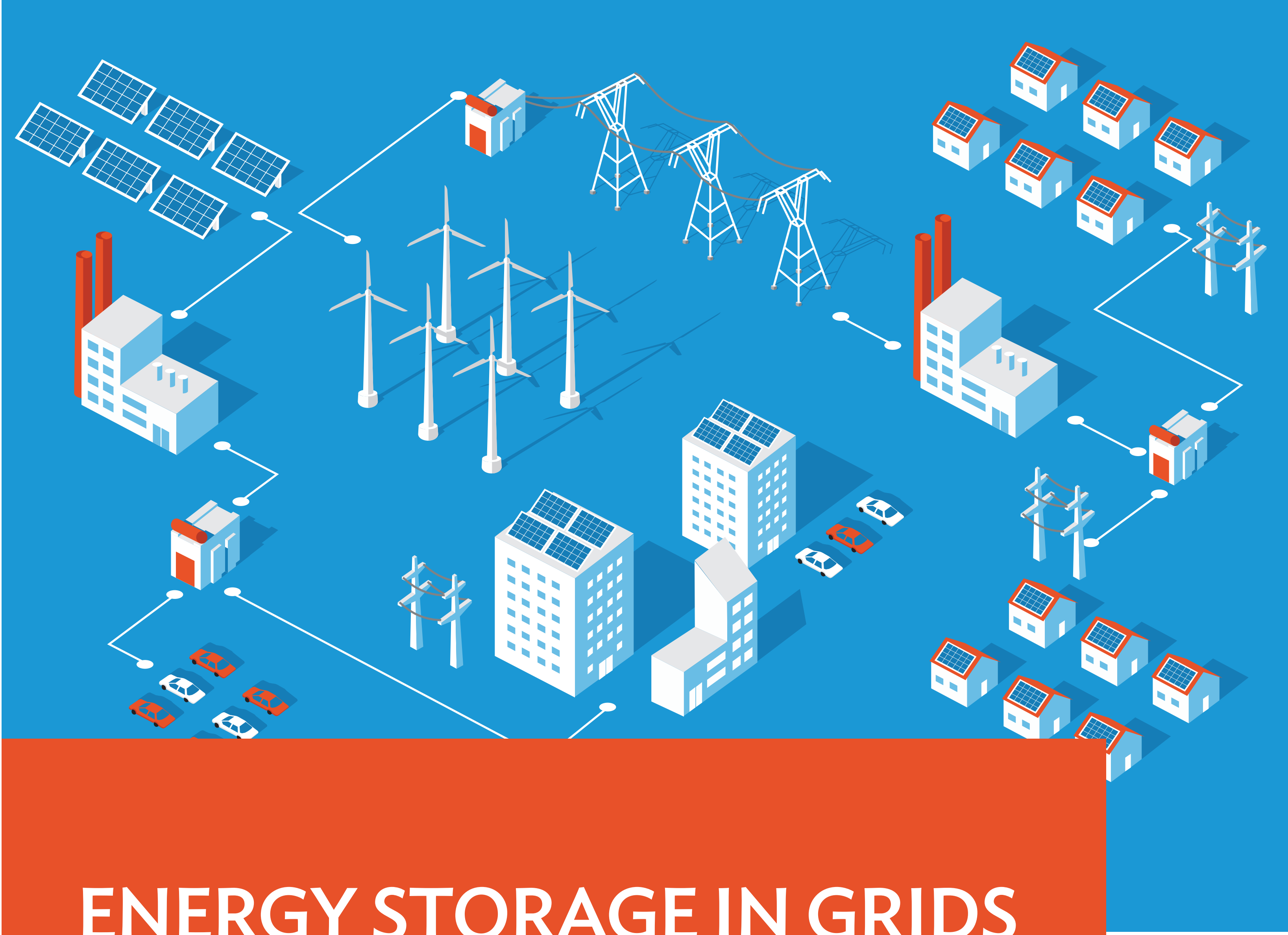

ENERGY STORAGE IN GRIDS WITH HIGH PENETRATION OF VARIABLE GENERATION

ASIAN DEVELOPMENT BANK

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Executive Summary

Grid-level energy storage is likely to dominate the conversation in the power industry in the coming years, just like renewable energy dominated the conversation in the past 2 decades. The drivers for grid-level energy storage are rapidly decreasing cost of energy storage, and the multitude of benefits provided by energy storage to the grid in general and to grids with high penetration of renewable energy in particular.

The rapid decrease in cost is primarily driven by rapid innovation and scale in the electric vehicle market. Currently, a large amount of investment is being channeled into energy storage for such applications. This has led to rapid innovation in terms of use of cheaper raw materials, longer-life, safer operations, and better control. It has also led to large-scale production facilities (gigawatt factories) for energy storage, which promises to achieve reduction in costs similar to those seen in solar photovoltaic industry.

The focus of this report is on energy storage for the power grid in support of larger penetration of renewable energy. The emphasis is on energy storage and associated power electronics that are deployed in the grid in order to support utility scale renewable energy projects (wind and solar) by providing services like frequency support, voltage support, ramping support, peak-shaving, load-shifting, transmission deferral, and others. The following applications of energy storage are important, but are beyond the scope of this report: residential, commercial or industrial behind-the-meter energy storage. Although most of the content in the report is applicable to the benefits of energy storage deployment in grids with minimal or no renewable energy penetration, that is not the focus of the report; instead, the focus is on grids that have or will soon have high renewable energy penetration.

The intended audiences of the report are investors, developers, utility planners, power sector policy makers, and others who want to understand the important role energy storage is likely to play in the smart grid of the future. For the developing member countries of the Asian Development Bank, this report provides an introduction to the necessary technical background on energy storage, the role it is likely to play as penetration of renewable energy increases in the grid, and the policy prescriptions to realize the wide range of benefits of energy storage.

The first chapter of the report introduces broad categorizations of energy storage and specific technologies that belong to each category. The energy storage technologies are mapped out in terms of amount of power and energy content, and the different applications in the power sector. The maturity of the different technologies is also discussed.

The next chapter lays out the case for energy storage in grids that are planning large penetration of renewable energy. The characteristics of renewable energy that require storage as the penetration of renewable energy rises are described. Other than the obvious concerns related to mismatch of renewable energy production compared to load, there are issues related to lower grid inertia and lower spinning reserves during times of high renewable energy production. Energy storage is a solution for addressing these concerns.

The third chapter describes the various roles and applications of energy storage in a grid. The applications are grouped into four clusters—bulk energy services, ancillary services, dispatch-ability, and transmission and distribution deferral. The characteristics of energy storage that support each of the applications are described in the context of high penetration of renewable energy in the grid.

The fourth chapter presents the control systems that accompany energy storage. There are three tiers of control systems: battery management system (BMS), power conversion system (PCS), and supervisory control system (SCS). BMS manages the health, longevity, and safety of the battery by monitoring parameters like state of charge, state of health, temperature, and others. PCS manages delivery of active and reactive power to the grid. The SCS monitors grid parameters like bus voltages, grid frequency, and others to send commands to PCS and BMS.

The next chapter outlines the technical studies that should be performed for an energy storage project. The first is power systems analysis of the grid with renewable energy and energy storage using methods like power flow, short-circuit, and stability analyses. The second is sizing of storage based on grid-specific conditions.

The sixth chapter addresses financial modeling and economics of energy storage projects. The financial model for energy storage is more complicated than that of a renewable energy project—the cost of charging, the stacking of revenue based on services provided, and the cost of replacement of energy storage units. The estimation of the first two components requires an hour-by-hour simulation model for a year of the energy storage unit, renewable energy production, and schedule of conventional generators.

The final chapter covers policy support required for energy storage projects. Best practices for policy include setting tariff for each of the services provided by energy storage, incorporating energy storage in an energy master plan, incentivizing codevelopment of energy storage and distributed renewable energy, and support for pilot projects.

Abbreviations

BESS	–	battery energy storage system
BMS	–	battery management system
IGBT	–	insulated gate bipolar transistors
kW	–	kilowatt
kWh	–	kilowatt–hour
LCOS	–	levelized cost of energy storage
MW	–	megawatt
PCC	–	point of common coupling
PCS	–	power conversion system
SCS	–	supervisory control system
SOC	–	state of charge
SOH	–	state of health

1 Introduction to Grid Energy Storage

The advantages of energy storage in the grid are well understood. Pumped-storage hydroelectricity is one of the oldest forms of grid-level energy storage and was first used in the 1890s. These storage systems have provided a wide range of services to the grid including load balancing, load following, reserve generation, and frequency and voltage support. With increased penetration of variable generation like solar and wind, there will be higher demand for such services, therefore energy storage will become critical to the grid.

> **"I believe energy storage is the single most important area for investment in research and demonstration into the marketplace today,"**
>
> **— Sir David King, United Kingdom Foreign Office permanent representative, 21st Conference of Parties, Paris, December 2015.**

At the 21st Conference of Parties in Paris in December 2015, there was wide spread recognition that for the individual countries to meet the Intended Nationally Determined Contributions, the following transformation needs to occur in the power generation sector:[1]

(i) widespread deployment of mature and commercially available low-carbon technologies like wind and solar; and
(ii) as the penetration of wind and solar increases, energy storage technologies will be required to safeguard the reliability of the grid.[2]

Since energy storage is the key enabler to high level of renewable energy penetration, significant research and development investments are planned to achieve the cost reductions and efficiency increases seen in solar photovoltaics and wind.

Capacity Versus Energy

Energy is defined as the ability to do work, and power is defined as the rate at which energy is supplied. Energy is measured in kilowatt-hours (kWh) or megawatt-hours, while power is measured in kilowatts (kW) or megawatts (MW). This concept can be best explained with examples. Consider a flywheel energy storage device with a power rating of 500 kW that can deliver energy for 30 seconds, when fully charged. Such a device is useful for delivering a large amount of power for a short duration, for example during a transient disturbance caused by a loss of a large generator on the grid; this burst of power from a storage device prevents the frequency from dropping in the grid, giving governors of other online generators time to react in order to make up for the

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1 International Energy Agency. 2015. *Energy and Climate Change*. https://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf

2 The exact level of penetration of variable renewable energy that would require energy storage is grid-specific.

loss. The flywheel therefore has a low amount of energy (500kW*30 sec=4.17 kWh) and a large amount of power (large power relative to the amount of energy).

