Battery Storage Systems

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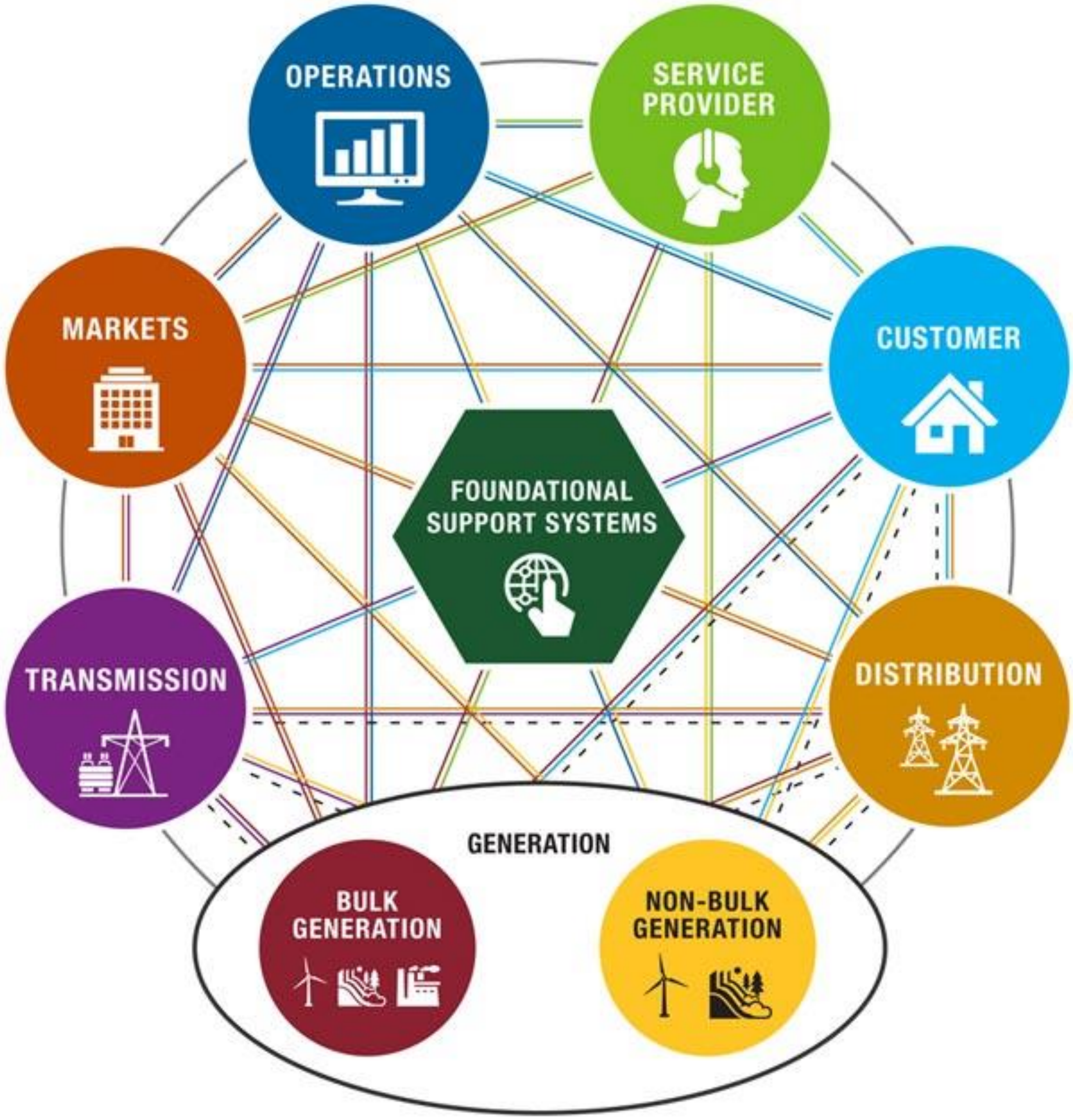

Battery Storage Systems

CONTRIBUTORS

IEEE Smart Grid Battery Storage Working Group

Chair

Wei-Jen Lee	IEEE Industry Applications Society

Members and Contributors

Merlinda Andoni	IEEE ABCD Society
Salam Bani-Ahmed	IEEE ABCD Society
David Flynn	IEEE ABCD Society
Balint Hartmann	IEEE ABCD Society
John Hewson	IEEE ABCD Society
Josh Lamb	IEEE ABCD Society
Afshin Majd	IEEE Industry Applications Society
Valentin Robu	IEEE ABCD Society
Mehrdad Rostami	IEEE ABCD Society
Chris Searles	IEEE ABCD Society
Sima Seidi	IEEE ABCD Society
Istvan Taczi	IEEE ABCD Society
Istvan Vokony	IEEE ABCD Society
Gaetano Zizzo	IEEE ABCD Society

Staff

Phyllis Caputo	IEEE Smart Grid
Angelique Rajski Parashis	IEEE Smart Grid

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1. Introduction

Electrical power infrastructures are changing dramatically around the globe due to smart grid initiatives, the establishment of renewables and the resulting distributed nature of creating electricity, the need for independent microgrids to ensure grid reliability, new demands from end users, the need to reduce greenhouse gas emissions, as well as the capability to accommodate mixed energy resources. As a result, the power network faces great challenges in generation, transmission and distribution to meet new and many times unpredictable demands of providing coherent electricity supply. Electrical Energy Storage (EES) has been considered a game-changer with a number of technologies that have great potential in meeting these challenges. According to the U.S. Department of Energy the suitability of a storage technology is determined primarily by its power and energy capacity and the rate at which these can be stored and delivered. Other characteristics to consider are round-trip efficiency, cycle life, calendar life, safety, reliability, effect on the environment and ramp rate (how fast the technology can respond to a command).

However, the wide variety of options and complex performance matrices can make it difficult to appraise a specific EES technology for a particular application. This white paper intends to contribute information that will give a Smart Grid user a clearer picture of the state-of-the-art electrochemical technologies available, and where they would be suited for integration into a power generation and distribution system. The white paper starts with an overview of the operation principles, technical and economic performance features and the current research and development of important EES technologies, sorted into six main categories based on the types of energy stored. Other energy storage technologies such as compressed air, fly wheel, and pump storage do exist, but this white paper focuses on battery energy storage systems (BESS) and its related applications.

There is a body of work being created by many organizations, especially within IEEE, but it is the intent of this white paper to complement those activities and provide solid insight into the role of energy storage, especially as it relates to the Smart Grid.

2. Overview of the Energy Storage Technologies

Today, most common battery chemistries are based on lead, nickel, sodium and lithium electrochemestries. Emerging technologies like flow batteries utilize various transition metals like vanadium, chromium and iron as the electroactive element. Carbon electrodes are a critical part of several of these battery systems. . Each storage type has distinct characteristics, namely, capacity, energy and power output, charging/discharging rates, efficiency, life-cycle and cost that need to be taken into consideration for possible applications. Understanding their chemical characteristics and related regulations are critical steps for possible use. This includes the application, siting, installation, operation and maintenance, as well as shipping and disposing of used batteries. This chapter presents a review of available and emerging battery technologies and their design and performance characteristics. Electric Double Layer Capacitors (often referred to as ultracapacitors or supercapacitors) are also addressed in this chapter.

2.1. Lead acid batteries

The lead-acid battery was invented in 1859 by French physicist Gaston Planté and it is the oldest and most mature rechargeable battery technology. There are several types of lead-acid batteries that share the same fundamental configuration. The battery consists of a lead (Pb) cathode, a lead-dioxide ($PbO2$) anode and sulfuric acid electrolyte ($H2SO4$). The deep cycle/traction and the traditional stationary battery types are the most commonly used in Smart Grid applications. The deep cycle battery is composed of very thin plates and has a low energy density; however, its relatively high power density makes it attractive for use in motor vehicles to provide the high current required for power engine starters.

The larger format and thicker plate stationary battery is used in a number of applications where interruption to the load cannot be tolerated. Common use in the energy space includes standby backup power for switchgear, turbine motors, data centers and any other application where reliability of the load is critical. Lead-acid batteries are widely used because they are less expensive compared to many of the newer technologies and have a proven track record for reliability and performance.

In North America the use of calcium along with other alloys is common for vented lead-acid (VLA) cell. In Europe and other parts of the world, lead-selenium along with a small amount of antimony (low antimony) cells are commonly used for standby applications. However, the leas-selenium, low-antimony battery has been more widely used in North America in recent years.

Valve-regulated lead-acid (VRLA) cells also use a calcium alloy in the plate structure, however, they differ in the way the electrolyte is incorporated. The two most common types are an absorbed glass mat (AGM), often referred to as a “starved electrolyte” topology, or with the use of specialized silica that is called a gelled electrolyte. VLA and VRLA batteries ~~are~~ can be designed for optimal performance in either a power application and/or an energy application. There are several designs and chemistries, (both old and new) such as a tubular plate design coupled with a gelled electrolyte that provides a very decent cycling capability. Another uses a carbon electrode in which the battery becomes a battery-supercapacitor hybrid. These various VRLA types present distinct advantages and disadvantages. While the technology is well-known and can offer a lower-cost advantage, lead-acid batteries have greater weight due to their lower energy density; they may also have life-cycle performance and long term performance issues depending on the type, which make the technology ~~not~~ less suitable for many applications.

2.2. Nickel–Cadmium batteries

The nickel–cadmium battery (NiCd) is a rechargeable battery using nickel oxide hydroxide and metallic cadmium as electrodes. Wet-cell nickel-cadmium batteries were invented in 1899. A NiCd cell delivers around 1.2 volts output voltage until nearly the end of discharge. Compared with other types of rechargeable batteries, NiCd batteries offer satisfactory life-cycle characteristics and improved performance at low temperatures with a good capacity retention at high rates. However, the material costs are higher than that of the lead acid batteries. Moreover, NiCd cells experience the so called “memory effect” and high self-discharge rates which have a great impact to their performance characteristics. In addition, environmental concerns on the disposal of the toxic metal cadmium has dramatically reduced the use of NiCd batteries. As a result, NiCd rapidly lost market share to nickel-metal-hydride (NiMH) and Li-ion batteries in the 1990s. Within the EU, NiCd batteries can only be supplied for replacement purposes and their use is limited for certain types of new equipment such as medical devices.

2.3. Nickel–metal hydride batteries

A nickel–metal hydride battery (NiMH) is also a type of rechargeable battery. Similar~~ly~~ to NiCd batteries, NiMH cells use nickel oxide hydroxide (NiOOH), which is formed in the positive electrode. The use of Cd in the negative electrode is replaced by a hydrogen-absorbing alloy. A NiMH battery can have two to three times the capacity of an equivalent size NiCd, and its specific energy of 80Wh/kg is about 50% of a lithium-ion battery. Main applications of the NiMH batteries are found in consumer electronics and plug-in electric vehicles and hybrid vehicles due to the technology maturity and their competitive cost to Li-ion batteries. However, Li-ion batteries are considered to most promising for the EV industry mainly due to their continuously falling cost and improved performance.

