heating of salts through large area solar collectors in its charging cycle, whereas the discharging cycle consists of using the salts at sufficiently high temperatures to generate steam and drive turbine generators.

When designing an energy storage system, it is common to first identify the minimum technical requirements of the desired grid applications and then disregard any technologies that do not meet them. However, even if a certain storage technology meets these minimum requirements, there are multiple other factors to consider during the planning stage of an ESS. More specifically, the following factors must be taken into account for the technology selection of a storage system:

- Technical requirements of the desired grid application(s): minimum storage capacity, charge/discharge powers, discharge duration at rated power, ramp rate, and expected number of cycles per year.
- Deployment location: grid location (transmission, primary distribution, or secondary distribution level and front-of-the-meter or behind-the-meter, which determines the ownership of the ESS and which entity has control over its charge/discharge schedule) and electricity market area. Further, geographical location must also be taken into consideration, as it might restrict the deployment of some ESS technologies. For example, deployment of pumped hydro and cavern-based CAES systems is dependent on

the availability of reservoirs at different levels and geologic formations with appropriate air storage integrity, respectively.

- Installation, operation, and maintenance costs, which are uncertain and have been decreasing significantly in recent years.
- Regulatory policies: despite being a technically feasible option for the desired grid applications, certain ESS technologies might be unavailable due to applicable regulations at the deployment location. A clear example is pumped hydro storage systems, which raise environmental concerns over water and land use; in the U.S., no new pumped storage plant has been commissioned since the 1980s due to environmental opposition.

The best ESS technology for a given project is the one that meets all technical and regulatory requirements at the lowest total cost; however, identifying such technology for each project is not an easy task. This process would require a detailed analysis of the return on investment of the storage systems, which in turn requires a perfect foresight on how the ESS would be used throughout its lifetime. This analysis depends on various operational and business-related factors, such as deliverable power, efficiency, discharge time, lifecycle, number of grid applications implemented in the ESS, synergy between stacked grid applications, and ability to monetize the benefits of such applications. Oftentimes, the economic benefits of a certain grid application is location-specific; for example, the benefits of upgrade deferrals depend on factors that are unique to each location: investment size, load growth rate, and frequency and duration of peak load events.

On the other hand, identifying the most feasible and suitable – but not necessarily optimal – ESS technologies for a given project is attainable by considering the intersection between the minimum technical and regulatory requirements for the desired applications and the capabilities of each ESS technology. Generally, this is an iterative process, especially for cases in which stacked grid applications are under consideration.

One approach for screening suitability of ESS technologies for a given project consists in analyzing the characteristics of past successful ESSs deployment, such as the ones present in the *DOE Global Energy Storage Database* (GESDB) [46]. Currently, this database contains information on 1,697 operational, under construction, or planned grid-connected energy storage projects worldwide. These projects cover a wide range of storage technologies, deployment location on the grid, and applications.

Figure 12 depicts the number of ESS projects contained in the GESDB by storage technology; it is clear that the vast majority of these projects represented (approximately 70%) use either lithium-ion batteries, pumped hydro storage systems, or thermal storage (not including molten salt thermal storage). Further, Figure 13 represents the share (in %) of ESS technologies that have been deployed for each grid application. Notice that lithium-ion batteries are the most common storage technology used for most of the grid applications. On the other hand, large amounts of energy arbitrage and operating reserve applications are achieved through pumped hydro storage systems; also, many time-of-use energy cost management applications are based in thermal storage systems (in the form of ice and chilled water or hot water).

The predominance of lithium-ion batteries is partially due to their high energy density, high power, high efficiency, and low self-discharge. Although newer than other storage technologies, lithium-ion technology has already achieved large manufacturing scale and dominate the current deployment of new grid-connected ESSs. The family of lithium-ion batteries is available in several chemistries (see Chapter 3: Lithium-ion Batteries), each with specific power-energy

characteristics. Thus, lithium-ion batteries are a strong candidate for the consideration of any grid-scale storage project.