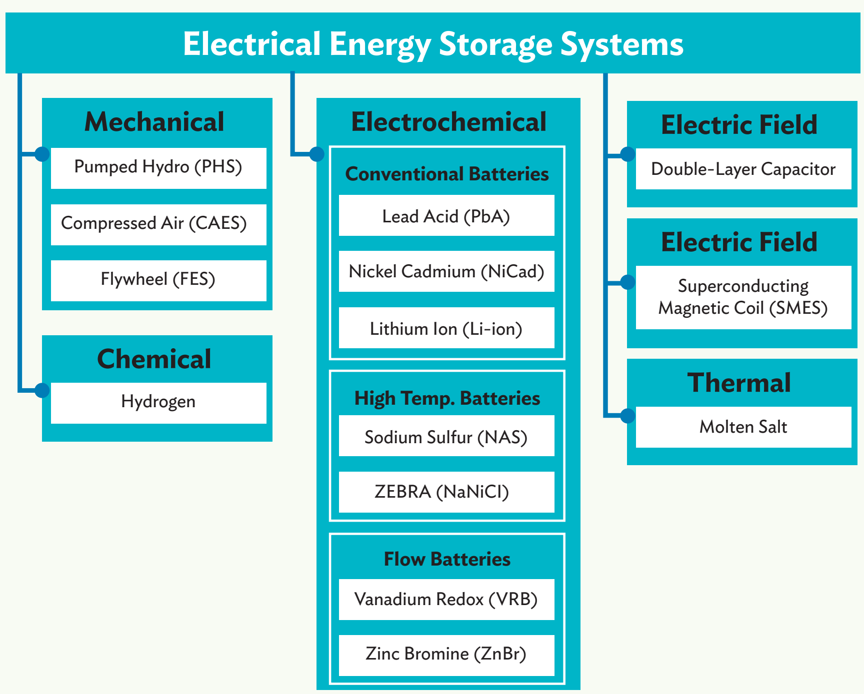
Next, consider a battery with a power rating of 500 kW that can deliver energy for 2 hours, when fully charged. This has an energy rating of 1,000 kWh, which is a large amount of energy relative to the amount of power. For applications that involve peak shaving or load shifting, storage units with higher energy rating are required—for example, storing energy during periods when renewable energy resource is high but load is low and discharging energy during periods when load is high and there is no renewable energy resource.

Applications such as long-duration load shift require a large volume of energy storage capacity, making energy cost (dollars per kWh or megawatt-hour) a particularly important consideration for selecting an appropriate storage technology. Similarly, applications such as grid frequency and grid voltage stability require power to be absorbed or injected, making power cost (in dollars per kW or MW) a particularly important consideration in choosing the appropriate storage technology.

Different Types of Storage

There are different types of storage units commercially available in the market. These units are mainly classified based on the form of energy that the unit stores. Figure 1.1 gives the classification of storage technologies and its grouping.

Figure 1.1: Classification of Storage-Based on Technologies



Source: R. Carnegie et al. 2013. *Utility Scale Energy Storage Systems: Benefits, Applications, and Technologies*. West Lafayette.

Thermal Energy System

In this storage technology type, the storage unit has the capability to store energy in the form of thermal energy, for example, ice or heat. There are a number of thermal storage technologies that could be employed to provide benefits to the electric power grid but this report briefly describes only one technology that is widely used. A simple, two-tank, direct molten salt energy storage system utilizes a receiver to reflect sunlight onto a heating chamber. Fluid from a cool tank is pumped to a heating chamber where it is brought to a very high temperature. It is then transferred to a tank containing heated fluid for storage. When heat energy needs to be recovered, it is used to create steam that powers a generator. There are other configurations, but the overall principle remains the same.

Mechanical System

The term "mechanical" determines the type of energy that is used to store energy in these storage technologies. This category of energy storage technologies includes

(i) pumped hydroelectric storage – potential gravitational energy,
(ii) compressed air energy storage – pressure potential energy, and
(iii) flywheel energy storage – rotational kinetic energy.

Pumped hydroelectric and compressed air energy storages are primarily energy storage technologies, whereas flywheels are primarily used for power applications.

Electrical and Magnetic Field Storage System

Under this category there are two main types of storage units. The first is a double layer capacitor, which is a capacitor consisting of two electrical conductors separated by a nonconducting material. It is used to store energy in the form of an electric field. The other is a superconducting magnetic energy storage system, which uses the flow of direct current superconducting coil to generate a magnetic field. This magnetic field is used to store energy. Both discharge in very short durations and are thus suitable for power applications.

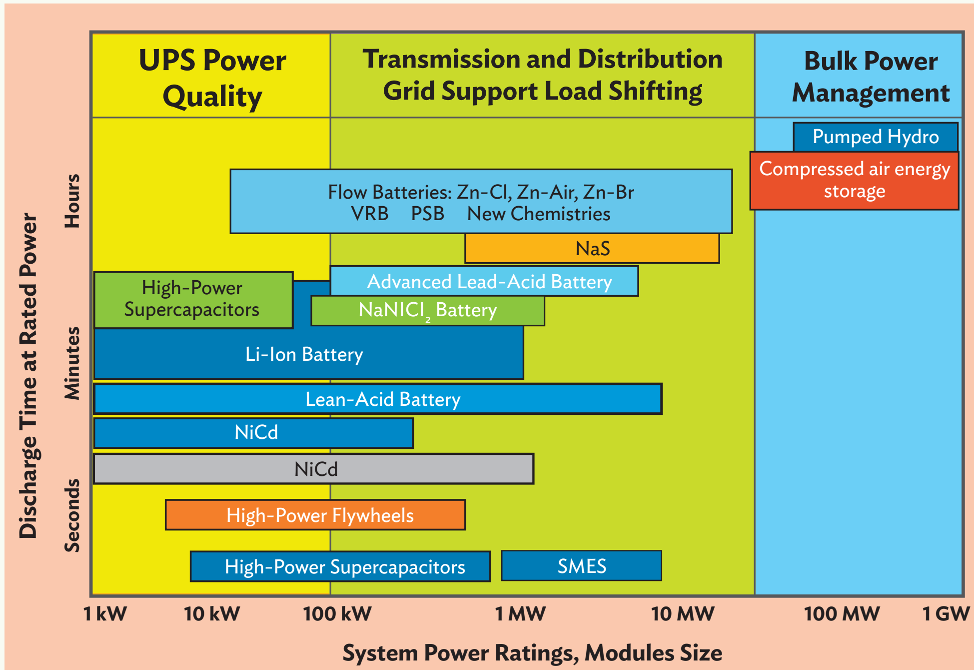
Electrochemical Storage System

This category contains storage technologies that convert electrical energy into chemical energy when charging. Electrochemical batteries use chemical reactions within a battery cell to facilitate the flow of electrons through a connected load, thereby generating an electric current. Storage units under this category are lead acid battery, nickel cadmium battery, lithium ion battery, sodium sulfur battery, sodium nickel battery, vanadium redox flow battery, and zinc bromine flow battery.

Comparison of Energy Storage Technologies

Figure 1.2 illustrates the relative positioning of various energy storage technologies. The x-axis is the power capacity, the y-axis is the discharge time, which is a measure of energy capacity (= power × discharge time), and the second x-axis is categorization of energy storage technologies for different applications.

Figure 1.2: Positioning of Energy Storage Technologies with Respect to Discharge Time, Application, and Power Rating



NaNiCl=Sodium Nickel Chloride, NaS=Sodium Sulfide, NiCd=Nickel Cadmium, PSB=Polysulfide Bromide, SMES=superconducting magnetic energy storage, UPS=Uninterrupted Power Supply, VRB=Vanadium Redox Battery, Zn-Air=Zinc Air, ZnCl=Zinc Chloride.

Source: A. A. Akhil. 2015.

Pumped hydroelectric and compressed air energy storage are used for bulk power management with largest power and energy capacities. Chemical batteries with 30 minutes to multiple hours of storage are commonly used for load shifting with project size in the range of 100kW to approximately 30MW. Flywheels, super capacitors, and superconducting magnetic energy storage can provide large amounts of power for very short amounts of time (seconds) and hence are valuable for providing frequency response in order to stabilize the grid.

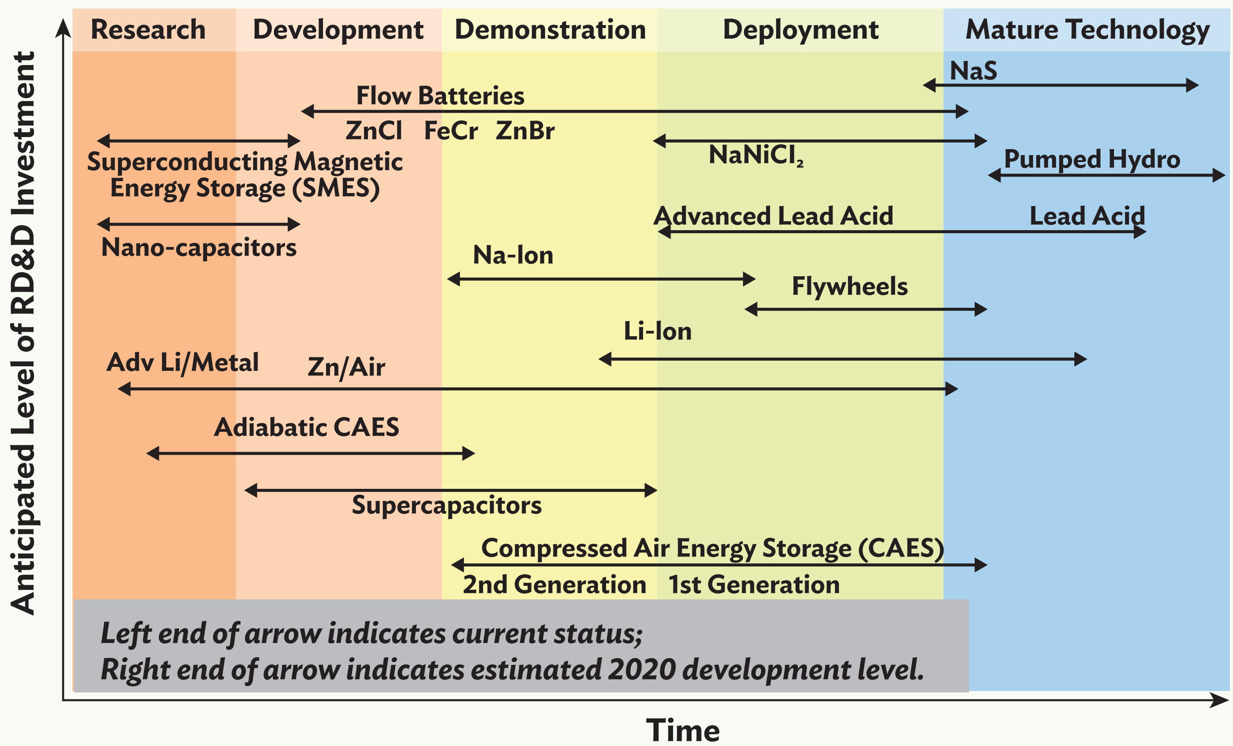
Figure 1.3 contains a chart of energy storage technologies, categorized by maturity. The possible applications of the energy storage technologies are shown in Table 1.1.