2.4. Lithium-ion batteries

In 1991, Sony and Asahi Kasei released the first commercial lithium-ion battery. A lithium-ion battery (Li-ion) is a type of rechargeable battery where lithium ions move from the negative electrode to the positive electrode during discharge. The process is reversed during charging. With a high energy density, negligible memory effect and low self-discharge, Li-ion batteries are one of the most popular types of rechargeable batteries for portable electronics. In recent years, they are also growing in popularity for military, Plug-in electric vehicle (PEV), and aerospace applications. Different types of Li-ion battery chemistries present different performance, cost and safety features that can suit a variety of applications. For example, lithium cobalt oxide ($LiCoO_2$) batteries are used in most handheld electronics due to their high energy density and low weight. Other types such as Lithium iron phosphate ($LiFePO_4$), lithium ion manganese oxide batteries (LiMn2O4, Li2MnO3, or LMO) and lithium nickel manganese cobalt oxide (LiNiMnCoO2 or NMC) offer lower energy density, but can provide longer lifetime and inherent safety. These types are widely used for electric tools and medical equipment. The newer emerging type of lithium–sulfur batteries promise the highest performance-to-weight ratio. Li-ion batteries present a high efficiency and a long lifespan. The technology is still under development, therefore further performance improvements may be expected in the future. Their cost currently lies at approximately $700/kWh but it is expected to continue to drop in the following years due to massive manufacturing developments and the resulting economies of scale. In January 2017, Tesla Motors began production of lithium-ion battery cells for energy storage at its Gigafactory in Nevada, ~~a~~ in what will be a sprawling 5.5 million-square-foot manufacturing facility (see Fig. 2-1). The high-performance cylindrical “2170” cell, jointly designed by Tesla and its Japanese partner Panasonic, will be used in Tesla’s Powerpack 2 and Powerwall 2. In 2018, it is expected to be used for its Model 3 electric vehicles as well.

Fig. 2-1 Tesla Motors’ lithium-ion battery “Gigafactory” outside Sparks, Nevada broke ground in June 2014 and began production in January 2017 even though it was only 30% complete [1]

Li-ion batteries can pose safety hazards since they contain a flammable electrolyte. There have been several battery-related recalls by different companies, including earlier laptop computer batteries and the 2016 Samsung Galaxy Note 7 recall for battery fires due to overcharging. Because of these risks, testing standards are more stringent than those for acid-electrolyte counter parts. There are concerns related to the availability of Lithium, which are mainly concentrated in reserves in South America. The price of nickel and cobalt (lithium related alloys) have doubled over the last two years. This is a concern as to the effects for promised cost reductions.

2.5. Flow batteries

Flow batteries are considered unique in that the power and energy of the battery are entirely decoupled. A flow battery is consists of multiple electrochemical cells connected in series in a stack. These stacks are then connected in series and/or stacks to form a Flow Battery Energy Storage System (FBESS). The stack configuration dictates the power of the cell while the energy is controlled by the chemical energy contained in the electrolyte tanks that are external to the stack. Positive and negative electrolyte solutions are pumped into the stack where they are separated by ion-exchange membranes or a porous separator. Ion exchange (accompanied by flow of electric current) occurs through the membrane while both liquids circulate in their own respective space. There are several types of flow batteries such as Fe-Cr, Fe-V (vanadium redox) and hybrid flow systems such as Zinc-Bromide (Zn-Br2) and Zinc-Chloride (Zn-C12). These are typically aqueous based solutions, and thus cell voltages are limited between 1.0 to 1.8 volts to prevent hydrolysis of the water. Non-aqueous electrolyte flow battery systems have the potential for higher energy density due to high open circuit voltage and a potential for more than 1 electron per mole of the active species. However, these are still under development.

Currently, the most cost effective flow battery that exhibits good performance and safety is the all vanadium redox flow battery. The Pacific Northwest National Laboratory (PNNL) have demonstrated newer mixed sulfuric-hydrochloric acid technology with a vanadium concentration up to 2.5M with an energy density near 40Wh/l in an operating window of -10°C to 50°C.

Since the power and energy of the flow battery are separate, specialized cost performance models are required to determine the optimal energy to power rations for grid storage applications. Flow batteries are analogous to a fuel cell to the extent that reactants flow past or through the electrodes. The conversion is less than 100% per pass. Flow batteries have several technical advantages over conventional rechargeable batteries, but a monitoring and control mechanism~~s~~ is required.

Flow batteries are inherently safe as the aqueous electrolyte is non-flammable. They have demonstrated long cycle life and the cycle life is not dependent on the depth of discharge. Energy is determined by the tank volume and electrolyte concentaration while power is determined by the stack area. Charge and discharge times will vary as a function of the energy to power ratio, thus recharge times will vary. Flow batteries may not be cost effective for very short duration applications since the stack costs dominate. Flow batteries are most cost-effective for longer duration, energy intensive applications. However, they do retain their ability to do fast ramp rates. This enables them to provide multiple power and energy services. This operational flexibility makes the flow battery very attractive for grid scale applications.

2.6. Sodium–sulfur batteries

A sodium–sulfur (NaS) battery is a molten-salt battery constructed from liquid sodium (Na) and sulfur (S). NaS batteries are fabricated from inexpensive materials, which forms one of the main advantages of this technology type. NaS batteries have high energy density, high efficiency of charging/discharging (89–92%) and long cycle life. The main drawbacks of the NaS battery are the operating temperatures of 300°C to 350°C and the highly corrosive nature of the sodium polysulfides. Battery cells become more economical with increasing size, therefore NaS batteries are considered more suitable for stationary energy storage applications. Typical applications of NaS batteries are distribution network support and grid services and renewable energy integration. The technology has a great potential for grid services since it has a long discharge time and can respond precisely to improve power quality issues in the grid.

2.7. Sodium-nickel-chloride batteries

Sodium-nickel-chloride ($NaNiCl_2$) are high-temperature batteries similarly to NaS batteries. Their operating temperature lies within the 270 C-350 C range. During the charging process, salt (NaCl) and nickel (Ni) are transformed into nickel-chloride ($NiCl_2$) and molten sodium (Na). The process is reversed during discharge. Typical applications of $NaNiCl_2$ batteries are grid support services and renewable energy integration.

2.8. Electric double layer capacitors

Electric Double Layer Capacitors (EDLCs), also known as “ultracapacitors” or “supercapacitors” store electrical charge in an electric double layer (non-Faradic) at the interface between a high-surface-area carbon electrode and a liquid electrolyte. This mechanism is highly reversible and therefore just as with ECs, conventional capacitors, can be charged and discharged at high power rates with low capacitance fade for hundreds of thousands of cycles. The electrode surface area in capacitors determines the capacitance and thus, the energy storage capability of the device. The amount of energy stored by EDLCs is very large compared to conventional capacitors because of the use of a porous carbon-based electrode material of high surface area. While ultracapacitors have very high specific power (10-20 kW/kg), and longer lifetime relative to batteries, they have a low specific and volumetric energy density (<8Wh/kg).

Ultracapacitors exhibit significantly less sensitivity to temperature than Li-ion batteries with possible operating temperatures in the range of -40 to 65°C. DC lifetime (where a cell is continuously held at rated voltage) is typically 1500 h at elevated temperature (65˚C). In terms of cycling behaviour, 500K to >1M cycles are common. Ultracapacitors are well-suited for high-power applications in a variety of areas, with applicability at Transmission, sub-transmission, as well as distribution voltage levels. The key features of ultracapacitors are extremely appealing in electricity grids: fast response time in milliseconds, high-energy efficiency (> 95%), high power density and long calendar and cycle life. Driven by economies of scale and advancements in manufacturing, the cost of EDLCs has decreased dramatically for their deployment in grid energy storage systems. At present, fully installed costs are estimated to be $1000/kW, decreasing to $517/kW by 2021 [1] Given this customer value improvement and the ability to pair with batteries to “stack” grid services and improve battery lifetime, ultracapacitors are now being piloted in systems across the globe.

Deployment of EDLCs has accelerated greatly over the last 15 years; they are now widely commercialized in hybrid bus, rail, and automotive applications, as well as back-up power applications such as wind pitch control systems and uninterrupted power supplies. Moreover, there are several trials and pilot projects that study the utilization of supercapacitors for grid energy storage systems. They can be a stand-alone technology or hybridized with a second, low cost high energy density technology such as flow batteries or high energy Li-ion batteries.

2.9. Comparison of battery storage technologies

A summary of the energy storage technologies discussed above is presented at Table 2-1. Different types are compared by their main technical characteristics, such as cycle life performance and efficiency. Main pros and cons of different types are also highlighted in Table 2.9.1.

Table 2-1. A comparative summary of different battery technologies by current state-of-the-art [4-7]

Storage technology	***Cycle life at 80% DOD***	***Efficiency***	***Advantage***	***Disadvantage***
Lead Acid	300-3000 [5]	70-90%	- Inexpensive - Mature technology	- Limited cycling capability for most standard types - Low energy density - Environmental hazard
NiCd	3000	80 %	- Good cycle life - Good performance at low temperatures - More tolerant to hostile environments or conditions	- Memory effect - High self-discharge rate - Environmental hazard
NiMH	2000	50-80 %	- High energy density - Good abuse tolerance - Good performance at low temperatures	- Damage may occur with complete discharge - High costs
Li-ion	3000	75-90 % [6]	- High energy density - Low self-discharge rate - No memory effect	- Expensive although costs are decreasing - Not safe depending on type
Flow batteries	2,000-20,000	65-85 %	- Scalability - Lifespan not dependent on DOD	- Need for electrolyte tanks - High maintenance - Complex monitoring and control mechanisms
NaS	4500	89 %	- High efficiency and cycle life	- High operating temperatures

			- Low cost battery materials - High energy density	- -Temperature is to be maintained close to 300°C which might affect battery performance [7] - Corrosive materials
NaNiCl2	1,500-3,000	85-95 %	- Long cycle life - High energy density	- High operating temperatures - Thermal management requirement
EDLC	1,000,000	95%	- High power Density, fast response - Lifetime - Safety - Wide operating temperature range (-40 to 65°C)	- Low energy density

In addition a conceptual classification of energy storage devices is shown in Fig. 2-2 in terms of their power and energy relationship and potential use-cases and applications focusing to grid services provision.

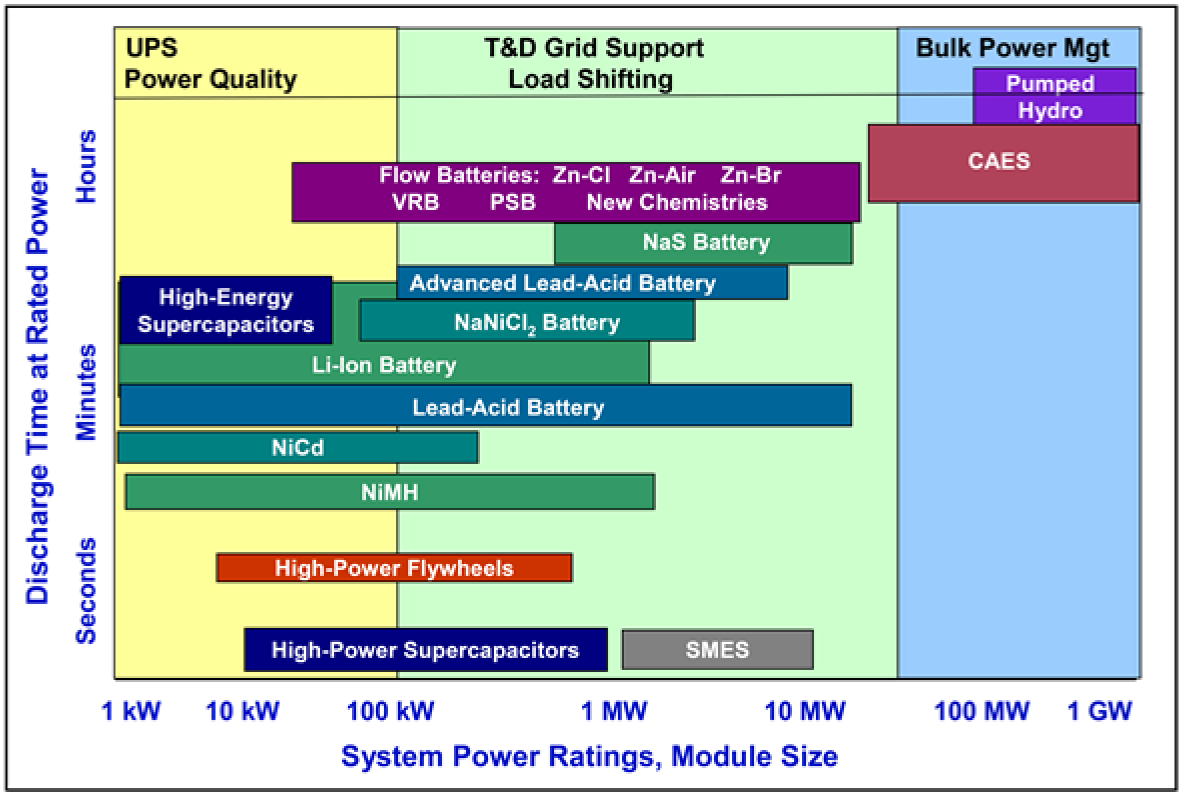

Fig. 2-1 Energy storage technologies and their main applications (Source: EPRI [8])

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3. Current Applications of Battery Storage

Companies deploy storage technologies for a number of different purposes. Coordinating and rearranging energy from diverse resources to optimize the overall production/operation cost is only one of the many applications of energy storage. Energy storage can also improve the quality of power through frequency regulation and provide an uninterruptible source of power for critical infrastructure and services.