Pumped hydro storage systems are the second most common storage technology for grid-scale applications, although only a few projects have been commissioned worldwide in recent decades due to environmental concerns. This is a very mature technology and its main advantages are long expected lifespan and high storage capacity, which is limited only by the size of the available upper and lower reservoirs.

Sodium-based batteries are another electrochemical technology that has experienced significant improvements recently. These batteries are characterized by long discharge durations and fast response time, which make them strong candidates for power quality and area regulation applications. Further, they are projected to have long lifespans, rated at 4500 cycles and 15 calendar years.

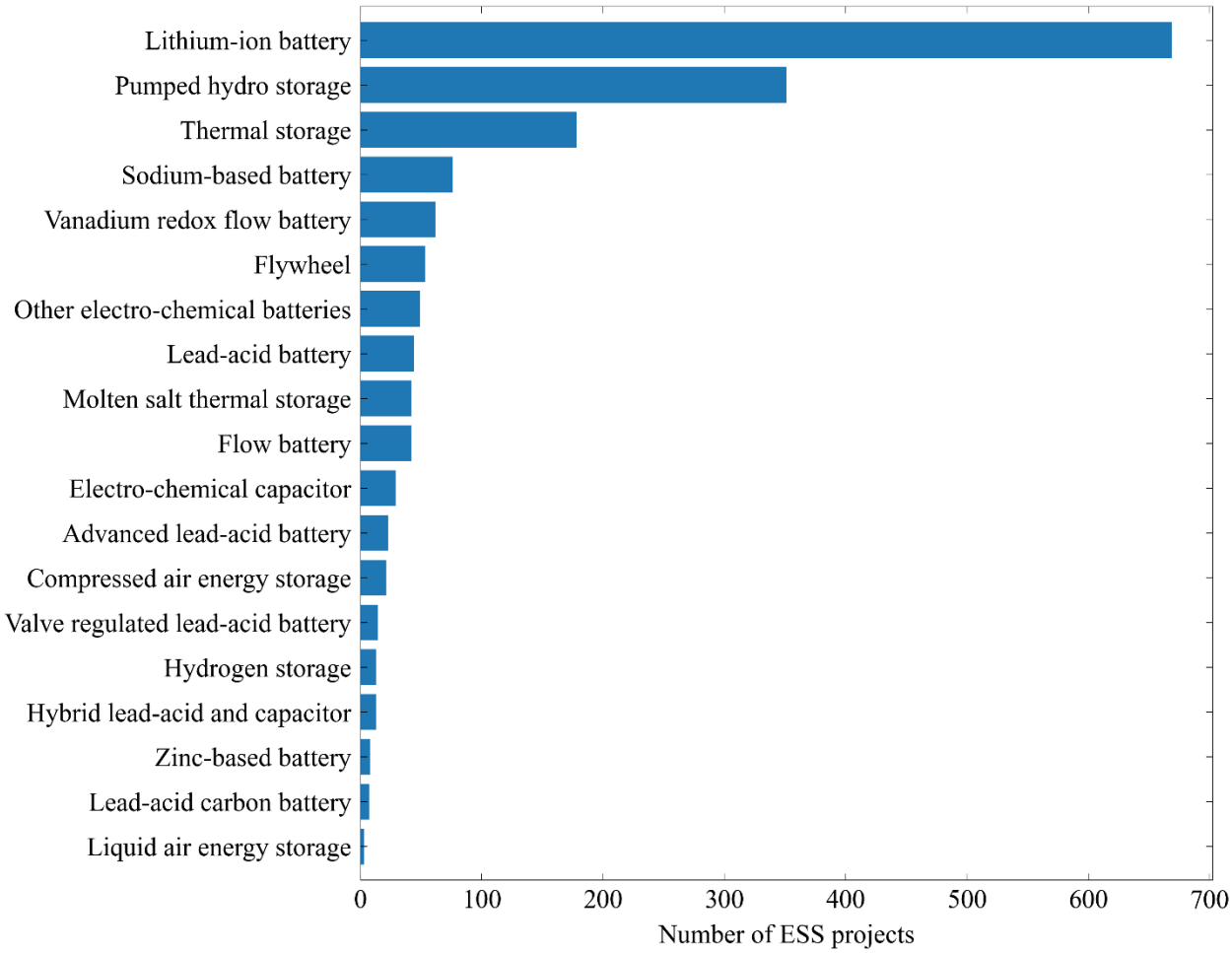


Figure 12. Distribution of ESS projects in the GESDB by storage technology (as of 11/17/2018)