Table 1.1: Storage Technologies and Their Duration, Maturity, and Applications

Storage	Duration (hrs)	Maturity	Application
Mechanical Energy Storage System			
Pumped hydroelectric	6–10	Mature	• Load leveling • Peak shaving • Renewable integration
Compressed air energy storage (underground)	20	Commercial	• Load leveling • Renewable integration
Flywheels	0.25	Commercial	• Frequency regulation
Electrical and Magnetic Storage System			
Superconductive magnetic energy storage		Demo	• Power quality • Frequency regulation • Voltage Support
Electrochemical capacitors	~ 1 min	Demo	• Power quality • Frequency regulation • Voltage Support
Electrochemical Storage System			
Advanced lead acid batteries	4	Demo	• Power quality • Frequency regulation • Voltage support • Renewable source integration
Lithium ion batteries	0.25–1	Commercial	• Power quality • Frequency regulation
Sodium sulfur	7.2	Commercial	• Time shifting • Frequency regulation Renewable source integration
Vanadium flow redox	5	Demo	• Peak shaving • Time shifting • Frequency regulation • Renewable source integration

Source: F. Valenciaga, P. Puleston, and P. Battaiotto. 2003. Power control of a solar/wind generation system without wind measurement: a passivity/sliding mode approach. IEEE Transactions on Energy Conversion. 18 (4).

Figure 1.3: Comparison of Technology Maturity



Adv=Advanced, FeCr=Iron Chromium, NaNiCl2=Sodium Nickel Chloride, NaS=Sodium Sulfide, Zn=Zinc, ZnBr=Zinc Bromide, ZnCl=Zinc Chloride.

Source: R. Carnegie et al. June 2013. *Utility Scale Energy Storage Systems: Benefits, Applications, and Technologies.* West Lafayette.

Cost of Energy Storage Technologies

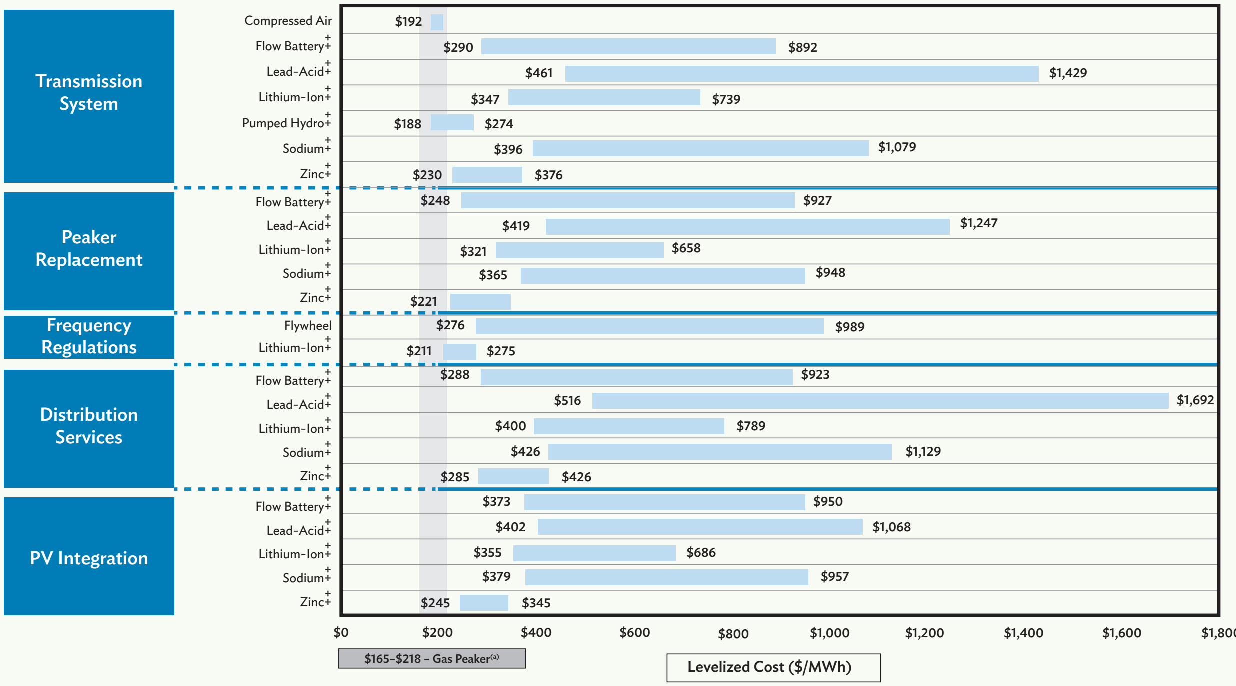
The cost of energy storage is usually expressed in two units: US dollar per MW and US dollar per megawatt-hour. Rapid technological development in energy storage has led to persistent decline in costs, therefore reports of cost are by nature 6 to 12 months old. In November 2015, Lazard reported levelized cost of storage (LCOS) for various energy storage technologies, which is presented in Figure 1.4. Refer to the Lazard report for assumptions and methodology.[3] LCOS are defined for different use-cases and include total capital cost, operations and maintenance cost and charging cost. Since each use-case has a different use profile in terms of number of cycles, depth of discharge and others, the LCOS estimates are different. Notice that the range of LCOS values is wide.

According to the Lazard report

(i) for large-scale energy storage to improve transmission grid performance (labeled "transmission system" in Figure 4.1) and assist in integration of large-scale renewable, pumped hydroelectric is the most inexpensive form of storage;

[3] Lazard. 2015. *Lazard's Levelized Cost of Storage Analysis Version 1.0.* https://www.lazard.com/media/2391/lazards-levelized-cost-of-storage-analysis-10.pdf

Figure 1.4: Lazard Estimates for Levelized Cost of Energy Storage



MWh = megawatt-hour.

Source: R. Carnegie et al. June 2013. *Utility Scale Energy Storage Systems: Benefits, Applications, and Technologies*. West Lafayette.

(ii) for peaker replacement, zinc batteries (wide variations including zinc-air) are the lowest LCOS; however the technology is unproven in widespread commercial deployment, while flow batteries have a slightly higher LCOS;

(iii) for frequency regulation, lithium-ion is the lowest LCOS while flywheel is slightly higher;

(iv) for distribution services, zinc and flow batteries are low LCOS technologies; and

(v) for photovoltaic integration, zinc battery is the low LCOS technology (footnote 3).

2 Role of Energy Storage in Integrating Renewable Energy

In this section, the characteristics of renewable energy sources like wind and solar (also called variable generation) are described. Table 2.1 summarizes the unique properties of variable generation, the impact it has on the grid, and the role energy storage can play in reducing the impact on the grid.

Highest Priority Dispatching of Renewable Energy

Marginal cost of production is a well-established concept in the power industry and it is used to determine which generators should be used to meet the projected demand of electricity in the grid, hour-by-hour. Generators with the lowest marginalized cost of production are scheduled first, and the last scheduled generator has a cost that is lower than all the generators that are not scheduled for the hour of interest. The logic gets complicated as cost of startup and shutdown are taken into account.

It is also well-established that marginalized cost of production for a generator is the cost of fuel consumed per kWh of electricity produced. As a simplification, all other costs are considered fixed costs that do not vary with production. Wind and solar power plants have zero marginalized cost of production because the cost of fuel is zero. Therefore, wind and solar power plants are dispatched with the highest priority, unless the grid is likely to experience instability or other problems. For this reason, most power purchase agreements are "take-or-pay," which means that the buyer of renewable energy pays for the energy produced and curtailed. Curtailment of renewable energy is quite common in instances when high amounts of renewable energy are produced during times of low demand and conventional generators cannot be shut down because of high cost of shut down and startup or grid stability. In take-or-pay contracts, the utility pays for curtailed renewable energy—electrical energy that it did not receive.

Energy storage can alleviate this problem by storing the curtailed energy and delivering it during times of peak demand. A business case for energy storage in this situation involves detailed analysis of largest duration of curtailment, differential in price of energy from time periods of peak and off-peak demand, and others.

Table 2.1: Impact of Integration of Renewable Energy in Grid and Solutions that Storage Provides

Characteristics of Renewable Energy	Impact on the Grid	Role of Storage in Alleviating the Impact
Zero marginal cost, hence renewable energy gets the highest priority for dispatching	(a) During periods of low demand, renewable energy displaces conventional generation. It may lead to lower capacity operation or shutdown of spinning reserves, and in some cases base load generators. This decreases the efficiency of conventional generators. (b) During periods of low demand, there is drop in inertia and drop in droop based governor response due to shutdown of conventional generators.	Energy Storage can remove inefficiencies by storing energy during times of excess renewable energy generation Energy storage with smart inverters can provide primary frequency response through the fast response of energy storage technologies.
Variable and Uncertain Power	(a) On second-by-second or subsecond basis, grid inertia compensates for the change in net-load. With high renewable energy penetration the grid inertia is reduced. (b) On a minute-by-minute basis, spinning reserves compensate for the change in net-load. High penetration of renewable energy during low load can lead to shutting down of spinning reserves. (c) On hour-by-hour basis, variability and uncertainty is managed by the dispatching operation.	(a) Fast-acting energy storage can provide subsecond to second level response, thereby acting like inertia. (b) Energy Storage can act provide spinning reserves and provide load following service. (c) Energy Storage can be dispatched as capacity.
Fast ramping	The ramp rates of renewable energy may be too high for it to be supported by load following generators	Fast acting renewable energy can provide the required ramp rate

Source: Author.

Variability and Uncertainty of Power

The energy output of wind or solar power plant is variable and uncertain because the wind speed or solar radiation is variable. The variability and uncertainty of generation is in all time scales—second-to-second, minute-to-minute, hour-to-hour, day-to-day, month-to-month, and year-to-year. Demand for electricity is also variable in all time scales. Grids manage the combined variability and uncertainty by managing net demand (= demand – renewable energy production), which is fulfilled by conventional generators (combination of base-load and load-following generators).