3.1. Transmission level

3.1.1. Current Installations and plans

Energy storage using grid-connected electrochemical battery systems has widely been considered as a potential solution for seamless integration of renewables, improving grid flexibility, and enhancing grid reliability. Several examples are provided in this section.

In the US, battery storage is now clearly an established market. According to the first quarter report from GTM Research and the Energy Storage Association (ESA), battery storage deployments grew to 336 MWh in 2016, doubling megawatt-hours deployed in 2015. As shown in Fig. 3-1, 230 MWh came online in the final quarter of 2016 alone, which is more than the sum of the previous 12 quarters combined.

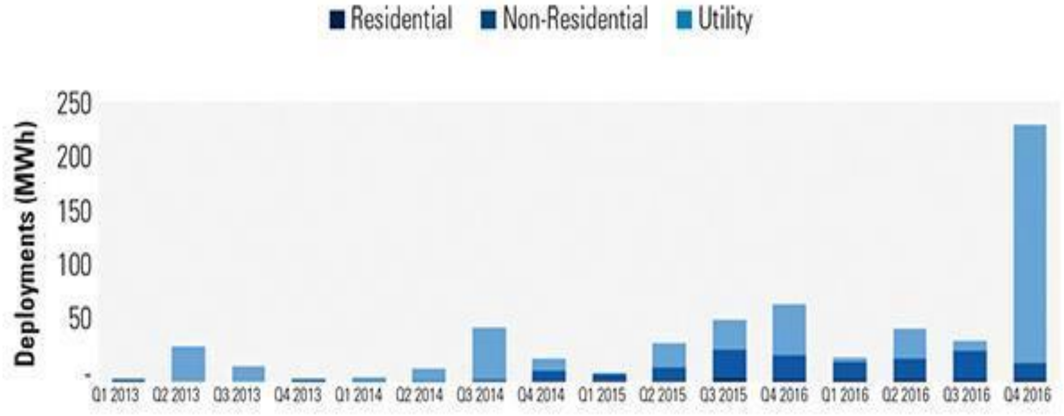


Fig. 3-1 U.S. energy storage deployments (MWh). [1]

According to the U.S. Department of Energy's Global Energy Storage Database, about 733 grid-connected electrochemical projects with a total rated power of 1.8 GW (of varying duration) have been installed around the world by April 2017.

According to Ofgem, the UK regulator, 550 MW of battery capacity was contracted in 2016 to come online by 2020.

Terna S.p.A., the Italian TSO (Transmission System Operators), installed two battery energy storage plants connected to the HV transmission grid with a total rated power of 12.5 MW and planned to install a total capacity of 40 MW by 2020. The installation site in Codrongianos (Sardinia) is, nowadays, one of the biggest battery energy storage plant in Europe.

An Ontario utility company in (Festival Hydro) is going to install one of the largest North American BESSs including four 2 to 2.4MW inverters and 6-14.4MWh batteries, providing 8.8MW power and 40.8MWh energy storage capacity for 27.6kV local distribution network. Such a large-scale battery energy storages can support frequency control and share the load in peak operating times beside of reactive support and voltage control in other periods. [2]

3.1.2. Area of Applications

3.1.2.1 Integration of Distributed Renewable Energy Sources

Integration of large scale wind generation or other distributed renewable energy sources into the electric supply and transmission systems, by creating voltage and frequency instability, poses some well-characterized challenges. In response, utilities, governments and regulators are now imposing strict grid interconnection requirements, including frequency control (i.e. inertia), voltage control and power injection to the transmission grid. Interconnectivity Solutions include complete VAR compensation and voltage control, enabling wind and solar energy generation systems to meet these new and emerging requirements. STATCOM and hybrid STATCOM-Energy Storage (Battery and/or Ultracapacitor) systems provide a solution that allows power plants to stay online and prevent the nuisance tripping that may be caused by solar inverters and wind turbine generators.

This value proposition combines renewable integration electricity storage benefits with “locational” benefits associated with distributed storage, such as storing “low value” energy to distribute it during peak demand.

The same storage system can also be used to provide most of the “ancillary services” needed by grid system operators to keep the electricity grid operating in a stable and reliable manner. Depending on the location of the storage, it may also provide benefits related to improved local electric service reliability and power quality.

As an example, Nova Scotia Power Inc. (NSPI), in a recent pilot project in Canada, runs a 1.5MW BESS in Nova Scotia province, which supports the wind farm, located more than 20km far from point of connection on a same feeder. BESS can act as micro grid and support 300 selected households during the outages while regulating feeder voltage when feeder is lightly or heavily loaded. [3]

3.1.2.2 Merchant Electricity Storage

The merchant business model is a very important value proposition for battery storage. Although situations vary among markets, benefits derived from operation of a merchant storage plant include: a) electric energy time-shift (peak-shaving), b) electric supply capacity (power) and c) the ancillary services that are needed to maintain a stable and reliable electrical grid. Other potential benefits could include transmission support and/or transmission congestion relief.

Currently there are GigaWatts of merchant storage capacity in operation or planned – primarily pumped hydroelectric, but interest in compressed air energy storage (CAES) is growing. Battery storage will become one of the major players once it becomes more economically feasible.

Storage systems can be owned by the utility companies or independent storage providers, who can either have direct access and trade in the wholesale energy, capacity, balancing and ancillary services markets or have a contractual agreement with a utility company or a third-party to whom they provide their services. The model requires significant changes from a regulatory perspective. Ownership of BESS is in fact crucial as it may inhibit healthy competition in the marketplace. Ofgem, the UK regulator, is planning to take an action in order to discourage ownership or operation of storage systems, as flexibility assets, by utility companies. Such models may also refer to storage aggregators emerging in the marketplace that operate a portfolio of multiple smaller-scale storage technologies that act as a single virtual storage provider. Advanced artificial intelligence algorithms, data analytics and machine learning techniques are increasingly playing an important role in managing distributed storage devices in such settings.

3.1.2.3 Transmission upgrade deferral and congestion relief

Energy storage systems can be used to delay or postpone capital-intensive transmission upgrade investment. Specific nodes within the transmission system may operate near their designed capacity and may be inadequate to serve the demand requested. In such cases the thermal limits of the transmission assets are usually exceeded for a very short time period of a few hours or a single day per year. A much smaller investment in storage systems can provide a solution to this problem and can further assist to extend the lifetime of transmission assets operating close to their operational limits or remaining useful lifetime. Similarly, BESS can be used to store excess generation that causes transmission congestion for later use. Transmission congestion is reflected in high transmission charges or LMP.

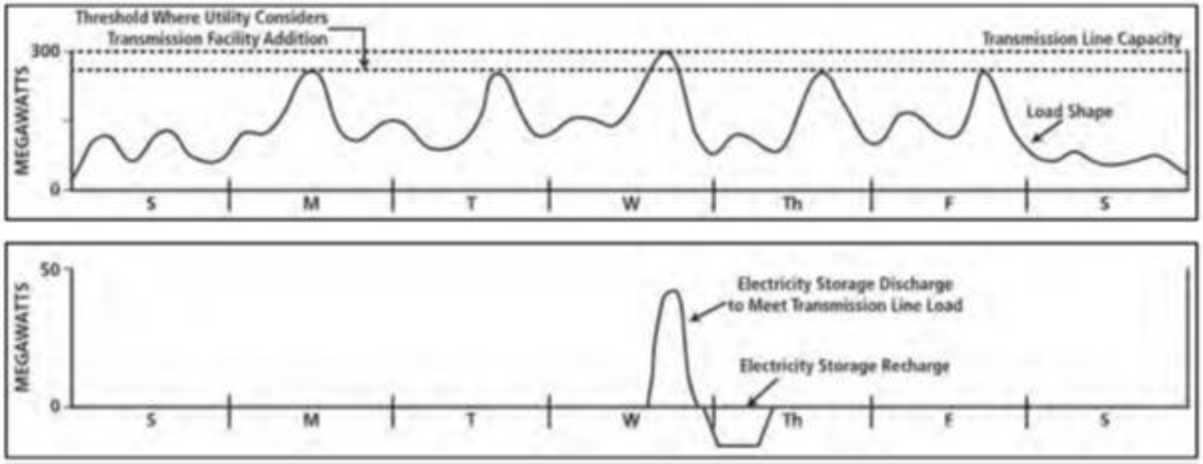


Fig. 3-2 BESS for transmission or distribution deferral [4]

3.1.2.4 Energy arbitrage

Battery energy storage systems (BESS) can be used to shift the electricity use purchased from the grid (energy arbitrage). Energy is purchased when it is cheap and used to charge the storage system, typically when demand is low or availability from renewable resources exists in abundance. Later, batteries are discharged when price or costs of energy is high, typically during peak demand times. In a similar fashion, batteries are used to store the energy surplus of renewable energy systems that needs to be curtailed as it cannot be absorbed by the power system, due to low demand or insufficient transmission capacity. The use of batteries for such applications depends on the relation of the costs incurred for installing the battery system and its use, to the value of the energy and potential revenues when it is sold back to the grid. As a result, in addition to cost considerations, fit-for-purpose battery performance is required that is characterized by high round-trip battery efficiency, low energy losses and satisfactory lifetime and battery degradation mechanism.

3.1.2.5 Load following

Technical requirements for integration of RES are similar to load following, when generating assets adjust their power outputs according to the changes in demand in a specific area. Adjustments are typically required every several minutes. BESS is suitable for this service as it can operate at partial power output without having a significant impact in its lifetime performance and can act very fast. BESS can be used both for ramp-up and ramp-down. On the contrary, conventional power plants can have reduced efficiency, as they consume more fuel and have increased emissions when operated below their desired technical set points.

3.1.2.6 Power quality improvement

Utility companies need to provide electricity to consumers that fulfils specific technical requirements. However, in certain occasions, a customer may experience short-term or long-term voltage variations, frequency variations, harmonics, low power factor and power supply interruptions. Battery or ultracapacitor energy storage systems can be placed on the customer side to prevent such violations and improve power quality characteristics.

3.1.2.7 Power reliability

BESS can be used as an alternative electrification source when power cannot be supplied by the main grid due to a severe failure event. With the help of battery systems, areas of the grid can operate in islanded mode until the fault is mitigated and normal operation is restored. Storage systems can operate alone or in synergy with backup diesel generators.

3.1.2.8 Ancillary services

Control Performance Standards 1 (CPS1) of NERC requires the system operator to maintain the system frequency within certain range. To achieve the goal, ISO/RTO acquires different Ancillary Services (AS) from generators and load to perform Regulation Up/Down, Responsive Reserve, Non-Spinning Reserve, and Replacement Reserve services. Each of these methods has pros and cons, and the implementation of these methods takes from a millisecond to 30 minutes. In the group of “ancillary services” provided in the open market management of the grid, frequency regulation has the highest value. It typically takes minutes rather than seconds if the frequency regulation is provided by ramping (up and/or down) of generation assets.