	Energy arbitrage	Renewable energy time-shift	Frequency regulation	Operating reserve	Voltage support	Ramp support	Black start	Transmission upgrade deferral	Transmission congestion relief	Distribution upgrade deferral	Reliability and resilience	TOU and net-metering	Back-up power
Lithium-ion battery	22	46	48	20	38	49	40	38	45	68	56	47	55
Pumped hydro storage	46	3.9	19	48	17	6.9	21	8.3	4.7	0.78	1	0.94	1.3
Thermal storage	12	4.4	1.7	14	0.46	1.4	0	0	9.4	3.1	2.1	32	0.64
Sodium-based battery	4	6.4	5.8	3.1	7.3	5.6	11	17	14	6.2	5.4	3.5	6.4
Vanadium redox flow battery	2.4	6.9	3.5	1.8	5.5	2.8	6.8	8.3	6.2	0	5.7	4	6.4
Flywheel	0.99	1.7	8.1	2.9	8.2	2.8	0	4.2	3.1	2.3	5.4	0.7	2.5
Other electro-chemical batteries	1.7	4	1.7	1.5	1.4	0	2.7	0	0	2.3	8	2.1	8.9
Lead-acid battery	2.3	3.4	1.7	1.9	3.7	4.2	2.7	0	1.6	3.9	4.4	2.1	3.8
Flow battery	1.6	5	1.2	1.2	2.3	4.2	9.6	8.3	3.1	4.7	4.4	1.6	3.8
Molten salt thermal storage	0.28	7	0	0.29	0	0	0	0	0	0	0.26	0	0
Electro-chemical capacitor	2.6	1	1.7	0.44	11	1.4	0	8.3	3.1	0.78	0.52	0	1.3
Advanced lead-acid battery	0.43	2.3	2.3	1	2.3	11	0	0	0	0.78	1.6	1.4	4.5
Compressed air energy storage	1.4	2.3	1.2	1.3	0.46	4.2	2.7	0	1.6	0	1	0.94	0.64
Valve regulated lead-acid battery	0.71	1.3	0.29	0.73	0	0	0	0	1.6	1.6	0.52	1.4	1.3
Hybrid lead-acid and capacitor	0.71	0.84	0.29	0.88	1.4	1.4	0	0	0	0	1.8	0.23	1.9
Hydrogen storage	0.14	2	0.87	0.44	0	1.4	0	0	1.6	1.6	0	0.47	0
Zinc-based battery	0.43	0.5	0	0	0	1.4	0	0	0	2.3	1	0.47	0
Lead-acid carbon battery	0.28	0.84	1.7	0.29	0.91	2.8	4.1	8.3	3.1	1.6	0.78	0.7	1.9
Liquid air energy storage	0.28	0	0.29	0.15	0.46	0	0	0	1.6	0	0	0	0

0 10 20 30 40 50 60 70

Share of ESS technologies for each grid application (%)

Figure 13. Share of ESS technologies deployed for each grid application (as of 11/17/2018)

Redox flow batteries also exhibit a relatively fast response time, being capable of stepping from zero to full power output within seconds. Another advantage of this technology is the absence of self-discharge when the electrolytes are stored in separate tanks. On the other hand, redox flow batteries have a low energy density.

Unlike the electrochemical batteries discussed above, flywheels are a mechanical ESS technology based on the angular momentum of a spinning mass; they can be used in either energy or power applications and have high power densities. These ESSs can be charged and discharged relatively quickly, even as low as a few seconds; thus, they are not a suitable option for large-scale grid applications that require large storage capacities but are strong candidates for voltage and frequency regulation services and mitigation of power quality issues. Further, flywheels have very long lifespans, which can exceed 100,000 full charge/discharge cycles, and have no environmental concerns related to their operation.