On a second-by-second or subsecond basis, the variation and uncertainty in net demand is managed by grid inertia, which is provided by traditional conventional synchronous generators. With higher penetration of wind and solar (both do not provide inertia to the grid), the grid inertia falls, which may cause stability issues. Fast acting and bidirectional energy storage can stabilize the grid by storing and delivering energy within a few microseconds; the types of energy storage devices that have these capabilities include electrochemical batteries like lithium-ion, flywheel, and capacitors.

On a minute-by-minute basis, the variation and uncertainty in net demand is managed by load-following generators, which sense frequency rise or drop to determine the power output using governor controls. When the rate of change in renewable energy production is large, then the rate of change of net demand could become larger than the ramp response that can be provided by the load following generators in the grid. Electrochemical batteries can support the grid with minute-by-minute response.

On an hour-by-hour or longer timeframe, electrochemical batteries, pumped storage, and compressed air energy storage can store and provide energy for longer periods.

Fast Ramping

One of the uncertainties of renewable energy is the ramp rate, which is defined as an increase or decrease in power over a defined period. Even if accurate forecast of hourly renewable energy generation is available, knowledge about the ramp rate, which is the highest rate of change of energy production during the hour, is important because it governs the amount of spinning reserves required for managing the renewable energy ramp. The ramp rate of a solar plant can be large because of moving in or moving out of cloud cover. Ramp rates of wind plants are smaller in comparison. However, with high penetration of renewables, there may not be enough spinning reserves to respond to high ramp rates. Fast-acting batteries can respond to positive ramp rate of renewable energy generation by absorbing energy and to negative ramp rate by supplying energy.

3 The Goal of Energy Storage in Grids

Before we delve into the goal of energy storage, a quick preview of the unique characteristics of renewable energy sources (specifically wind and solar) and associated grid issues is presented.

The goals of energy storage on a grid can be classified into five categories,[4] as shown in Figure 3.1:

(i) bulk energy services,
(ii) ancillary services,
(iii) transmission infrastructure services,
(iv) distribution infrastructure services, and
(v) customer energy management services.

In grids with existing or planned high penetration of renewable energy, the goals of energy storage are primarily the first three items; therefore, only these goals will be covered. Note that although each subgoal within each goal is described separately, most types of energy storage devices can support multiple subgoals. In addition, servicing just one subgoal is unlikely to provide sufficient revenue to make an energy storage project feasible. Hence, policies and tariffs play an important role in determining which of the subgoals are worth pursuing.

Figure 3.1: Grid Energy Storage Services

Bulk Energy Services	Transmission Infrastructure Services
Electric Energy Time-Shift (Arbitrage)	Transmission Upgrade Deferral
Electric Supply Capacity	Transmission Congestion Relief
Ancillary Services	**Distribution Infrastructure Services**
Regulation	Distribution Upgrade Deferral
Spinning, Non-Spinning, and Supplemental Reserves	Voltage Support
Voltage Support	**Customer Energy Management Services**
Black Start	Power Quality
Other Related Uses	Power Reliability
	Retail Electric Energy Time-Shift
	Demand Charge Management

Source: A. Akhil et al. 2015. A. Akhil et al. 2015. *DOE/EPRIL Electricity Storage Handbook in Collaboration with NRECA*. New Mexico: Sandia National Laboratories.

[4] A. Akhil et al. 2015. *DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA*. New Mexico: Sandia National Laboratories.

Bulk Energy Services

Electric Energy Time-Shift

High penetration of renewable energy can lead to situations in which renewable energy generation is higher than the grid can handle. The limitations on the amount of renewable energy generation in a grid can be due to a variety of reasons, a few are listed below:

(i) **The difference between demand and must-run generation is lower than renewable energy generation.** This typically occurs at late night hours when demand is low, wind production is high, and the net demand (= demand – wind production) is lower than the minimum allowable generation. Inflexibility of generators in a grid causes a high minimum allowable generation. For example, grids in which the base load is met by nuclear and coal power plants, the inability to cycle on and off, and inability to run at lower capacity factor determines the minimum allowable generation. When the net demand is lower than the minimum allowable generation, renewable energy generation has to be curtailed. Since the marginal cost of production of the curtailed energy is zero, an energy storage device on the grid can store this energy for use at a time period when the marginal cost of generation is the highest.

(ii) **This situation may also occur during daytime in grids with low industrial load and high lighting load.** It happens when demand is low, solar production is high, and the net demand (= demand –solar production) is lower than the minimum allowable generation. Instead of curtailing solar production, an energy storage device can store this energy (with zero marginal cost) and deliver when the marginal cost of production is high.

(iii) **In both situations described above, thermal generators are forced to run at the lowest acceptable capacity factor.** The inefficiencies associated with low capacity factor of thermal generators causes the unit cost of electricity to rise during these periods. Energy storage devices can mitigate this by allowing the thermal generators to run at higher capacity factor and higher efficiency and then storing the excess energy. This cheaper energy can be delivered when the marginal cost of production is higher.

Energy storage, therefore, plays an important role in reducing the cost of energy. An alternate perspective is that wind and solar curtailment is a waste of resource, akin to spilling of water in a hydroelectric project; hence, energy storage is useful in grids with curtailment or mismatch of renewable energy generation and load, because it can do an energy time shift by storing energy when it is cheap and delivering when it is expensive. This is also referred to as load leveling or peak shaving.

Electric Supply Capacity

Peaking generators provide capacity and in most grids are paid for providing both capacity and energy. Since the energy supply requirement is usually low (such units provide energy only during periods of high load), such peaking generators are also compensated based on the capacity. An energy storage unit can provide the same function as a peaking unit and therefore must be treated as a peaking generator; the only twist is that the energy storage unit must be charged during off-peak hours.

Ancillary Services

Regulation

Regulation is an ancillary service used to reconcile momentary differences between generation and demand that are caused by fluctuations in generation and demand. Traditional generators provide this service by changing the power output, which can cause significant wear and tear. Energy storage devices are ideal for regulation because it can provide fast ramp rate in response to area control error or automatic generation control signal.

Grid Stability with a High Penetration of Renewable Energy (Frequency and Voltage Stability)

In this article penetration of renewable energy will be defined in terms of the ratio of average annual renewable energy production and average annual energy demand. For the sake of completion, other definitions of renewable energy penetration that are popular are the ratio of average hourly renewable energy production and peak demand, the ratio of average renewable energy production at hours that are concurrent with peak demand, and the ratio of average renewable energy production at hours that are concurrent with off-peak demand.

In this article, high penetration of renewable energy will be defined as 20% or higher, that is, the ratio of average annual renewable energy production and average annual energy demand is higher than or equal to 20%. It is important to note that high penetration of renewable energy leads to lower inertia[5] in the system because wind and solar generators do not provide inertia.[6]

In normal grid operations, spinning reserves provide fast frequency response (10 seconds) for large disturbances to maintain frequency. Prior to 10 seconds, frequency response is provided by inertia of generators on the grid. The rate at which the frequency changes after a disturbance—for example, loss of generator or transmission—is directly proportional to the aggregate inertia within the grid at that instant. The inertia of synchronous generators instantaneously transfers energy from the rotating mass of prime mover to the grid thereby reducing the imbalance and stabilizing the grid. These events need fast response, which the storage systems excel in. The presence of fast-acting storage guarantees an easier transition from rapid rate of change of grid frequency after a disturbance to restoring the grid to normal frequency. Frequency response mode of the storage requires the storage to act within a timeframe of milliseconds to a few seconds.

Voltage stability in a grid is managed by injecting or absorbing reactive power. Traditionally this is done by synchronous generators and with special equipment like static synchronous compensators (a device to regulate voltage by supplying or absorbing reactive power from the grid). Inverters of energy storage units can instantaneously inject into or absorb from the grid reactive power to stabilize the voltage.

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5 Inertia of grid is a property that resists decline in grid frequency. In a grid with low inertia, the drop or increase in frequency is rapid when there is loss of generation or loss of load; on the other hand in a high inertia grid, the frequency change is gradual for the same change in generation or load. High inertia, therefore, facilitates grid stability when there are disturbances on the grid.

6 New wind turbine generators are starting to provide inertia, but it is not common.

Spinning Reserves

In grids with high penetration of renewable energy, instability can result because during high renewable energy production only must-run base load generators operate; the lack of sufficient amounts of spinning reserves during such periods can cause grid instability because the changes in net load (load–renewable energy generation) cannot be supplied by spinning reserves. Energy storage can plug into this need by quickly providing energy to the grid. The energy storage unit thus becomes a provider of spinning reserve.

Other Related Uses

Ramp rate support, as described in Section 2.3, is an ancillary service that energy storage can provide.

Dispatching of Renewable Energy

There is a lot of talk about making renewable energy dispatchable. The reason is grid operators want to have generators (sources of energy) that can be called upon as and when needed—when load is high, other generators are down, etc. Renewable energy is only available when the resource (wind or solar) is available. Energy storage can achieve dispatchability of renewable energy. If renewable energy plus storage is used as a single resource from the grid standpoint, then it can commit to delivering a fixed amount of power for a block of time. This is typically done with storage technologies like compressed air energy storage or pumped hydroelectricity.

This approach to dispatchability of renewable energy is not a preferred approach because it causes the storage unit to be oversized, thereby making it a higher cost solution. Other inexpensive approaches to make renewable energy dispatchable are reducing the unit commitment and economic dispatch intervals shorter. Most grids with higher renewable energy penetration have moved or are moving to subhourly dispatches, which reduces the forecasting error and makes the renewable energy close to dispatchable.

Transmission and Distribution Services

One of the benefits of energy storage is deferral of transmission and distribution upgrades. High renewable energy penetration on the grid can often require transmission line upgrades, but only for cases when the wind plants are producing at rated capacity. For example, a 100 megawatt (MW) wind farm may overload the transmission line when higher than 90MW is transported on an existing line. Instead of incurring the cost of constructing a new transmission line for 1% of the time when wind plant production exceeds 90MW, it may be more economical to deploy a storage unit at the wind plant to store the excess energy during high wind periods.

Similar cases are found with solar photovoltaic plants on a distribution line. A small amount of storage placed strategically can alleviate distribution line congestion, thereby deferring upgrade.