Electricity storage has the capability for doing the job in milliseconds, and Pacific Northwest National Laboratory (PNNL) has suggested millisecond electricity storage should have a value of at least twice that of 20 minute assets. In ERCOT, a new category of AS, Fast Responsive Reserve, is added. Taking advantages of quick charging/discharging capability of the battery storage system, millage (receive credit on both charge and discharge) is implemented in some ISOs/RTOs such as PJM.

Regulation

Regulation is used to compensate for short-time fluctuations between generation and the demand. When the service is provided by conventional fossil-fuel based generators that adjust their power output as the demand fluctuates, these assets may operate below their designated operational constraints leading to reduced lifetime and decreased performance. In addition to reducing damage to generation assets, fast-ramp energy storage can provide regulation services with great accuracy.

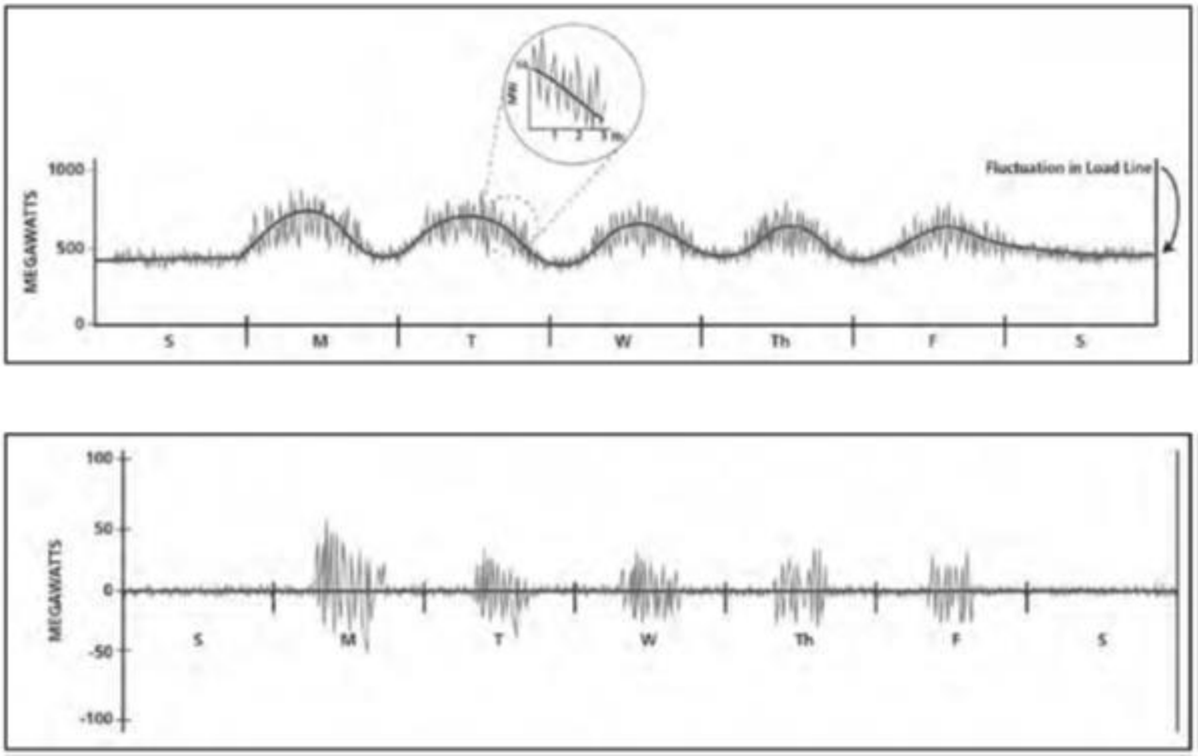


Fig. 3-3 BESS for regulation services [4]

Responsive, non-spinning and supplemental reserves

There are services of reserve capacity that can be utilized when there is a sudden deficit on the generation supply, loss of transmission/distribution lines or sudden increase of the demand that was not predicted. The service comprises generators that are synchronized to the grid but operate at no-load conditions, generators that are not connected to the grid but can respond at short notice, demand reduction services and interruptible loads and additional reserves that act as a second line reserve capacity service in the case that previous measures do not work. Storage would need to be discharged only when similar events occur typically 100-200 h per year.

Frequency response

Frequency response depends on the system's inertia or the aggregated inertial response of all synchronous generators and rotating masses connected in the power system. Primary response may include governor or demand responsive mechanisms and acts from the first seconds of the disruption. After 30 s, secondary response is initiated through the automatic generation response which is followed by the tertiary response by dispatched generators that aims to restore the system's frequency within operational limits. Energy storage systems can act very fast to frequency disruptions and can assist to achieve a smoother transition until the frequency is restored. The effectiveness of the storage systems depends on its location with respect to other system components within a specific region of the grid.

Black start services

BESS has black start capabilities that can assist in restoring normal operation of the power system after a blackout or a catastrophic failure has occurred. In this occasion, battery storage can be used to recharge power lines, startup backup diesel generators and restart power plants that have gone offline.

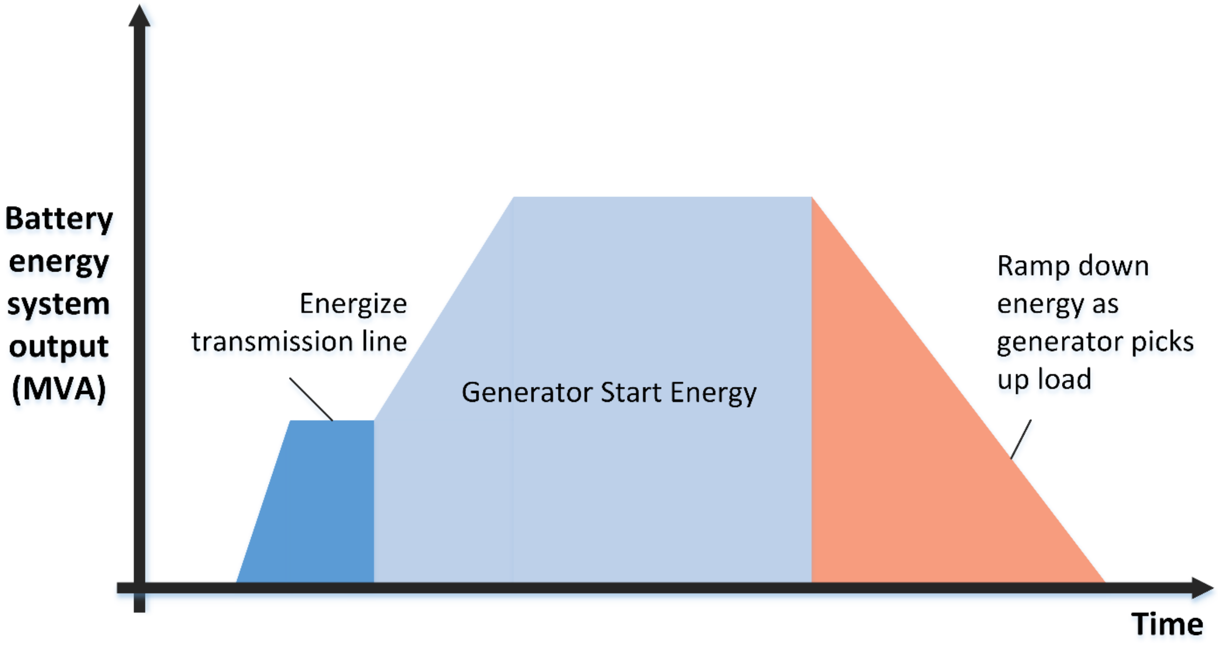


Figure 3-4 Black start service by BESS (image redrawn by [4]

Reactive Support Voltage Control (RSVC)

Batteries exchange power to the grid through high power inverters. Those inverters are capable to work in four quadrants which allow them to inject or absorb reactive power as well as active power sourced from stored energies in batteries. In some applications, the inverter rating is chosen higher than batteries to feed full power of batteries to the grid plus injecting or absorbing reactive power for supporting reactive power demand and controlling the bus voltage (RSVC).

The service provided by battery storage systems is usually required for a period of 30 min, before additional services are utilized for voltage stabilization and support.

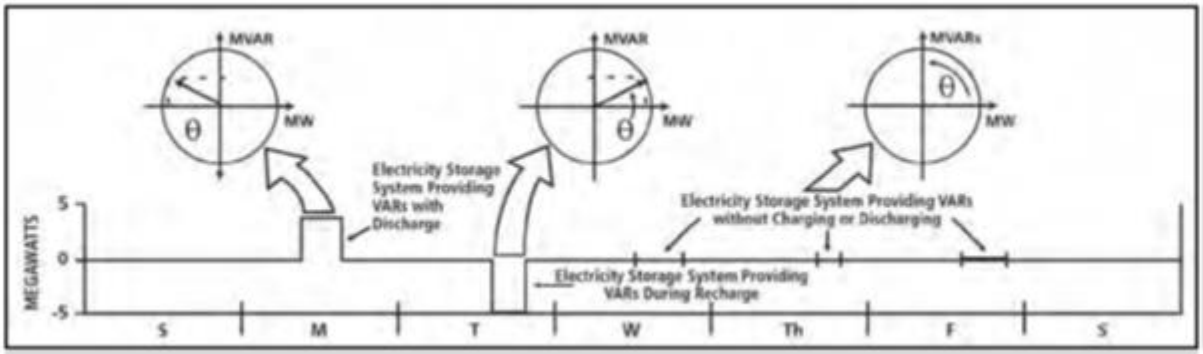


Fig. 3-5 BESS for voltage support [4]

3.2. Distribution level

In addition to large-scale implementation of Battery Energy Storage Systems at the transmission level, multiple benefits can be achieved by implementation of BESS at the distribution level. These applications are discussed in this section.

3.2.1. Current activities

The concept of community energy storage (CES) or the community UPS has captured the imagination of the growing ranks of stakeholders with interest in electricity storage (storage). CES is a good example of grid-connected and utility owned and operated distributed energy storage systems (DESS). DESSs are modular storage systems that are located at or near end-user homes and businesses. Although it is not a value proposition per se, CES embodies many attractive facets of the broader storage value proposition for the electricity grid and marketplace of the future.

Community energy storage entails utility deployment of modular, distributed energy storage systems (DESS) at or near points in the utility distribution system that are close to residential and business end users. The genesis of the CES concept was investigations by American Electric Power (AEP), starting in about 2005, to evaluate the prospects for and merits of locating advanced sodium sulfur (NaS) battery storage, rated at about two MegaWatts (MW), at substations. Eventually, AEP added a different twist on the concept involving numerous much smaller units – rated at 25 kiloWatts (kW) for three hours, or 75 kiloWatt-hours (kWh) – that are distributed and located at or near end-user sites. Recently, Oncor Electric Delivery has installed five 25kWh Li-ion battery next to its Pad-Mount transformer to improve the reliability of certain residential areas that require high service continuity. One notable advantage of using many smaller units is “unit diversity”. Because there are so many units, it is unlikely that a substantial amount of CES power will be out-of-service at any time. Said another way, at any time one or maybe a few CESs may be out-of-service. That is helpful if reliability is especially important.

3.2.2 Area of applications

3.2.2.1 Distribution upgrade deferral

BESS can be used to defer building new or reinforcing existing distribution assets such as transformers and distribution lines, by accommodating peaks that typically occur for a duration of a few hours per year. In addition to the investment deferral, BESS can have additional benefits. For example, when a new transformer is upgraded, the planning procedure needs to account for potential load growth in a 20-years' time horizon, which leads inevitably to low utilization of the distribution assets built. BESS can be transportable to other locations maximizing the value of storage investment and simultaneously minimizing the risks and uncertainties in the planning procedure.