The previous discussion focused on analyzing past ESS projects present in the GESDB. Another approach for energy storage technology selection is the software ES-Select [47]. This tool assesses the feasibility of each storage technology according to inputs such as deployment location and desired grid applications. The computation handles uncertainties in application value, storage cost, cycle life, round-trip efficiency, and discharge duration; then, each technology is assigned a feasibility score in the 0-1 range according to the user's inputs. This tool, however, assumes that the field operation of the ESS will match the assumptions made during the feasibility computation, which might not be true. Thus, it is recommended that anyone using this tool for energy storage technology selection also take into account the information about the hundreds of successfully deployed ESSs in the DOE Global Energy Storage Database.

8. Energy Storage Evaluation Tools

Project development is an exercise in risk management and the development and deployment of energy storage systems is no exception. Understanding the performance of the energy storage project is essential for all stakeholders to assess the project's viability. While it is most likely the economic performance that greenlights the project, it should be understood that technical performance affects economic performance. Given the previously enumerated applications and services that energy storage can provide, how can the system monetize these value streams to outweigh investment and operating costs? Simulation and modeling can be instrumental in answering such questions about project performance. A project economic model can account for cash flows and costs that will address the dollar portion of the equation. However, understanding technical performance potential and how that can translate to cash flows can be complex to address.

Modeling and software tools

System simulators and energy storage evaluation tools can be used to model technical performance. They can simulate both the hypothetical and the counterfactual to assess energy storage system performance given certain conditions and available value streams. Typically, these tools will determine optimal operating policies of an energy storage system by assigning monetary value to available services and applications and co-optimizing to maximize revenue over a specified time horizon. For example, a year of operation may be assessed for a BTM energy storage system coupled with an on-site photovoltaic power installation and building load. Given a utility rate structure, load profile, and photovoltaic power profile, the optimal state of energy management policy that minimizes costs through options such as demand charge reduction via time-shifting can be determined.

For value streams that are discrete (i.e., tied to actual services or products in formal electricity markets), technical performance modeling is more straightforward as the dollar value of such value streams is already formalized. An example of such a stream is providing frequency regulation.

Value streams that are definable have value to another market participant but are typically location or case-specific, and don't generalize well to entire markets. An example of this is providing black start. It is often the case that value streams like these are contracted for directly or consolidated into the purchase price of the asset.

On the other hand, there are indeterminate value streams that are not easily quantifiable on a systematic valuation basis. They are often in the conversation as market drivers but are difficult to contract for specifically. A quintessential example is resiliency applications of which a simple case is backup power applications. It can be argued that the monetary value of backup power is directly related to the value of lost load which can be difficult to establish. With respect to energy storage evaluation, a system expected to provide backup power may be modeled with a "hard constraint" in which it is always required to reserve some energy and power capacity to meet its backup power obligation. It may also be modeled as "soft constraint" in which it is heavily penalized for not being prepared to serve as backup power, but it may violate this constraint if the price is right. More complex definitions of resiliency applications will further complicate attempts to quantify their value [48].

Many lenders have expressed the desire for standardized modeling tools that would be instrumental in assessing projects from different developers. To date, many such tools have been developed. A sample selection of currently available software tools for energy storage valuation is summarized in Table 4.

Table 4. Representative energy storage evaluation tools

Name	Organization	Licensing	Open Source	Notes
System Advisor Model (SAM) [49]	NREL[1]	Free[2]	Yes	Project-based performance and financial model; targeted toward renewable energy industry; not intended for stand-alone wholesale energy storage assets; desktop application with software development kit
Hybrid Optimization Model for Multiple Energy Resources (HOMER) [50]	Homer Energy, LLC	Free and commercial options[3]	No	Microgrid- and distributed energy resource-centric; free online web tools and paid desktop varieties; microgrid design and operation
Storage Value Estimation Tool (StorageVET 2.0) [51]	EPRI[4]	Free[5]	Yes	Designed for site-specific energy storage projects; desktop standalone environment
QuESt [52]	Sandia National Laboratories	Free[6]	Yes	Designed for site-specific energy storage projects; desktop standalone environment