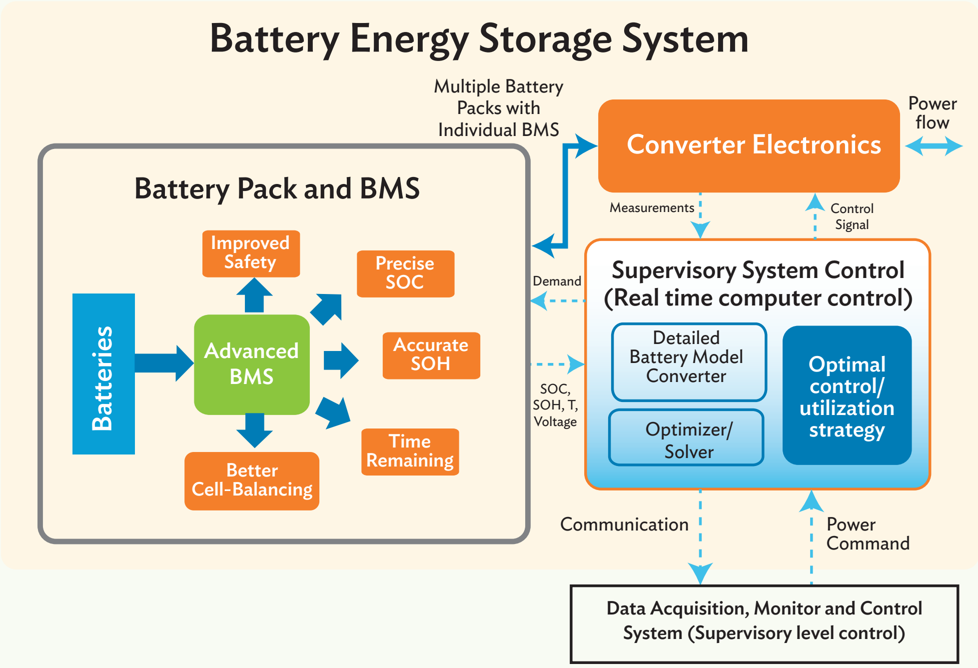
4 Smart Control Systems for Managing Energy Storage in a Grid

Need for Smart Control Systems

Unmonitored supply or absorption of power from a battery can lead to faster degradation of the battery. Even under normal conditions the battery will degrade during cycling. This degradation can be accelerated by deep discharging, overcharging, undercharging, and increased temperature. This makes it difficult to operate a battery in a safe mode and also increases the need for a smart storage control system.

A typical battery energy storage system (BESS) consists of battery packs, a battery management system (BMS), a power conversion system (PCS), and a supervisory control system (SCS), as shown in Figure 4.1.

Figure 4.1: Overview of Battery Energy Storage System Components



BMS = battery management system, SOH = state of health, SOC = state of charge, T = temperature.

Source: Battery Energy Storage System (BESS) and Battery Management System (BMS) for Grid-Scale Applications. 2014.

The PCS is used to convert the direct current power of battery pack to alternating current power and vice-versa; it connects the BESS unit to the grid via a transformer.

The SCS collects battery status information from BMS, power input and output information from PCS, and grid information from the centralized control system. The purpose of SCS is to synthesize the collected information in order to send command signals to BMS and PCS.

Detailed descriptions of the three main parts of BESS are contained in the sections below:

Battery Management System

A BMS controls a battery unit, or in general, a storage management system controls a storage unit. The functions of BMS include meeting the power demand and managing the battery's health to ensure long life and safety of operations. The BMS manages two key parameters of the battery: state of charge (SOC) and state of health (SOH). The SOC and SOH are battery states which are difficult to determine because the only battery states that can be measured are voltage, current, temperature, and electrolyte ion concentrations. However, advanced models can accurately estimate many internal variables that will allow BMS to determine the battery SOC and SOH. SOC represents how much charge is left in a battery for the current cycle, while SOH represents the battery capacity in the present cycle compared to the original battery capacity.

An ideal BMS must have a precise knowledge of battery states including SOC, SOH, and temperature. It also requires exact knowledge of the action required by the grid for it to determine the amount of current it can supply. A predictive and adaptive BMS model is especially important for efficient operations of large battery packs.

Power Conversion System

The PCS is a four-quadrant direct current and alternating current converter connecting the direct current system to the grid via a transformer. PCS is bidirectional, which means direct current is converted to alternating current and vice-versa. As an example, consider the following: based on SCS's determination of amount of reactive power needs, it sends the firing angle signals to PCS. PCS then manages the IGBTs such that the appropriate phase angle between voltage and current is introduced.

Supervisory Control System

The SCS is mainly responsible for monitoring the full BESS system. It has two-way communication with BMS and PCS. A large installation of energy storage has many battery packs; each pack has its own BMS. SCS collects information from BMSs about the battery packs. SCS also collects all the grid parameters like system frequency, voltages at buses, loadings on transmission lines, and others. Based on the information received from BMS and the grid, SCS then commands (i) individual packs to supply power such that the final active power demand can be met and

(ii) the PCS to produce a phase angle such that the reactive power requested by the central control system can be met.

The BMS coordinates the operation of individual power blocks while the SCS coordinates the operation of all the power blocks, which manages the total system power. The PCS receives firing angle signals to determine the reactive power output.

5 Grid Integration and Sizing of Storage

Power Systems Analysis

Power systems analysis is used to determine the impact on the grid of installing any new equipment—new conventional generation, new renewable energy plant, storage, etc. There are three main analyses: load flow analysis, short-circuit analysis, and transient analysis (system stability analysis).

The load flow (also called power flow) analysis is performed to analyze the steady-state conditions of a power system network. It is used to determine (i) voltage levels at buses, (ii) loading of transmission and distribution lines, and (iii) flow of active and reactive power through the grid. This analysis is performed for a variety of scenarios that encompass extreme operating conditions such as high renewable energy production and low demand, high renewable energy production and high demand, and peak shaving scenario when the storage is discharging and/or charging.

Short-circuit analysis is performed to determine the short-circuit power ratio at point of common coupling (PCC) and short-circuit contribution of the new generation to existing buses. The short-circuit power ratio determines whether the PCC is a weak or a strong point of coupling; weak PCC results in large voltage fluctuations depending on level of generation. The short-circuit power ratio is used to determine the amount of power that can be injected at the PCC by wind and/or solar plant or storage.

In the power systems world, stability is a complex concept that involves variability of load, variability and responsiveness of generators, and responsiveness of protection system. It is important to note that power system stability refers to the starting state of the grid before a disturbance, and not the end state (which is always stable). A power system is considered stable if all the loads and generators stay connected after the disturbance. The implication is that after the disturbance, the state variables must stay in an acceptable range such that protective relays are not triggered; hence the loads and generators stay connected. A grid configuration is considered unstable if a disturbance leads to tripping of protective relays which then disconnects loads and/or generators in order to reach a stable state.

Transient stability analysis is used to check frequency, generator swing angle, and voltage stability during large disturbances in power systems, which are caused by a variety of events, for example, sudden loss of a generator, loss of load, fault on a transmission line, fault at a substation, and others. The impact of such disturbances is analyzed in a transient stability study.

One of the primary faults analyzed is loss of generation from the renewable energy plant. In grids with high renewable energy penetration and one renewable energy plant contributes a large amount of generation (for example, greater than 20%), transient stability analysis may reveal that inertia and headroom of online conventional synchronous generators are insufficient to compensate for the loss of renewable energy. Such a situation would lead to rapid drop in frequency followed by loss of synchronism. Transient analysis of energy storage equipment with automatic voltage regulation and governor controls can be used to illustrate the response of energy storage in order to stabilize the grid.

Sizing of Energy Storage

The primary objective of deploying energy storage determines the method used for sizing storage. Methods to size storage include a variety of factors such as capital and recurring cost of storage, power requirement, and energy requirement. The power and energy requirements are estimated using simulation or other analytical methods in which a variety of grid-related factors are taken into account, i.e., hourly generation and load profiles, dispatching logic for deploying generators, marginal cost of each generator, reserve requirement, and others. Such a simulation is usually done for 1 year.

Bulk Energy Services

When the use-case for energy storage is bulk energy services, then the goal of sizing is to determine the optimal size of storage which yields an acceptable return on investment, or the levelized cost of energy storage is less than the anticipated levelized revenue or a combination of financial metrics. Financial models are described later in this report. A simulation model has to be constructed for computing the levelized cost and revenue or return on investment. Different energy storage sizes are run through the simulation in which hour-by-hour amount of charging and discharging of the energy storage unit is determined based on hour-by-hour load, dispatched generators, renewable energy production, and the logic for operating the grid.

Ancillary Services

When the use-case for energy storage is ancillary services, the criteria of sizing are complex: to improve grid stability and ensure the financial metrics of the energy storage project are in acceptable range (similar to 6.2.1). To determine the size of energy storage, the most critical transient events should be identified. For each transient event, the power and energy requirement of energy storage can be computed. This is best illustrated using an example. Consider a grid with an off-peak load of 4MW and the critical transient event of interest is loss of 1.5MW wind turbine generator during high wind and low load period. Suppose the headroom is 0.4MW (based on transient analysis simulation of grid with no storage) of the dispatched generators with total capacity of 2.5MW. In this case, a fast-acting energy storage unit of capacity 1.1 MW would be adequate to provide stability. Furthermore, if energy storage needs to supply energy for 30 seconds until cold start of a backup diesel generator, then the energy rating of the energy storage should be 1.1 MW × 30 seconds/3600 = 9.17 kWh.

In simplistic terms, as each critical transient event is analyzed, the power and energy requirement for energy storage to manage the critical event is computed. The maximum requirement is then analyzed using a financial model. The tradeoff is between cost (or other financial metric like return on investment) and the ability to manage the most challenging disturbance. If the financial metric of the energy storage project is unacceptable, then other solutions like partial load shedding are deployed.

6 Financial Modeling and Economics of Energy Storage

Current and Future Costs of Storage

The price of energy storage is falling rapidly. It is led by a large amount of public and private research and development funds spent on a wide range of energy storage technologies. The rapid growth in energy storage in the automotive industry (led by Tesla and others) has produced an order of magnitude increase in demand for energy storage compared to just 2 years ago. This had led to a scale up of lithium-ion battery technology as evidenced by the construction of a gigawatt-scale energy storage factory in the United States. This facility will produce storage units for automobiles, grid storage, and residential storage. The forecasted pricing for grid scale storage is in the range of $150/kWh for the battery (not including power converter).