3.2.2.2 Voltage excursion support

When placed in the distribution network, BESS can assist network operators to deal with voltage excursions caused by high RES penetration, especially at sunny/windy periods of low local demand. In residential areas, demand peak occurs typically in the early evening, while PV power production is high around noon. When the volume solar installations is high, this can lead to reverse power flows and overvoltage. DSOs respond to voltage excursions by altering the tap changers position or by utilizing capacitor banks. However, the lifetime of this voltage support equipment is reduced with usage. BESS can provide an alternative to this issue that might extend the lifetime of distribution assets.

3.2.2.3 Grid support

In Italy, energy storage systems must contribute to the improvement of the security of the National Electric Power System by providing specific grid services. In particular, grid connected systems must assure:

- Low voltage ride through function;
- Active power regulation;
- Voltage regulation.
- Voltage support in case of short-circuit (only for MV grids).

These services must be granted by the static converters connecting the batteries to the AC grid. Voltage regulation by reactive power injection can follow local control logics.

In order to drive the choice of the most suitable energy storage technology to use in a given situation for providing the above grid services, manufactures are obliged to specify in datasheets some critical parameters, such as: discharge rated power, charge rated power, discharge maximum power, charge maximum power, and useful capacity. In all cases, system behaviour must comply with specific capability curves established by two mandatory technical rules [5].

3.2.2.4 Duck curve improvement

In 2013 the California Independent System Operator (CAISO) published a net load curve representing the difference between the forecasted load and expected electricity production from variable generation sources including wind and solar. In certain times of the year, especially during spring afternoons, the curve produces a “belly” curve shape followed by a quick ramp similar to the “neck of a duck”. Fig. 3-6 shows the duck chart in a typical spring day in California.

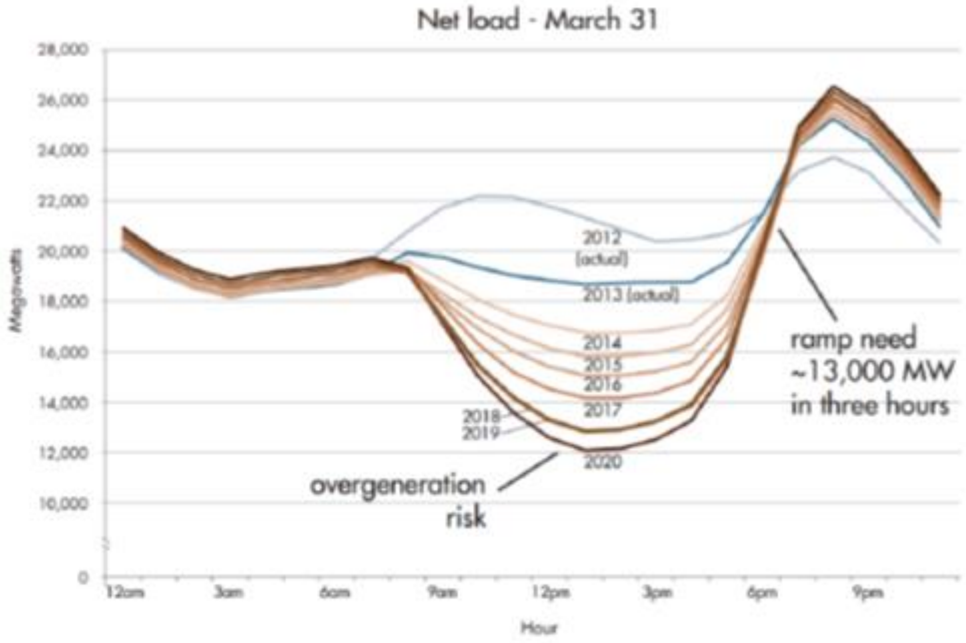


Fig. 3-6 the California Duck Curve [6]

California’s energy and environmental policy targets including 50% of retail electricity from renewable sources by 2030 and GHG reduction goal to 1990 levels, has significantly increased the capacity of installed renewables on both sides of the meter, causing the duck curve to arrive earlier than originally estimated. Similar patterns have also been observed in other countries including Austria.

California’s climate conditions i.e. sunny and cool spring days with abundant wind result in increased solar, wind and run-of-the river hydro generation, which combined with reduced demand produce the duck belly in the net load curve. Approaching the late afternoon hours, the decrease in the solar output and peak demand causes a steep ramp of almost 13,000 MW during early evening hours. The challenge is how to curtail free and green renewable energy during overgeneration periods, since during hot summer days all renewable energy including solar, wind, biomass and biogas is used and hence essential for the system.

In order to operate reliably in these conditions, the ISO requires flexible resources that insure the following:

- Balanced supply and demand to mitigate overgeneration: store energy or modify use.

- Resource flexibility: to insure upward or downward ramping flexibility for a defined period and start and stop multiple times a day as the current resources including nuclear, CHP, biomass and other resources either cannot ramp down or have binding contracts allowing them to operate at full capacity.
- Automated frequency response measures.

Energy storage is a fast acting and flexible resource that can help flatten the duck curve by:

- Reducing the net load ramp that other resources must meet.
- Reducing overgeneration because less generation is needed online.

Fig. 3-7 shows ramping capability of energy storage technologies compared to traditional slow-ramping generators.

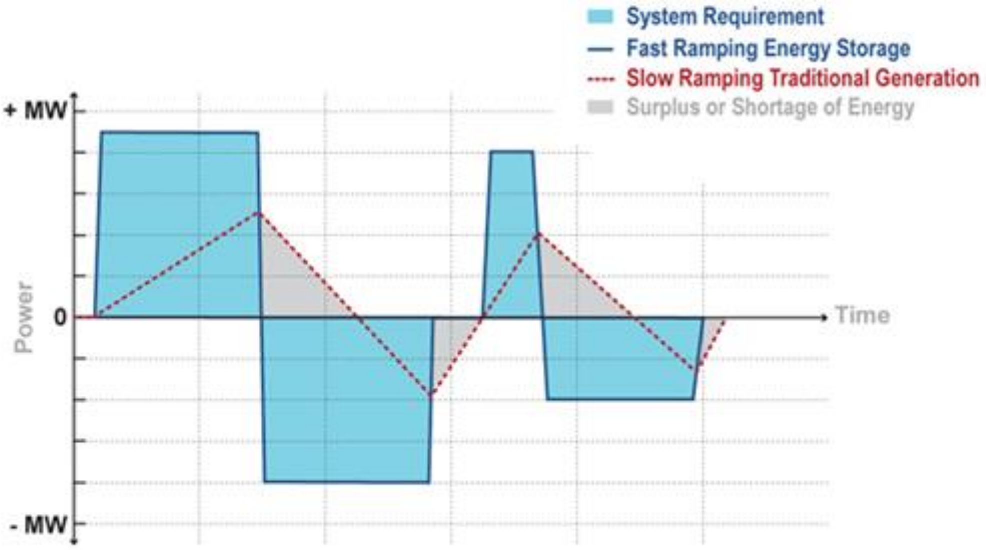


Fig. 3-7 Ramping Performance of Energy Storage vs. Traditional Generators (Source: NRSTOR)

As seen flexible energy storage technologies can provide quick response to dispatching signals with ramping rates that in some cases are hundreds of times faster than traditional generation. Additional factors that limit traditional generators to provide flexible ramping during California duck curve ramps are long start-up time and minimum run-times of these resources. Fig. 3-8 shows a ramping scenario with and without energy storage.

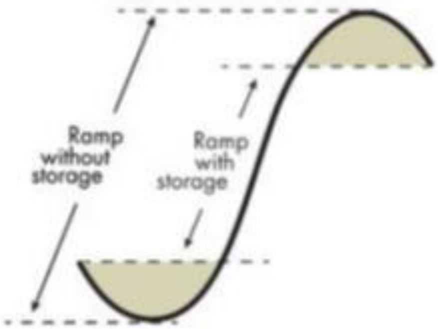


Fig. 3-8 Ramping with and without Energy Storage (Source: California ISO [7])

As battery storage charges during the low-price periods and discharges during peak hours when the price is high, it also acts as a down reserve in the system. Application of battery storage in combination with solar PV or in stand-alone utility scale form not only helps to flatten the duck belly and provide economic arbitrage, but also indirectly improves the stability margin and flexibility of the grid by allowing the thermal units to work at higher power points.

California mandates the utilities to acquire 1,325 MW of storage by 2020 and encourages behind the meter energy storage.

Current Practices

CAISO has been developing new policy and market mechanisms to support the development of flexible resources including energy storage to cope with the Duck Curve phenomena:

- Mandates the utilities to acquire 1,325 MW of energy storage by 2020 and encourages behind the meter storage technologies. The state’s storage capacity as of Sept. 2016 was 73.2 MWs.
- Encourage electric vehicle adaptation.
- California Government’s September 2016 directive to the California Public Utilities Commission to:
  - Evaluate the role of large-scale storage for integration of renewable energy
  - Urge the state’s IOUs (investor owned utilities) to invest in up to 500 MW of storage in addition to the existing 1,325 MW target [8]
  - Create an independent body to resolve storage interconnection disputes [9]
  - Increase SGIP (Self Generation Incentive Program) funding by $249 million: the revised SGIP program has a much bigger focus on energy storage, however, with eligible storage projects receiving 85% of the additional SGIP funds, with 90% going to (non-residential) projects larger than 10 kW (overall, 75% of all SGIP funds are dedicated to energy storage projects)

3.2.2.5 Microgrid/Nanogrid development

Microgrids are groupings of LV or MV distributed energy resources (DERs) and loads that work together and are connected to the grid from a single (or multiple) point of connection. A microgrid should be capable of working in the grid-connected mode as well as the islanded or autonomous mode. Different energy storage mechanisms including battery storage, flywheels, etc. have been used in microgrid applications; however due to their positive impacts on system operation (including energy management and power quality improvement) and falling costs, battery storage technologies have received greater attention. Battery storage benefits the microgrid and nanogrid by providing generation and load balance, mitigating variable nature of renewable energy systems, and unlocking additional revenues from energy arbitrage. An application of BESS is under implementation in Nova Scotia in Canada, which supports 300 households in absence of grid power as an Islanded DG. This application, guarantees quick restoration of power for selected consumer till the main supply energizes back the substation. The benefits of battery storage in microgrids is summarized in Table 3-1 [10], [11].

Table 3-1 Battery Storage Benefits at Microgrid/Nanogrid Capacity Level

Benefit	Description	Capacity and Duration
Energy Management	Daily load shifting and peak shaving for home, commercial and industrial	10s to 100s kW Hours
Power Quality	Avoiding voltage sags and power disruptions for home, commercial and industrial	10s to 100s kW Minutes
Reliability	Islanding backup during grid outages for home, commercial and industrial, UPS bridge	10s to 100 kW Hours
Distributed Energy Storage System	On utility side of meters, feeders and substations	10s to 100s kW Hours
T&D System Support	Urban and rural T&D systems upgrade deferrals. Congestion management	10s kW to 10s MW Hours
Renewable Integration	Ramp and voltage support, off-peak storage, time-shift, rapid demand support	100s kW to 10s MW Minutes to hours

Wholesale Services	Frequency regulation, ancillary services, arbitrage, spinning reserve	> MW Minutes to Hours

Battery storage system interacts with the utility grid and provides service at different levels including end-use customers, community and distribution system.

Fig. 3-9 shows the utilization of energy storage systems (including battery storage) in the microgrid sector in 2015 and 2016.