[1] National Renewable Energy Laboratory
[2] Software key delivered via email upon initial installation and setup
[3] Free online tools (HOMER QuickStart and HOMER QuickGrid) and desktop options (HOMER Pro and HOMER Grid) with monthly license fees
[4] Electric Power Research Institute
[5] Access to download is provided after submission of a registration form
[6] Distributed as source code on GitHub along with packaged versions

The use cases for energy storage systems are diverse which results in modeling tools having a variety of focuses and capabilities. Some tools are oriented toward renewable energy systems and treat energy storage as a supplemental asset. Other tools focus on microgrid design and simulation and treat energy storage systems as a component of a larger microgrid. On the other hand, some tools are designed specifically to analyze standalone energy storage systems first while adding capabilities for other use cases that may include other asset types such as the ubiquitous solar plus storage configuration. As a result, different evaluation tools may fit user needs better depending on the specific use case.

QuESt

QuESt is an open source software application suite for energy storage valuation developed by Sandia National Laboratories. It is distributed freely as source code that can be installed as a standalone desktop environment but is also available as a packaged executable. QuESt is an application suite consisting of several distinct yet interconnected applications that collectively assist in evaluating energy storage systems for different use cases.

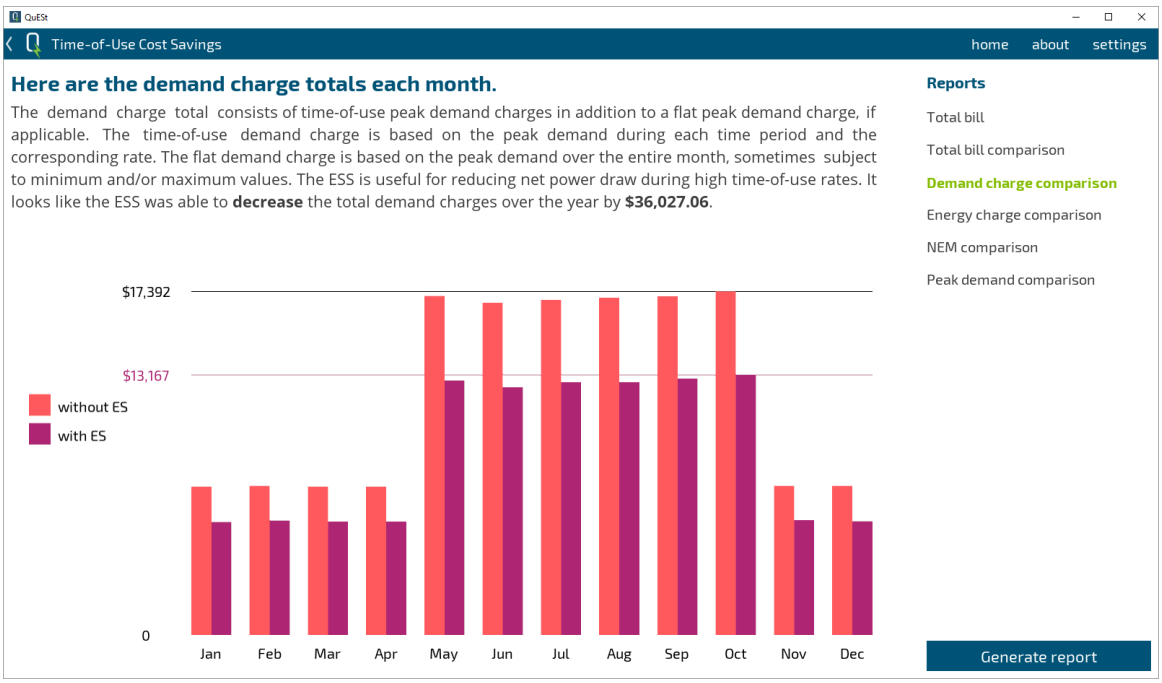


Figure 14. Sample output from the QuESt BTM application illustrating demand charge reductions achieved with an energy storage system