Financial Models to Value Storage

One of the most suitable financial metric for energy storage is the levelized cost of energy storage (LCOS). It is expressed in terms of dollars per kWh. The definition of LCOS is the price of energy that yields zero net present value. In simple terms LCOS is the cost of each unit of energy delivered to the grid from the energy storage device, taking into account capital costs, financing costs, and operations and maintenance cost. The parameters used to compute the LCOS are listed in Table 3.

Table 6.1: Cost and Performance Data of Storage

Description	Units	Sample Values
System Size		
Charge/Discharge Capacity (kW)	kW	1000
Hours of storage at rated capacity	hours	4
Depth of Discharge per cycle	%	0.8
Useable Energy Storage Capacity (kWh)	kWh	4,000
Installed Energy Storage Capacity	kWh	5,000
Useful Life		
End-of-Life Residual Energy Storage	%	100.00%
Degradation Factor (%/yr)	%	0.00%
System Life	years	15
Efficiency		
AC/AC Efficiency OR	%	80%
Energy Charge Ratio	kW in/kW out	-

continued on next page

Table 6.1 *continued*

Description	Units	Sample Values
Output		
Cycles per Year	#	365
Installed Cost		
DC Battery Cost per kWh of usable storage	$/kWh	$390
Total DC Battery Cost	$	$1,560,000
$/kW installed (incl PCS)	$/kW	$527
Total $/kW Cost	$	$527,000
Total	$	$2,087,000
Cost per kW	$/kW	$2,087
System Cost - Regional Multiplier	Ratio	1
System Cost - Regional Cost	$/kW	$2,087
$/Useable kWh		$522
Fixed O&M		
Fixed O&M Cost	$/kW-Yr.	$4.50
Periodic Major Maintenance	$/kW	$0
period between maintenance	years	8
Property Tax	% of $/kW capex	1.00%
Insurance Cost	% of $/kW capex	0.50%
Variable O&M		
Variable Costs	$/kWh produced	$0.00
Charging Costs		
Avg. Charging Cost	$/MWh	$30.00
Fuel Cost	$/MMBtu	$3.00
Fuel Cost Escalation	%	5%
CO_2 Emission Rate by Fuel	lb/MMBtu	117
CO_2 Allowance Price	$/ton	$30
Heat rate	Btu/kWh	-
Annual Heat Rate Degradation	%	
Fixed O&M Cost-Escalator	%/yr	2.00%
Variable O&M Cost-Escalator	%/yr	2.00%
Finance		
Ownership		IOU
Percent Financed with Equity	%	30%
Debt Interest Rate	%	6.60%
After-Tax WACC	%	8.00%
Cost of Equity	%	17.54%
Target average Debt Service Coverage Ratio	ratio	1.4
Debt Term	years	15

AC=Alternating Current, Btu=British thermal units, capex=capital expenditure, CO2=Carbon dioxide, DC=Direct Current, IOU=Name of owner, O&M=Operations and Maintenance, OR=Operating Ratio, WACC=Weighted Average Cost of Capital.

A. Akhil et al. 2015. *DOE/EPRIL Electricity Storage Handbook in Collaboration with NRECA*. New Mexico: Sandia National Laboratories.

The financial model for an energy storage project is more complex compared to a renewable energy project. The primary differences are as follows:

(i) The fuel cost of renewable energy projects is zero, while the fuel cost of energy storage can be a significant cost in the income statement. The fuel cost in this case is the cost of electrical energy purchased from the grid in order to charge the storage unit, and therefore may be variable depending on when the energy storage unit is charged. This total cost of charging is closely related to the revenue side, when examined over longer time horizons like month-to-month, so it is similar to conventional generators.

(ii) Replacement cost of energy storage unit is a significant cost of energy storage in the 20-year life of a project.

(iii) Revenue of energy storage is uncertain, as it depends on the frequency and duration of use of energy storage, which is dependent on a complex and interlinked relationship among a variety of factors. Some of these factors are unpredictable like the weather (solar and wind), faults on the grid, maintenance of generators, etc.

7 Policies for Grid Storage

The benefits of grid-level energy storage, as described above, cover a wide gamut of services—energy time-shift, ancillary services, making renewable energy dispatchable, deferring transmission and distribution upgrades, and others. These benefits cannot be realized unless investments in energy storage can yield returns that are commensurate with similar investments in the power sector. Return on investments can be obtained only if policies related to tariff, licensing, and other aspects of the power sector are in place.

Tariffs

Sustainable development of energy storage will not occur unless tariffs for the various services provided by energy storage are established, and the tariffs are sufficient for energy storage investors to recover cost and make an acceptable return on investment.

Each type of service provided by energy storage should have a tariff. Setting a tariff is a difficult problem requiring the balance between the quantifiable benefit of a service and the cost of the service. For example, the benefit of peak-shaving can be quantified in terms of the following factors: (i) tariff for electricity hour-by-hour at peak time, amount of energy supplied to grid by ES hour-by-hour at peak time; and (ii) tariff for electricity hour-by-hour at off-peak time, amount of energy used for charging of energy storage hour-by-hour at off-peak time. Suppose the benefit to the grid is $0.12 per kWh for 1,000 hours in a year. Let us also suppose that the LCOS, if used only for this peak-shaving application, is $0.20 per kWh. Here the policy maker's dilemma is clear: if tariff is set to $0.20, then the tariff is higher than the benefit realized from this service. If the tariff is set to $0.12, then an energy storage project is financially infeasible.

In the above case, if the energy storage project can provide multiple (non-overlapping) benefits, then the benefits add up. For example, if an energy storage project can provide reactive power (voltage support) services and frequency support services, in addition to peak-shaving service, then the benefits-based tariff approach to energy storage projects may be financially feasible. Since the number of hours each service is provided is different and tariffs of each service are different, the financial model is complex.

The intention of this illustration of benefits-based tariff approach is to demonstrate that policy makers must consider the totality of services that energy storage can provide and assign tariffs for each service, because an energy storage tariff for a single service is unlikely to make projects feasible.

An approach to determining the value of energy storage, as a sum of operational and capacity values, is proposed by the National Renewable Energy Laboratory.[7] The operational value is determined by comparing the difference in production costs with and without storage, which is done by using production simulation software like PLEXOS, PROMOD or PROSYM. There are three components to the operational value of energy storage: regulation reserves, spinning reserves, and load leveling (energy price arbitrage). In general, regulation reserve has highest value followed by spinning reserves, while load leveling has the lowest value; however, the relative value is grid-specific. Although in general, regulation reserve has the highest value, the market potential is smaller because the need is for fewer hours. The National Renewable Energy Laboratory report also points out that in the case of use of energy storage for load leveling, 50% of the savings comes from fuel cost while a surprising 50% comes from avoiding unit starts.

Capacity value, the second component of the value of energy storage, on the other hand, cannot be estimated using simulation because the value of providing firm system capacity cannot be accounted for in a simulation. Note that capacity value depends on the need for additional capacity to provide adequate planning reserve margin: if a system has sufficient planning reserve margin, then the capacity value of energy storage would be zero. However, this is rarely the case in developing markets, where demand exceeds supply during peak hours. In such cases energy storage provides an alternative to construction of new peaking resource. In the United States, this capacity value has a range from $77/kW per year to $212/kW per year, depending on the region. This capacity value is generally higher than the operational value (load-leveling energy arbitrage), which implies that energy storage has a higher value in replacing conventional generation capacity than operational benefits. Overall, the National Renewable Energy Laboratory report concludes that the value of energy storage is largely dependent on it obtaining a capacity value, even if the device is providing higher-value reserve services.

Table 7: Components of Benefits of Energy Storage

Benefit of Energy Storage	Method of Estimation
Operational value	
Load leveling (energy arbitrage)	Use dispatch simulation to calculate operational savings—fuel cost and avoid unit starts. Subtract cost of energy used to charge energy storage and losses
Spinning reserve	
Regulation reserve	
Capacity value	Avoided cost of adding reserve capacity

Source: Author.

This approach would set the tariff for storage based on accounting of the benefits (sum of operational and capacity values) to the grid of the services provided by energy storage. The following benefits should also be added to compute the overall benefit:

(i) Avoided cost of greenhouse gas emissions, which would be in grids with renewable energy. The accounting of this would need to be done with care to

[7] Denholm, 2013

avoid counting the benefits twice—renewable energy generation and energy storage. One approach is to assign a benefit to energy storage only when there is curtailment of renewable energy generation.

(ii) Local environmental benefit, which would be in grids with renewable energy. Same considerations apply as the avoided cost of greenhouse gas emissions.
(iii) Energy security, when energy storage enables a grid to use the energy source with the lowest marginal cost of production and avoid use of the highest marginal cost source. For this reason energy storage cushions the grid from increases in fuel prices that contribute the highest marginal cost of production.

A tariff for energy storage that is less than or equal to the sum of the benefits would be economically prudent.

It is worth noting that there is a lack of research and data related to value of energy storage in grids with a large penetration of renewable energy.

Role of Government and Regulators

Often there is resistance among traditional utilities to transition to new technologies and new methods of operating and managing the grid, which is required with high penetration of variable generation. The push therefore has to come from policy makers and regulators. The imperative for push is further accentuated by the fact that although there are substantial benefits of energy storage to the grid, they are often difficult to quantify: for example, improvement to power quality, reliability, resiliency, energy security, and efficiency gains. The case for governments and regulators to play a leading role in development of policies is therefore clear.

Guidelines for Policies

The following policy prescriptions are recommended for encouraging deployment of energy storage. These guidelines are based on best practices (Footnote 1).

(i) Integrate energy storage into overall energy master plan and energy strategy. This clarifies the role of energy storage and begins the conversation about competing methods to provide the multitude of services required by the grid.
(ii) Enable energy storage to qualify for multiple streams of revenue for the individual services it provides to the grid.
(iii) Introduce time-of-use tariffs, pay-for-services tariff, and others to eliminate price distortions and increase price transparency.
(iv) Incentivize codevelopment and cofinancing of energy storage and distributed renewable energy projects.
(v) Support, in a targeted manner, demonstration projects and first movers with loan guarantees, low interest loans, grants, and others. A note of caution: policies and incentives should not be technology-specific.

8 Conclusions

With increased emphasis on reducing greenhouse gas emissions from the power sector, grids will see higher penetration of renewable energy. Grid-level energy storage can enable larger penetration of renewable energy into the grid. This is made possible by services provided by energy storage to compensate for the variability and uncertainty of renewable energy resources.