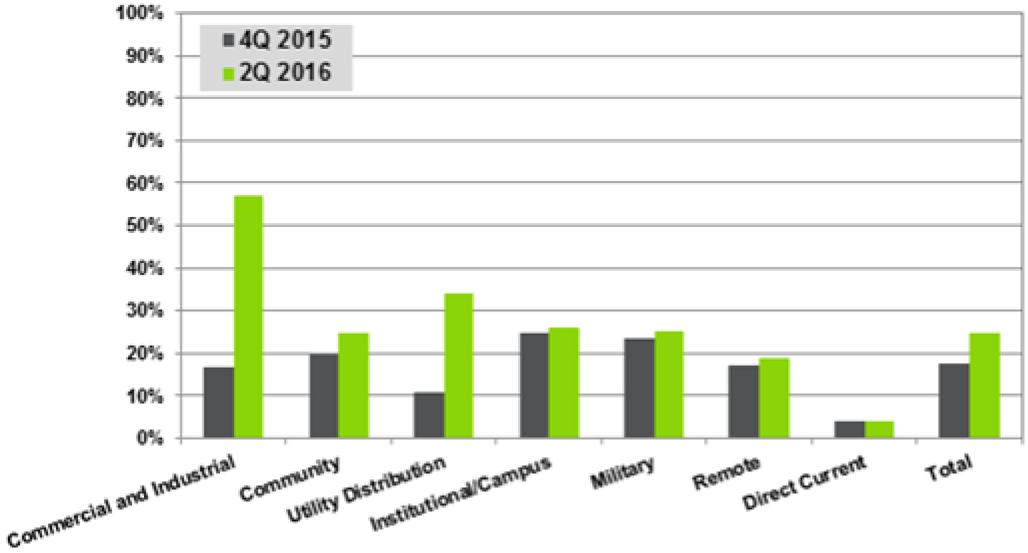


Fig. 3-9 Energy Storage System Utilization by Microgrid Segment, World Markets: 4Q 2015 and 2Q 2016 [12]

<u>Battery technologies for Microgrid/Nanogrid applications</u>

Depending on the capacity and applications, different battery storage technologies that can be used in microgrid/nanogrid applications include Lithium-Ion (Li-ion) batteries, Lead-Acid, flow batteries, etc.

Table 3-2 shows a comparison between the most common battery storage technologies that can be implemented in microgrid/nanogrid applications.

Table 3-2 Battery Storage Technologies for Microgrid/Nanogrid Applications

Technology	Benefits	Drawback	Applications

Sodium Sulfur (NaS)	High energy and power density High round-trip efficiency Long life cycle Fast discharge capability No self-discharge	Safety concerns due to high working temperature	Energy management Power quality improvement
Vanadium Redox Flow Batteries (VRB)	No energy to power ratio constraints High life cycle which does not depend of Depth of Discharge (DoD) Adjustable power rating Limited self-discharge Rapid response time	Poor energy-to-volume ratio Heavyweight	Energy management Power quality Ideal for solar-storage combination due to no DoD limits
Lead Acid (PbA)	High maturity Low cost High efficiency	Low power and energy density Low reliability Low cycle life	Power and energy applications In use in some off-grid microgrids
Lithium-Ion (Li-ion)	Very high efficiency Very high energy density High cycle life High DoD capability Fast response time Resilience to irregular discharging	Relatively expensive (cost going down rapidly) Lower energy to power ratio	Power applications Energy applications Residential microgrids

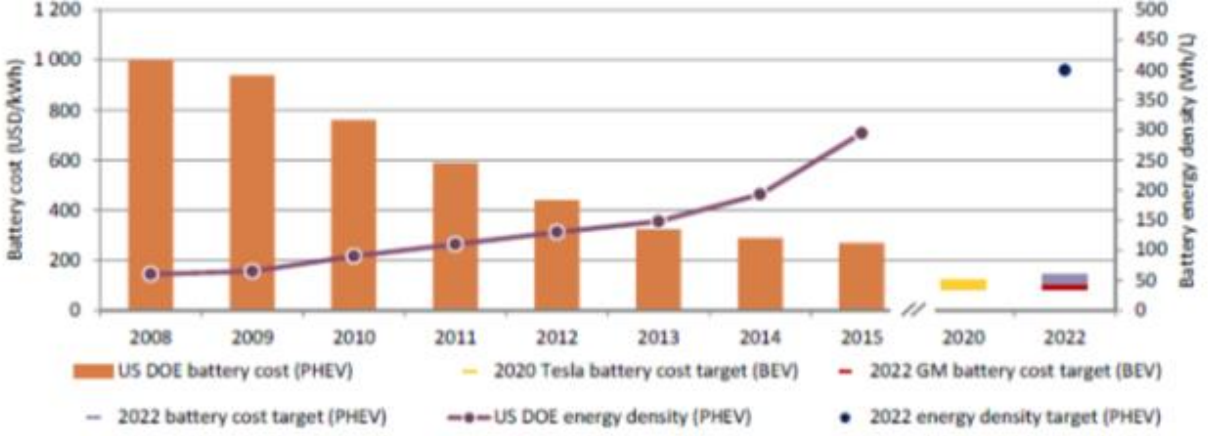
3.2.2.6 EV battery and charging station

According to IEA (International Energy Agency) Global EV Outlook 2016 [13], 1.26 million electric cars were added to the global vehicle fleet in 2015, and from this number 80% of in-use EVs are in United States, China, Japan, the Netherlands and Norway.

Major factors that impact the commercialization growth of Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV) include:

- Cost per kilowatt-hour of battery packs which has been cut by a factor four (4) since 2008
- Battery energy density improvement to allow longer ranges
- EV charging technology and infrastructure

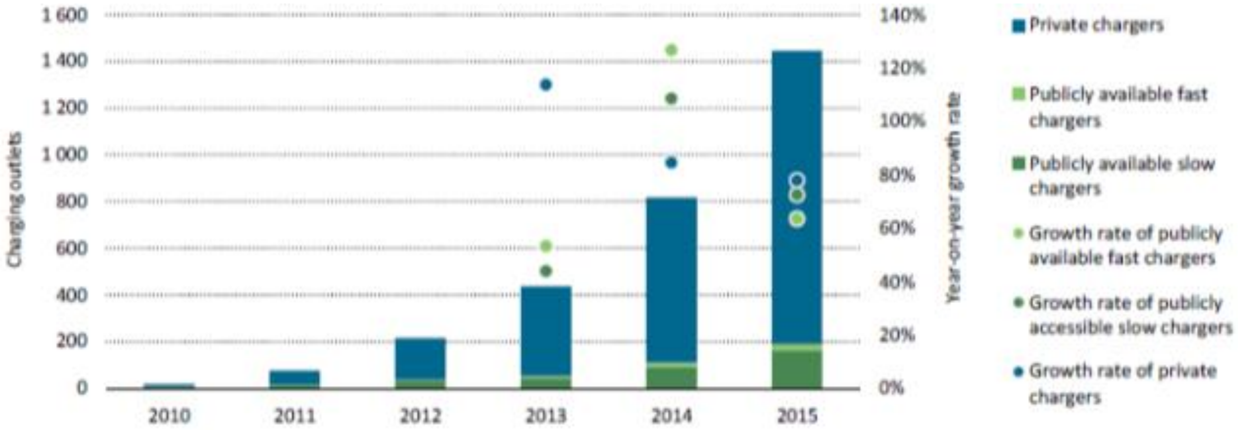
Fig. 3-10 shows the evolution and projection of battery energy density and cost from 2008 to 2022.



Notes: USD/kWh = United States dollars per kilowatt-hour; Wh/L = watt-hours per litre. PHEV battery cost and energy density data shown here are based on an observed industry-wide trend, include useful energy only, refer to battery packs and suppose an annual battery production of 100 000 units for each manufacturer.

Fig. 3-10 Battery Energy Density and Cost [13]

Fig. 3-11 shows available global EV charging stations (public and private Electric Vehicle Supply Equipment or EVSE) which reached 1.15 million in 2015.



Note: Private chargers are estimated assuming that each EV is coupled with a private charger.

Fig. 3-11 Global EV Charging Outlets [13]

EV Battery Technologies

The most popular technologies used in EV batteries include:

- Lithium-Ion: the most common battery type in EVs in 2015 due to its light weight, good power density, and high charge/discharge efficiency. Used in Tesla model S and X, Nissan Leaf, BMW i3, and other cars [14].
- Lead-Acid: common EV batteries in the past due to mature technology, and low cost.
- Solid state batteries: Solid state design replaces the flammable liquid electrolyte in Lithium Ion type. These battery types are already in use by BlueCars (Bolloré BlueCar), developed for a car-sharing service company in France [15]. Other car manufacturers such as Hyundai [16], Toyota and Volkswagen have also started developing solid state battery technologies for EVs [17], [18].
- Metal-Air: consist of metal anode (aluminum, iron, lithium, magnesium, vanadium, and zinc have been discussed) and ambient air (oxygen) cathode which significantly reduces the battery weight. The battery manufacturer Phinergy claimed to have built an Aluminum-Air battery that lasts 3,000 km per charge [19]. Electric car manufacturer Tesla has been recently looking into hybrid lithium-ion/metal-air batteries to power electric vehicles [20]. The main drawback of these batteries is the need to replace the battery instead of simply recharging.
- Aluminum Ion: similar to Li-ion batteries but using Al as anode.
- Lithium-Sulfur: typically have Lithium anode and Sulfur-Carbon cathode.

Table 3-3 Different EV Battery Technologies

Battery Type	Benefits	Drawbacks	Car Brands

Lithium-Ion	Light weight High energy density Good power density High charge/discharge efficiency New models have lower power density and higher safety and very long lifespan	Liquid electrolyte leak Fire hazard and safety concerns Short cycle life Degradation with age	Most used in EVs including: Tesla, BMW, Nissan, Kia, Chevrolet, etc.
Solid State	High power to weight ratio No electrolyte leaks or fire hazard Minimized self-discharge rate Extended lifetime Reduced cooling requirement Extended temperature range	Low power density due to high current limitations of solid material	Blue Cars, Hyundai, Toyota, Volkswagen
Lead Acid	Mature technology Low cost Highly available	Low energy density Low efficiency Temperature sensitivity of efficiency and capacity	EV1, RAV4 EV
Metal Air	Very high energy density Very high range Low weight	Limited cyclability Limited lifetime Not rechargeable via plugging-in	Experimental
Aluminum Ion	Higher safety (compared to Li-ion) Lower cost	Low cycle life (under improvement)	Experimental

Lithium Sulfur	Higher energy density Lower cost	Low cycle life due to reactions with the electrolyte	Experimental

As a highly dynamic and quick source of energy, BESSs (Battery Energy Storage Systems) are required to be studied for possible impacts while connecting to utility feeder as follows [21, 22, 23]:

1. Study of charge/discharge ramp rates
2. Study of flicker
3. Ensuring of 4 quadrant operation capability
4. Steady state voltage under the feeder light and peak loading conditions
5. Distribution system equipment thermal loading, identifying any equipment to be upgraded
6. Anti-Islanding operation and protection
7. Fault current contribution and relay coordination
8. Energization and sudden trip
9. Surge arrester rating
10. Need for transfer trip

Currently most of utilities require performing comprehensive study, called DCIA (Detailed Connection Impact Assessment) for BESS projects to ensure having less problems to utilize the energy storage system or prepare substation by upgrading some equipment ratings for the constant and safe operation of the BESS. Currently, DCIA becomes serious requirement of battery energy storage projects in North America.

3.3. Residential level

When used at the residential level, battery energy storage systems can provide several benefits including:

- **Load Shifting**: the cost of grid electricity and Time of Use rates are two major drivers for application of residential battery storage for energy management purposes. If used in parallel with the grid, batteries can charge during off-peak hours and discharge during peak hours to provide load shifting and subsequent economic benefits to residential customers.
- **Reliability and Resilience**: battery storage can act as backup energy provider for home-owners during planned and unplanned grid outages.
- **Coupling with Renewable Energy Systems**: home battery storage can be coupled with roof-top solar PV to cope with intermittent nature of solar power and maximize the self-consumption. Installing batteries allows charging during day-time when solar energy is abundant and probably on-site generation more than consumption and using the stored energy during peak load period.

GTM Research predicts that behind the meter storage segment in U.S. will grow from a 20% share of the annual storage market in 2016 to 52% in 2022 [24]. Fig. 3-12 shows GTM Research's projection of U.S. energy storage deployment by sector between 2013 and 2016. Among different technologies, the residential sector is dominated by battery storage and specifically Li-ion technology.