QuESt Valuation is an application targeted for energy storage systems participating in ISO/RTO electricity markets and providing services. It estimates revenue potential by co-optimizing over different value streams such as energy arbitrage and frequency regulation over historical data sets. For example, one can maximize the revenue potential for an 8 MW/32 MWh energy storage system operating in June 2017 in the PJM electricity market. The valuation algorithm uses a perfect foresight approach for the energy and services prices. This retrospective analysis approach is intended to estimate an upper bound on revenue potential by determining the best-case scenario of past data.

QuESt BTM is an application for behind-the-meter energy storage use cases. It includes a tool for estimating the cost savings from behind-the-meter energy storage for time-of-use and net energy

metering customers. It determines the optimal state of energy management policy that minimizes the total electricity bill for one month at a time (Fig. 14). The total electricity bill is the sum of energy, demand, and net metering charges. Optionally, the energy storage system may also be co-located with a photovoltaic system that can offset the combined system demand and/or be sold for net metering credits.

QuESt Data Manager is an application for acquiring data from web sources for use in other QuESt applications. Energy and service prices from ISO/RTO market sources can be pulled from their respective portals and used in QuESt Valuation for formulating the analysis. The application also taps into resources for U.S. utility rate structures, commercial and residential building load profiles, and photovoltaic power profiles for use in QuESt BTM. While users can download data from external sources for use in QuESt applications, it is also possible to import user data instead.

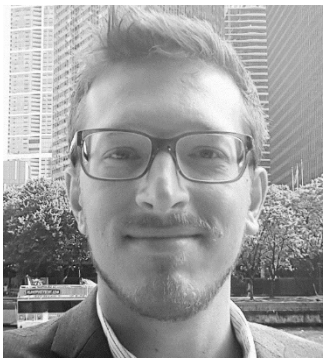
As development continues, modeling tools for additional use cases or augmentations to existing tools will be added to QuESt.

9. Summary

Energy storage is an extremely flexible grid asset that can provide a multitude of grid services. These grid services are often categorized as energy or power applications. Energy applications transpire over longer time scales, hours to days, whereas power applications occur over a much shorter time scale, seconds to minutes. Power applications are often associated with real time control to maintain the stability and reliability of the electric power grid. Energy storage valuation is challenging because it is highly location dependent. Market areas, vertically integrated utilities, and behind-the-meter applications require different analysis techniques because of different rules and rate structures. In addition, each market area has unique rules for the treatment of energy storage as well as unique market products. For example, some markets have a bidirectional product for frequency regulation while other markets have a separate product for regulation up and regulation down. In addition, more technical benefits like frequency support after the loss of a large generator require dynamic simulations to evaluate the efficacy of different energy storage scenarios. Given the complexity of energy storage sizing, siting, and valuation, much work is needed to develop the methods and tools to unlock the full value that energy storage can provide to the electric power grid, as well as to simplify the regulatory landscape. For additional information on energy storage applications, please refer to: www.sandia.gov/ess.

Tu Nguyen is a Senior Member of the Technical Staff at Sandia National Laboratories. He is also a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE) and an editor of IEEE Transactions on Sustainable Energy. He received his BS in Power Systems from Hanoi University of Science and Technology, Vietnam in 2007 and his PhD in Electrical Engineering from Missouri University of Science and Technology in 2014. Before joining Sandia National Laboratories in September 2016, he worked as a Postdoctoral Research Associate at University of Washington. In 2019, he received *Outstanding Young Engineer Award* from IEEE-Albuquerque Section. His current research interests include energy storage analytics, microgrid modeling and analysis, and the grid integration of distributed resources.