(i) Variability of renewable energy (higher solar resource during day time and zero during night; diurnal and seasonal pattern of wind) can be managed with high-energy content energy storage which would store energy during periods with high renewable energy production and low load, and discharge during low renewable energy production and high load.
(ii) Uncertainty of renewable energy (inability to predict renewable energy production) can be managed with energy storage similar to variability management.
(iii) High ramping rate of renewable energy (sudden fall in solar farm production due to arrival of clouds) can be managed with fast-response energy storage providing the ramping in the opposite direction.
(iv) Higher penetration of renewable energy leads to switching off of conventional synchronous generators during periods of high renewable energy production which can cause frequency management issues. Fast-response energy storage can provide frequency support to the grid.
(v) Higher penetration of renewable energy can lead to higher requirement for reactive power. Smart inverter in energy storage systems can absorb or deliver reactive power.
(vi) Higher penetration of renewable energy can lead to higher requirement for spinning reserves. Energy storage can provide spinning reserves.

Energy storage is likely to play a prominent role in a grid that is migrating to a higher penetration of renewable energy, smarter grids, and flexible grids. Newer technologies and trajectory of lower cost of energy storage is likely to transform the grid in the near future. In order to support deployment of energy storage projects, the following policy recommendations are made:

(i) setting tariff for each of the services provided by energy storage,
(ii) incorporating energy storage in the energy master plan,
(iii) incentivizing codevelopment of energy storage and distributed renewable energy, and
(iv) support for pilot projects.

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APPENDIX A

Examples of Grid-based Energy Storage Applications

This section contains a list of energy storage applications of size 1MW or higher worldwide. This list is not exhaustive, but covers most of them.

Table A.1: Examples of Grid-Based Energy Storage Applications

Name	Type	Size (MWh)	Application	Description	Commission Date	Country and Location
Sir Adam Beck Hydroelectric Generating Station	Pumped Hydro Storage, Open Loop	1,044 MWh (174 MW)		Sir Adam Beck Pump Generating Station and its 300-hectare reservoir adjacent to Niagara Falls were constructed alongside the Sir Adam Beck II Generating Station. Water diverted from above the falls to the generating complex is pumped into the reservoir nightly and used to generate electricity during subsequent periods of high electricity demand.		Canada, Ontario, Niagara-on-the-Lake
WEICAN Durathon Battery Project	Battery, Sodium-Nickel Chloride	20 MWh (10 MW)		The Wind Energy Institute of Canada contracted with S&C Electric Canada to provided a Sodium-Nickel Chloride Battery at their site on Prince Edward Island.	Fall 2013	Canada, Prince Edward Island, North Cape
Goldisthal Pumped Storage Station	Pumped Hydro Storage, Closed Loop	8,480 MWh (1,060 MW)		Goldisthal Pumped Storage Station is a pumped-storage power station in the Thüringer Mountains at the upper run of the river Schwarza in Goldisthal, Germany.	2004	Germany, Sonneberg, Thuringia

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Table *continued*

Name	Type	Size (MWh)	Application	Description	Commission Date	Country and Location
Huntorf CAES Plant	Compressed Air Storage, In-ground Natural Gas Combustion	870 MWh (290 MW)		First commercial CAES plant, operational since 1978, using nuclear-sourced night-time power to compress and inject the air into two caverns of 310,000 m^3 total volume.	1978	Germany, Huntorf, Elsfleth
Turlough Hill	Pumped Hydro Storage, Closed Loop	1,752 MWh (292 MW)	Energy time shift	Turlough Hill, Ireland's only pumped storage power station, is located 60 km south of Dublin in the Wicklow Mountains. Construction commenced in 1968, and the station became fully operational in 1974. During periods of lower demand the water is pumped to the upper reservoir.	1968	Ireland, County Wicklow, Glendalough
Hokkaido Battery Storage Project (provisional name)	Battery	60 MWh	Renewable support	Kyodo News Service reported the authorization by Japan's Ministry of Economy, Trade, and Industry for the installation of the world's largest storage battery, at a substation near several solar energy projects in Hokkaido Island, Japan, due to be online in March 2015.	March 2015	Japan, Hokkaido
SustainX/ General Compression	Compressed Air Storage	1 MW (4 MWh)	Renewables-both	1.5MW/1MWh nongrid tied aboveground isothermal CAES pilot system	November 2013	Seabrook, New Hampshire, USA
City of Painesville	Vanadium-redox battery	1 MW (6-8 MWh)	Frequency response	1 MW/8MWh vanadium redox flow battery for load following for Painesville Municipal Power station	Late 2013	Painesville, Ohio, USA
National Wind and Solar Energy Storage and Transmission Demonstraton Project (I)	Battery, Lithium Iron Phosphate	36 MWh (6 MW)	Renewable energy integration, frequency regulation and voltage support.	The project currently includes a total of 14 MW of lithium-ion batteries and a vanadium redox flow battery. The project is focused on using battery energy storage to enable interactive management of the electric power grid.		People's Republic of China, Hebei, Zhangbei
Guodian Supply-Side Energy Storage Project	Battery, Lithium Ion	10 MWh (5 MW)	Energy time shift	This project is State Power's first supply-side energy storage project, incorporating 49.5 MW installed wind capacity and a 5 MW lithium-ion battery system. The energy storage system provides power during low-wind conditions.		People's Republic of China, Liaoning, Jinzhou

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Table *continued*

Name	Type	Size (MWh)	Application	Description	Commission Date	Country and Location
Andasol Solar Power Station	Thermal storage, Molten Salt	1,030.5 MWh (134.7 MW)	Energy time shift	A thermal storage system absorbs part of the daytime heat absorbed by the solar field, heating a molten salt mixture of 60% sodium nitrate and 40% potassium nitrate. The heat is used to drive a turbine-generator when direct sunlight is not available, nearly doubling the available hours of operation.		Spain, Granada, Guadix
Drakensberg Pumped Storage Scheme	Pumped Hydro Storage, Closed-Loop	10,000 MWh (1,000 MW)		The scheme provides for up to 27.6 GWh of electricity storage in the form of 27,000,000 cubic meters (950,000,000 ft^3) of water. The water is pumped to Driekloof during times of low national power consumption and released back into Kilburn through four 250 MW turbine generators in times of high electricity demand.		South Africa, Free State & Kwa Zulu-Natal, Drakensberg, Jagersrust
Palmiet Pumped Storage Scheme	Pumped Hydro Storage	4,000 MWh (400 MW)	Energy Time Shift	Water is stored in an upper and lower reservoir. For power generating purposes, water flows from the upper reservoir to the lower reservoir via two reversible pump and turbines. During off- peak periods the water collected in the lower reservoir is pumped back again.		South (Analysis and control of PV inverters operating in VAR mode at night, January 2011) Africa, Western Cape, Grabouw
Ingula Pumped Storage Scheme	Pumped Hydro Storage	21,312 MWh (1,332 MW)		The pumped storage scheme consists of an upper and a lower dam; both of approximately 22 million m^3 < capacity. The dams, 4.6 km apart, are connected by underground waterways, through an underground powerhouse which house, 4 x 333 MW pump turbines.		South Africa, Kwa-Zulu Natal, Van Reenen's Pass

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Table *continued*

Name	Type	Size (MWh)	Application	Description	Commission Date	Country and Location
Steenbras Dam Pumped Storage Scheme	Pumped Hydro Storage, Open Loop	2,790 MWh (180 MW)		The Steenbras pumped-storage scheme affords an increased measure of security of supply to the city since, unlike thermal power stations, hydroelectric pumped storage installations can be brought into operation and up to full load within a matter of minutes.		South Africa, Western Cape, False Bay
KaXu Solar One	Thermal Storage, Molten Salt	300 MWh (100 MW)		KaXu Solar One is a 100 MW parabolic trough plant. The power station will have a storage capacity of three hours and use molten salt to store heat energy. In the parabolic trough system, the sun's energy is concentrated by parabolically curved, trough-shaped reflectors onto a receiver pipe running along the focal line of the curved surface.		South Africa, Northern Cape Province, Pofadder
Bokpoort Concentrated Solar Plant (CSP)	Thermal Storage, Molten Salt	450 MWh (50 MW)		The Bokpoort CSP Project, being contracted in 2014, comprises a solar field, a power block, a thermal energy storage system, and related infrastructure such as grid interconnection and water abstraction and treatment system. The solar field comprises loops of parabolic trough solar collector assemblies which will collect the heat from the sun. The solar collectors will be capable of heating the heat transfer fluid up to 393 °C. The power block comprises a solar steam generator and a steam turbine delivering 50 MW (net).		South Africa, Northern Cape Province, Globershoop
Dinorwig Power Station	Pumped Hydro Storage, Closed Loop	10,368 MWh (1,728 MW)		1,728 MW project near Dinorwig, Llanberis in Snowdonia National Park in Gwynedd, North Wales. It can switch from 0 to near full power output in 12 seconds.		United Kingdom, Wales, Dinorwig

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Table *continued*

Name	Type	Size (MWh)	Application	Description	Commission Date	Country and Location
Ffestiniog Power Station	Pumped Hydro Storage, Closed Loop	2,160 MWh (360 MW)		The project includes four water turbines of 360 MW combined capacity. The station, commissioned in 1963, was the first major pumped storage system in the United Kingdom.	1963	United Kingdom, Wales, Ffestiniog
Smarter Network Storage	Battery, Lithium-Ion	10 MWh (6 MW)		The project is about developing control and optimization systems for energy storage. Trials include providing service to distribution network operators and transmission system operators.		United Kingdom, England, Bedfordshire
McIntosh CAES Plant	Compressed Air Storage, In-ground Natural Gas Combustion	2,860 MWh (110 MW)	Peak shaving	The plant utilizes nuclear-sourced night-time power for compression and then produces peak power during the day by releasing the compressed air into a 110MW gas-fired combustion turbine. The system is fully operational within 15 minutes, uses one third of the fuel required for a fuel-only generating system, and can operate efficiently at low loads.	1991	United States, Alabama, McIntosh
Battery Energy Storage System (BESS)	Battery, Nickel Cadmium	6.7 MWh (27 MW)	Frequency response	Completed in December 2003, the BESS is a Golden Valley Electric Association (GVEA) initiative to improve the reliability of service to GVEA members.	December 2003	United States, Alaska, Fairbanks
Solana Generating Station	Thermal Storage, Molten Salt	1,680 MWh (280 MW)		At the time it was the world's largest parabolic trough plant, and the first solar plant with thermal storage in the United States.	2013	United States, Arizona, Gila Bend
Eagle Mountain Project	Pumped Hydro Storage, Closed Loop	24,050 MWh (1,300 MW)		Using open mine pits as reservoirs, water will be stored in the upper levels or allowed to flow to the lower pits to generate electricity as needed.		United States, California, Desert Center
Pacific Gas & Electric	Compressed Air Storage	300 MW (3000 MWh)	Renewables, spinning reserves, VAR	300MW CAES	March 2021	United States, California, Kern County