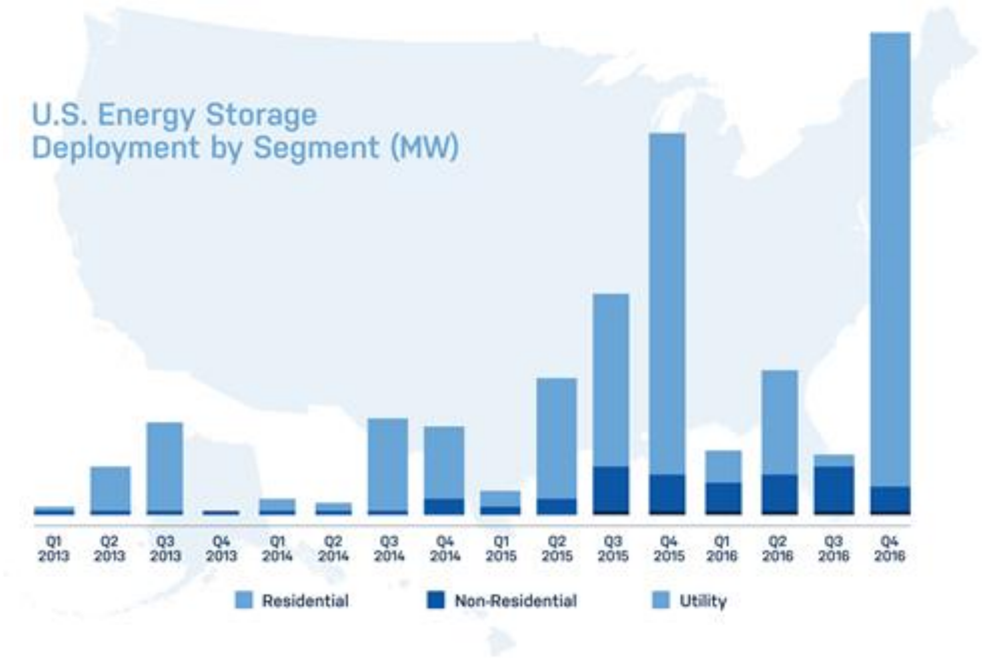


Fig. 3-12 U.S. Energy Storage Deployment by Sector in 2013-2016 [25]

In addition, storage devices in Smart Homes and EVs can provide flexibility behind the meter and offer grid services through demand side management and demand response schemes. Consumers can obtain greater control of their own energy use and reduce their energy bills, while utility companies can benefit from the flexibility services offered by end-consumers. Storage can play a vital role in achieving a more flexible and smarter energy system. It can be a critical enabler for the decentralization of the system and new business models, such as P2P energy trading between prosumers and consumers.

<u>Battery technologies for residential applications</u>

Due to specific application of home battery storage, i.e. multiple daily cycles especially when paired with solar PV, the battery technology must have a high cycle life. Due to declining cost, high cycling capability, and charge and discharge efficiency Li-ion batteries are the most popular choice in the residential battery storage market at the moment, however deep cycle Lead-Acid and flow batteries are also being used in residential applications.

The number of vendor and developer companies in residential battery storage is increasing rapidly, however Tesla and Sunverge are among the leading vendors. Other companies such as

LG Chem, Panasonic, Samsung and Mercedes Benz are also entering this market. Table 3-4 shows the specifications of the most popular technologies currently available in the market. Data is collected from different manufacturers’ websites.

Table 3-4 Home Battery Storage Technologies

Vendor	Technology	Specifications	Applications
Tesla	Li-ion	13.5 kWh 7 kWp DC and AC system 91.8% and 89% roundtrip efficiency 1150mmx755mm*155mm 125 kg	Capable of coupling with solar PV Solar self-consumption Time of use load shifting Backup Off grid Mobile app automatic management
Sunverge	Li-ion	7.7 kWh, 11.6 kWh, 15.5 kWh & 19.4 kWh 6 kWp and 7 kWp DC and AC coupled 92.5% and 93% CEC weighted efficiency for 6kWp and 7 kWp 1920mmx860mmx360mm 272 kg to 403 kg	Capable of coupling with solar PV Solar self-consumption Energy management Backup power Virtual power plant Cloud-based mobile software platform Dedicated connections for solar and critical load panels included in the AC system

LG Chem	Li-ion	5 models 3.3 kWh to 19.6 kWh In 48 V and 400 V packs 95% DC round trip efficiency Inverter not included Dimensions variable depending on capacity 31 kg to 99.8 kg	Capable of coupling with solar PV Energy management Self-consumption Backup power
LG ESS	Li Polymer	6.4 kWh 5 kWp (AC) 95.7% max system efficiency DC coupled PCS: 670mmx493mmx185mm Battery: 682mmx408mmx180mm PCS weight: 34 kg Battery weight: 58 kg	Available in Germany PV self-consumption Smart energy management system with 7inch touchscreen display Web monitoring with PC, tablet or smart phone Three-phase connection
Panasonic	Li-ion	8 kWh and 5.3 kWh 2 kW Built-in inverter 93% max inverter efficiency 1380mmx966mmx279mm 84 kg	Capable of coupling with solar PV Energy solutions Maximize self-consumption Programmed charge/discharge Back-up Charge/discharge remote control

Samsung SDI	Li-ion	1 kWh and 4.8 kWh battery module Scalable up to 16 and 188 kWh Inverter not included 8 kg and 37 kg per module Dimensions variable depending on capacity	Capable of coupling with solar PV Energy solutions Backup
Sunrun	Li-ion	LG Chem batteries combined with Sunrun solar PV	PV self-consumption Backup power Energy optimization

3.4. Transportation

The environmental issues, the economic situations, and energy security have reshaped the way people think about energy. Looking for the alternative energy sources that are both sustainable and clean will be substantial and fundamental for the generations to come.

On the environment side, as the evidence of climate change is getting more and more apparent, it becomes a global consent that actions must be taken to curbing greenhouse gas emission. According to the report from Energy Information Administration (Fig. 3-13), the transportation sector alone takes up to 33.1 percent of all energy-related emissions and is the largest producer of carbon dioxide emission in US. This presents the urgent needs for the transportation sector in the U.S. to act on emissions abatement.

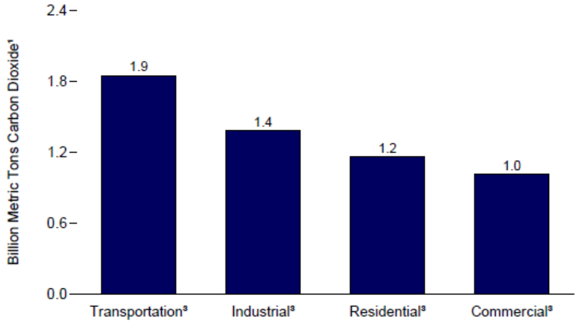


Fig. 3-13 U.S. energy-related Carbon Dioxide Emission by End User, 2009

To promote the deployment and public acceptance of PEV, it is necessary to reduce/eliminate the range anxiety of PEV users. A well-planned fast (Level 3) charging infrastructure plays an important role for PEV penetration. Therefore, one should consider the EV charging infrastructure from the regional point of view. In addition, it is desired to integrate renewable energy sources including wind and solar energy with electricity from power grid into PEV charging station for sustainable future development.

The PEV charging station with distributed energy storage system can also participate in deregulated market. Since the wholesale price of the electricity shows considerably volatility in the deregulated market, accuracy of market price prediction is one of the most important tasks to maximize the profit of the charging station.

Regional EV charging station system [26, 27]

The EV fast charging station is necessary for EV adoption. To avoid the negative impact on the distribution network and fully utilize the renewable energy, it should equip with distributed energy storage system that uses solar, wind energy, and electricity from power grid to simultaneously charge multiple EVs. The participation of this PEV charging station system in the deregulated market highlights the benefit of wind and solar energy as well as distributed energy storage system with the optimal operational strategies. However, the operation charging station should be determined from the regional point of view (Virtual Power Plant (VPP)) to achieve global optimization. Hence, the conceptual regional PEV charging station system is shown in Fig. 3-14 and overall regional with centralized control is shown in Fig. 3-15. To improve the renewable energy utilization, the PEV charging station can serve as source of flexibility by changing the charging rate to compensate the source of variability from the renewable energy.

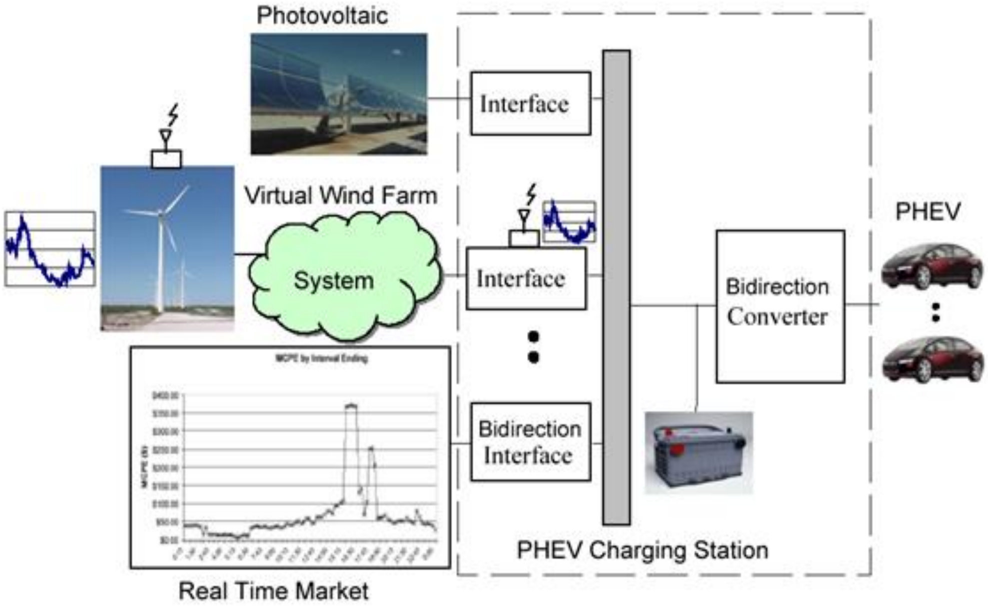


Fig. 3-14 PEV Charging Station

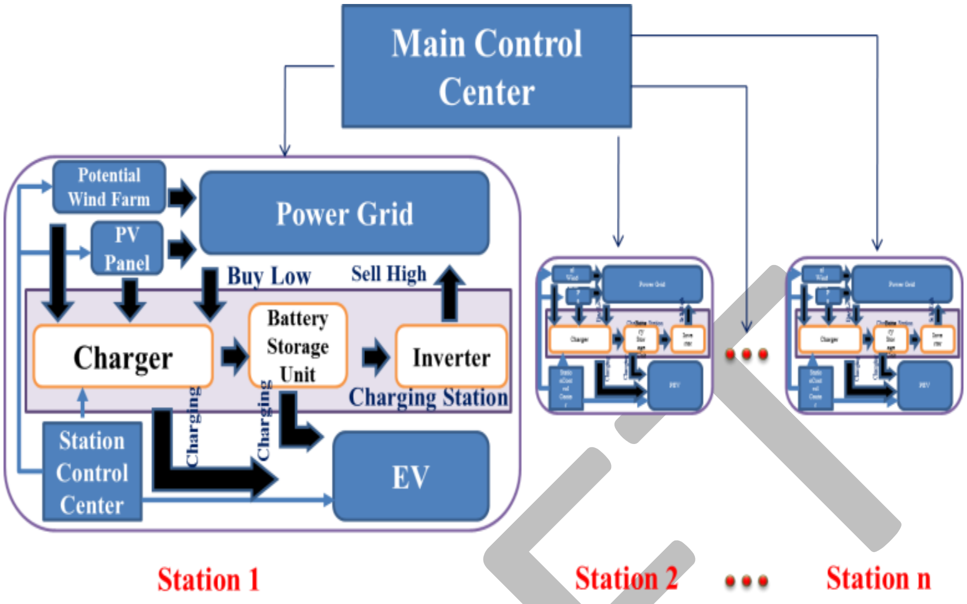


Fig. 3-15 Configuration of PEV Charging Infrastructure

Wayside Rail Energy Storage

Light rail and trolleys generally operate at voltages between 600-1500V DC, and these system voltages are derived from the available grid power. Grid power is susceptible to changes and fluctuations based on overall load on the system. As an example, if multiple train lines are running and stopping and starting simultaneously, the grid voltage could drop sufficiently to affect the performance of the train or tram. Ultracapacitor energy storage systems are deployed to mitigate the effects of grid system overload by rapidly accepting rail braking energy, and then discharging to support train acceleration out of the station.