Ray Byrne is manager of the Electric Power Systems Research Department at Sandia National Laboratories where he has been employed since 1989. Prior serving as manager, he was a Distinguished Member of the Technical Staff. He completed a BS in electrical engineering at the University of Virginia, an MS in electrical engineering at the University of Colorado, and a PhD in electrical engineering at the University of New Mexico. He also completed an MS in financial mathematics (financial engineering) at the University of Chicago. He currently serves as team lead of the Equitable Regulatory Environment thrust area of the Sandia energy storage program. Awards include Time Magazine invention of the year in robotics in 2001, as well as the Prize paper award at the 2016 IEEE Power and Energy Society General Meeting for a paper on maximizing revenue from energy storage in grid applications. He is a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi. He was elevated to IEEE Fellow in 2017 for contributions to miniature robotics and grid integration of energy storage.



Rodrigo D. Trevizan is a Senior Member of Technical Staff at Sandia National Laboratories. Rodrigo authored research papers on the control of energy storage systems and demand response for power grid stabilization, power system state estimation, and detection of nontechnical losses in distribution systems. Rodrigo received a BS and MSc degree in Electrical Engineering from the Federal University of Rio Grande do Sul, Brazil, in 2012 and 2014, respectively, a MSc in Power Systems Engineering from the Grenoble Institute of Technology (ENSE3) in 2011 and a PhD in Electrical and Computer Engineering from the University of Florida in 2018.

Alvaro Furlani Bastos is a Postdoctoral Appointee in Energy Storage Analytics at Sandia National Laboratories. He received his BS in Electrical Engineering from the Federal University of Viçosa, Brazil, in 2014, and his MS and PhD from The University of Texas at Austin in 2015 and 2020, respectively. His research interests include power quality, renewable energy integration, energy storage, data analytics, optimization, and machine learning.

Felipe Wilches-Bernal is a Senior Member of Technical Staff at Sandia National Laboratories. He received a PhD in Electrical Engineering from Rensselaer Polytechnic Institute in 2015, an MS in Electrical Engineering from Université Paris-Sud XI, Orsay, France in 2009, and the BS Degree in Electrical Engineering from Pontificia Universidad Javeriana - Colombia in 2008. He has 8+ years of experience in the energy sector with focus on electric power. Principal investigator or key technical contributor of multiple projects on renewable energy integration and control for resilient grid modernization. Expertise in signal processing, control theory and optimization applied to power systems. Recipient of multiple distinctions and awards. Internationally experienced and fluent in English, Spanish, and French.

Reinaldo Tonkoski (IEEE Membership: S'04--M'11--SM'18) received his B.A.Sc. degree in Control and Automation Engineering, in 2004 and his M.Sc. in Electrical Engineering in 2006 from PUC-RS (Pontifícia Universidade Católica do RS), Brazil, and, his Ph.D. in 2011 from Concordia University, Canada. He was with CanmetENERGY, Natural Resources Canada, from 2009 to 2010 where he worked on projects related to the grid integration of renewable energy sources and a Visiting Professor at Sandia National Laboratories from 2019-2020. Presently, he is an Associate Professor in the Electrical Engineering and Computer Science Department, South Dakota State University, Brookings, USA. Dr. Tonkoski has authored over eighty technical publications in peer reviewed journals and conferences and is currently an Editor of IEEE Transactions on Sustainable Energy, and Associate Editor of IEEE Access and IEEE Systems Journal. His research interests include grid integration of sustainable energy technologies, power electronics and control systems.

Ricky Concepcion is currently a Software Engineer at L3HARRIS Technologies. Before joining L3HARRIS in 2020, he was a Member of Technical Staff at Sandia National Laboratories. He received his BS degree in 2013 and Master of Science degree in Electrical Engineering in 2014 both from Cornell University, Ithaca, NY.

Alexander Headley is currently an assistant professor of Mechanical Engineering at The University of Memphis. He was a postdoctoral appointee in the Energy Storage Technology and Systems department at Sandia National Laboratories from 2018 to 2020. His current research is focused on evaluating the potential of energy storage systems for grid support, integrated system design, and the development of demonstration facilities for grid-connected energy storage. Given his background in Thermal/Fluid Systems, Alexander is also developing thermal models of grid-scale lithium ion battery systems for control and design support. Before joining Sandia, he earned his master's and PhD in mechanical engineering at The University of Texas at Austin.

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