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Table *continued*

Name	Type	Size (MWh)	Application	Description	Commission Date	Country and Location
Premium Power	Zinc Chloride flow battery	25 MW (75 MWh)	Renewable demand	1 MW Premium Power zinc bromine flow battery	2014/2015	United States, California, Modesto
Yerba Buena Battery Energy Storage System Pilot Project	Battery, Sodium-Sulfur	24 MWh (4 MW)		The project uses sodium-sulfur batteries to determine whether such batteries can improve power quality and reliability on the electrical grid.		United States, California, East San Jose
PG&E Vaca Battery Energy Storage Pilot Project	Battery, Sodium-Sulfur	14 MWh (2 MW)	load shaping, renewables integration, and ancillary services	This project will be located at a substation near the Vaca Dixon Solar Plant of Vacaville, California. It's a 2MW–14 MWh installation that will address load shaping, renewables integration, and ancillary services.		United States, California, Vacaville
Southern California Edison	Lithium-ion Battery	8 MW (32 MWh)	Voltage support, wind integration, frequency regulation, arbitrage	8MW (32 MWh) lithium-ion battery at substation within Tehachapi Wind Resource Area for voltage support, wind integration, frequency regulation, arbitrage	Early 2014	United States, California, Tehachapi
Mount Elbert Power Plant	Pumped Hydro Storage, Open Loop	2,400 MWh (200 MW)		Mt. Elbert's two units are also designed to operate as a 170,000-horsepower electric motor to drive the turbines in reverse and pump the same water back up to the forebay.	1981	United States, Colorado, Lake County
Cabin Creek Generating Station	Pumped Hydro Storage, Open Loop	1,296 MWh (324 MW)	Economic dispatch	Cabin Creek is a pumped storage plant with a lower and upper reservoir during periods of peak electricity demand on Xcel Energy's Colorado system.		United States, Colorado, Georgetown
Kahuku Wind Farm	Battery, Advanced Lead Acid	3.7 MWh (15 MW)	Electric supply capacity	A 15 MW fully integrated energy storage and power management system designed to provide load firming for a 30 MW wind farm in Hawaii.		United States, Hawaii, Oahu
Ludington Pumped Storage Power Plant	Pumped Hydro Storage, Open Loop	14,976 MWh (1,872 MW)		Its upper reservoir, of 27 billion-gallon capacity, feeds six turbine generators. The turbines function as water pumps at night to refill the reservoir with Lake Michigan water, raising the water some 360 feet.	1973	United States, Michigan, Ludington

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Table *continued*

Name	Type	Size (MWh)	Application	Description	Commission Date	Country and Location
Hazle Spindle LLC (Beacon Power)	Flywheels	20 MW (5 MWh)	Frequency response	20MW (200 x 100KW) flywheels for frequency regulation in PJM	September 2011	United States, New York, Stephentown
Bluffton NaS Energy Storage System	Battery, Sodium-Sulfur	14.4 MWh (2 MW)	Backup power	AEP Ohio has 2MW units which were deployed in 2008, and are capable of providing islanding (backup power) for over 7 hours when loss of utility power from a substation occurs.	2008	United States, Ohio, Bluffton
East Penn Manufacturing	Ultracapacitors/ Lead-acid battery	3 MW (1-4 MWh)	Frequency/ Demand	3MW East Penn UltraBattery (ultra-capacitor/lead-acid) providing frequency regulation services	June 2012	United States, Pennsylvania, Lyons Station
Fairfield Pumped Storage	Pumped Hydro Storage, Open Loop	3,577 MWh (511 MW)	peaking, reserve generation, and off-peak power usage.	The Fairfield Pumped Storage Facility utilizes four earthen dams and four penstocks that lead from the intake structure on the Monticello Reservoir to the powerhouse. It is primarily used for peaking, reserve generation, and off-peak power usage.		United States, South Carolina, Jenkinsville
Duke Energy Business Services	Lead-acid battery	24 MW	Renewable demand	36MW/24MWh Xtreme Power advanced lead acid battery for Wind Farm storage for frequency regulation as the targeted service.	January 2013	United States, Texas, Goldsmith
Notrees Wind Energy Storage Project	Battery, Advanced Lead Acid	9 MWh (36 MW)	Power management	A wind energy storage demonstration project at the Notrees Wind power project in western Texas created in 2013. The project provides 36 MW energy storage and a power management system.	2013	United States, Texas, Notrees
John W. Keys III Pump-Generating Plant	Pumped Hydro Storage, Open Loop	24,000 MWh (300 MW)		In the early 1960s reversible pumps were installed to allow water from Banks Lake to flow back through the units to generate power, with three generating pumps online in 1973, two in 1983 and a final pump 1984, with a total capacity now of 314,000 kW.	1960	United States, Washington, Grand Coulee

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Table *continued*

Name	Type	Size (MWh)	Application	Description	Commission Date	Country and Location
Charleston Energy Storage Project	Battery, Sodium-Sulfur	6 MWh (1 MW)	peak-shaving and transmission upgrade deferral benefits	Over the short term, the purpose of the Charleston Energy Storage Project is to mitigate current local capacity constraints and service reliability issues. The long term objective is to bring AEP one step closer to its vision of a storage-buffered grid of the future.		United States, West Virginia, Charleston
Batelle Memorial Institute	Lithium-ion Battery	5 MW (1.25 MWh)	Frequency response	5MW/1.25MWh EnerDel lithium-ion battery for high-reliability zone and microgrid support.	March 2013	Salem, Oregon
Kansas City Power & Light Co	Lithium-ion Battery	1 MW (1 MWh)		1MW/1MWh (13.2kV) Superior Lithium Polymer Battery Storage (SLPB) system, grid-connected	June 2012	Kansas City, Missouri
University of Hawaii	Lithium-ion Battery	1 MW (1 MWh)		1MW/1MWh A123 Li-ion battery installed at Wailea substation	April 2013	Hawaii, USA

CAES=Compressed Air Energy Storage, ft3 = cubic feet, GWh = gigawatt-hour, km = kilometer, kW = kilowatt, MW = megawatt, MWh = megawatt-hour.

Source: https://en.wikipedia.org/wiki/List_of_energy_storage_projects; Government of the United States, Department of Energy. Global Energy Storage Database. http://www.energystorageexchange.org/projects. June 2016

APPENDIX B
Bidirectional Inverter

A bidirectional power inverter is an electronic circuit that converts direct current power to alternating current power and converts alternating current power to direct current power. In power electronics, the direct current to alternating current conversion device is called an inverter, and alternating current to direct current conversion device is called a rectifier or a charger.

From the late 19th century to the middle of the 20th century, this conversion was accomplished using vacuum tubes and gas filled tubes. In 1957, the introduction of the thyristor or silicon-controlled rectifier initiated the transition to solid state inverter circuits. Later these devices were replaced by bipolar junction transistor (BJT) devices that have high power carrying capacity and metal oxide semiconductor field effect transistors (MOSFET) that have high switching speed. Nowadays these devices are being replaced with insulated gate bipolar transistors (IGBT) because it incorporates the advantages of both MOSFET and power BJT. The IGBT transistor has high input impedance and high switching speeds (same as MOSFET) with the low saturation voltage (same as power BJT).

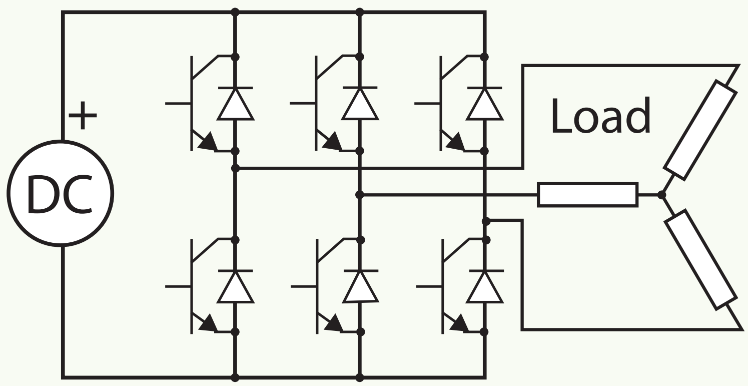
IGBT has three terminals: collector, emitter, and gate. Two of its terminals (collector and emitter) are associated with a conductance path and the third terminal (gate) is associated with its control. In inverters, IGBTs are used as a switching device by simply turning "ON" or "OFF" by activating and deactivating its gate terminal.

Full Power Conversion

The full power conversion inverter design consists of six such switching devices (IGBT) and six freewheeling diodes, as shown in Figure B.1. The inverters work by switching a direct current voltage into the alternating current circuit at high frequency, typically by using a pulse width modulation technique. These signals are applied at the gate terminals. The inverters used for storage unit need to have following functionalities:

(i) **Active and reactive power supply.** An inverter can supply both real and reactive power by controlling the delay in the switching devices. This delay creates a phase difference between voltage and current, thereby delivering active and reactive power. Inverters can supply reactive power even when the source is not generating active power (e.g., VAR delivery during night by inverters connected to solar panels).

Figure B.1: Schematic of Full Power Conversion Insulated Gate Bipolar Transistor-Based Inverters



DC = Direct Current

Source: Author.

(ii) **Bidirectional flow.** The battery operates in two modes: discharging and charging mode. In discharging mode the power is fed into the grid and in charging mode it is pulled from the grid and stored in the batteries. Thus, the inverter needs to be bidirectional. IGBT supports the discharging mode of operation, while the freewheeling diode across the IGBT facilitates flow of current from grid to the battery.

Energy Storage in Grids with High Penetration of Variable Generation

Grid-level energy storage is likely to dominate the conversation in the power industry in the coming years, just like renewable energy did in the past 2 decades. This report targets investors, developers, utility planners, power sector policy makers, and readers who wish to understand the role energy storage is likely to play in the smart grid of the future. For developing countries, the report provides an introduction to the necessary technical background on energy storage, the role it is likely to play as penetration of renewable energy increases in the grid, and the policy prescriptions to realize the wide range of benefits of energy storage.

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