Automotive Start Stop

Start/stop technology enables the engine in a conventional, electric or hybrid-electric vehicle to shut down when it comes to a stop at a red light or while sitting in traffic. The system is based on an intelligent combination of engine, brake and power management. Given that this application requires instantaneous response and high cycling, ultracapacitors are commonly deployed and have been deployed in over 1 million start/stop vehicles to support the restart of the engine during a start/stop event.

Hybrid Bus

Mass transit buses are now able to reduce emissions by as much as 75% using hybrid-electric propulsion systems. Ultracapacitors are often deployed in urban diesel and hybrid electric busses as the energy storage component in the regenerative braking system to rapidly store kinetic energy from braking, and release for propulsion.

Onboard Rail

Ultracapacitors and BESS can be deployed on-board in the same manner they are deployed at a wayside station, in this instance to reduce energy consumption during transit or eliminate the need of catenary lines in some sections that installing OCL (Overhead Catenary Lines) is difficult or expose hazard to surrounding area. Additionally, ultracapacitors and BESS can be being used to provide locomotive engine starting, and assisted starting (battery and ultracapacitor combined system) as a mechanism to eliminate large batteries, or in some cases, to extend the life of the large batteries historically used in locomotive engine starting applications.

Offshore Vessel with BESS

On-board batteries are the way of the future. Energy storage is the right approach to make energy systems on board ships more intelligent and efficient. Energy storage systems can be especially beneficial on vessels with a widely fluctuating fuel consumption profile.

Nidec ASI, retrofitted a Norwegian ship, the Viking Queen (a 6,000 tonne vessel built in 2008), with a battery energy storage system to help reduce fuel consumption and emissions for greener, more efficient power supply [28].

Eidesvik Offshore is a Norwegian ship company that specializes in offshore logistics, seismic and underwater operations. With two dozen ships in its fleet, the environmentally sensitive company has a keen interest in finding ways to reduce fuel consumption, emissions and maintenance costs. For The Viking Queen, one of its offshore support vessels, Eidesvik sought an energy storage solution that would help it achieve these goals.

To improve the energy efficiency, Eidesvik made the decision to retrofit the Viking Queen with a BESS, making it the first operating offshore vessel to benefit from such a system. Provided by Nidec ASI, the 650kWh, 1600kW containerized solution was custom-designed to match the vessel's operating profile.

The use of battery storage reduces the vessel's fuel consumption by approximately 18%. The BESS also makes it possible for Viking Queen to reduce nitrogen oxide, carbon dioxide and other greenhouse gas emissions by approximately 25%.

The project has demonstrated that the battery configuration can help manage energy use. For instance, when the ship has different loads, it normally has two generator sets running at low load settings. When a heavier-than-usual power load is required, a second generator is needed to quickly provide additional power. By adding a battery, it's possible to operate on just one generator set by allowing the battery to take the surge. The primary generator is then run at a higher, more efficient load. Different settings are also needed when in transit or using dynamic positioning. Here batteries replace the motor, alternating between running the generator set at much higher load to power the ship and recharge the battery. The ship can also run for an extended time on batteries only, useful for entering into harbours.

Fig 3-16 Offshore vessel with BESS

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4. Potential Solutions to the Energy Storage issues

4.1. Introduction

In this chapter, we discuss the application of the energy storage units as a solution to some of the power issuers in different generation, transmission, and distribution systems:

4.2. Generation

Conventional (fossil fuel based) plants mostly rely on battery storage units for the emergency power. They use either batteries or flywheel type of energy storage units to obtain power once part of their generation system is down. Both of these technologies are utilized in UPS systems. This takes us to the discussion of different type of UPS systems. Not to mention a generation unit needs additional back-up units if a long term shut down becomes necessary. There are two type of UPS systems, that is, static, and rotary UPS. Static UPS utilizes batteries to fill the gap between the time the main power source is out till the diesel (other sources) come online. Rotary UPS systems rely on flywheel technology to fill the gap between when the main power source is out until other sources come online. There are many differences between these two types of technology. There are also some manufacturers of flywheels, who offer their devices to increase the stability of the grid. That is, those devices will be spinning offline, and they will come online once there is a drop in the frequency. These devices need to be closely monitored to inject or absorb "real" power if the frequency decreases or increases. All these devices can be used with renewables, as well. The difference, though, is renewables such as wind, and solar don't normally have the large inertia that conventional power plants do. Generators have a large moment of inertia due to the rotor, and stator mass. Wind turbines lack that element, and solar is even worse due to going through a full inverter. Below we will look at some renewable energy sources, and how energy storage units can be integrated with them.

4.2.1 Renewable Energy Storage Units

This portion comes from the NREL report titled "The Role of Energy Storage with Renewable Electricity" in Jan 2010:

Renewable energy sources, such as wind and solar, have vast potential to reduce dependence on fossil fuels and greenhouse gas emissions in the electric sector. Climate change concerns, state initiatives including renewable portfolio standards, and consumer efforts are resulting in increased deployments of both technologies. Both solar photovoltaics (PV) and wind energy have variable and uncertain (sometimes referred to as "intermittent") [1] To determine the potential role of storage in the grid of the future, it is important to examine the technical and economic impacts of variable renewable energy sources. Renewable energy resources are sometimes used for peak shaving purposes. That is, utilizing them for the situations, where the consumption exceeds the predicted generation, hence normal generation units won't be able to meet the grid demand.

If renewables such as wind, solar, etc… are utilized as a primary source of electricity, they most often are controlled through the voltage, and frequency of the grid at the point of common coupling. That is, there should be mechanisms to control the reactive or active power generation so regulate the P, and Q in the system. In case of the drop of the frequency we need a source of energy storage. Battery storage units can be one viable option to meet this demand. There are response time, stability, power regulation, and other parameters involved, which the energy storage needs to meet.

NREL report titled "The Role of Energy Storage with Renewable Electricity" in Jan 2010:

"The challenges associated with meeting the variation in demand while providing reliable services has motivated historical development of energy storage. While a number of pumped hydro storage (PHS) plants were built in the United States before 1970, significant interest, research, and funding for new storage technologies began in the early 1970s, associated with dramatic increases in oil prices"

For wind applications, FERC order 661 or IEEE 1547 lays out the rules in terms of voltage, and frequency regulations. This will then translate to the requirements for an energy storage unit and its response time when it needs to come online. The demand from the industry is push the battery energy storage units to be more compact, capable of dispatching large amounts of energy in a very small amount of time. In this area, they can be competing with other technologies such as rotating flywheels.

4.3. Transmission

Transmission systems will utilize energy storage units in terms of all different power factor or reactive power compensators. FACTS (Flexible AC Transmission Systems) are good example of energy storage units application. These devices mostly regulate the voltage magnitude, which means they are directly dependent on the storage units. However, most of them are capable of injecting or absorbing active power, if necessary. STATCOM, and SVC's are good examples of such devices.

Another important aspect to consider is the impact of the installation of battery storage units on the long-term transmission expansion planning [2].

Indeed, the fulfilment of COP21 targets by 2020 will lead to the rise of new RES-based generation plants in EU, US and China. New transmission lines will be built in order to deliver the new installed capacity to the load centres, as demonstrated by the most recent grid expansion plans worldwide [3]-[4].

A very significant limit to the implementation of the above-mentioned plans is the delay in the authorization and construction of new lines that, often, causes also a delay in the connection of new plants to the transmission grid.

Battery storage systems coupled with wind or PV plants and suitably operated can be used for peak shaving actions, reducing the power injection and, consequently, the power flows on the existing transmission lines. This is particularly advantageous in areas characterized by old lines with low transmission capacity or by low load density.

Therefore, the installation of battery units offers the possibility of deferring in time the construction of new lines, maintaining the power flow on the existing lines below a desired value with the following main advantages:

- usually a reduction of energy losses in lines and transformers;
- reduction of the maximum voltage drop (corresponding to the circulation of the current due to the peak of production);
- increase of the lifetime of the conductors (due to the reduction of the maximum current flowing in the line) [5].

The same advantages can be achieved installing battery storage systems in strategic buses of the transmission grid.

For this reasons, future research on transmission grid planning should include the study of the possible contribution from storage. In this case, the optimal sizing and siting problem and the optimal management problem for battery storage systems must be formulated and solved. The problems can be mathematically expressed as multi-objective optimization problems, considering both technical and economical functions and constraints, such as:

- the overall cost of new lines and storage facilities;
- the energy losses in lines and transformers;
- the voltage profile in the grid;
- the battery total installed capacity;
- the maximum number of charge/discharge cycles in a period, etc.

4.4. Distribution

Distribution systems will utilize energy storage for Demand Response programs both in AC and in DC microgrids [6]-[7]. Electric storage can be designed and managed for providing various grid services.

At distribution grid, electric storage systems can be used for facing some serious issues due to the increasing of load demand and to high levels of DG penetration. Indeed, batteries can be sized, located and operated in order to:

- Mitigate DG production variability. In this case, batteries are connected to generation buses or in substations where inversion of real power flow may occur;
- Mitigate load variability. In this case, batteries are connected close to the load that show the most significant variability during the day, usually at MV level;
- Reduce voltage drops and provide a more uniform grid voltage profile. In this case, batteries are connected to buses characterized by the lowest voltage values.

The installation of battery units connected to the LV grid, as in rural areas, will favour the installation of DG units, whose operation is often limited during peak production periods by the unsuitableness of the lines.

The above applications of electric storage systems require an in-depth knowledge of the distribution grid and of its specific problems and, for a coordinated operation of the battery units, need the realization of a suitable monitoring and control system **Error! Reference source**

not found.. Often, new connections between existing buses must be realized for avoiding power losses increases, due to the batteries management.

In the same way as in transmission networks applications, research studies on electric storage systems application in distribution grid are looking at the definition of suitable optimization algorithm for optimal design and management of batteries.

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5. Electrochemical energy storage and safety

5.1. Introduction

The need for and benefits of enhanced energy storage and especially enhanced electrochemical energy storage to enable better utilization of grid resources have been discussed in the previous chapters. This chapter addresses the potential safety issues associated with large scale energy storage. Unintended release of the stored energy can be hazardous. For this, it is vital to note that the quantities of energy involved in grid applications are significant. The energy stored in a 1 MW-hr system is of the same approximate magnitude as 1000 kg of typical fuels (i.e. gasoline or diesel); this is based on an energy content of 44 MJ/kg of fuels and a conversion efficiency of 80%. Because grid scale storage systems are held to high safety standards, incidents are infrequent and the broader community is not often familiar with the potential consequences of system failures, though they do occur; several recent incidents with grid-scale storage facilities include [1-3]. It is important to note that this is not unique to electrochemical energy storage, and failures associated with pumped hydroelectric [4] or flywheel systems can still occur.

We divide this chapter into several sections, addressing first reliability and aging of cells as it relates to safety, then several sections addressing the hazards associated with the actual energy storage with an emphasis on lithium-ion systems that have the greatest need for mitigation, then the potential arcing hazard of DC systems and then the safety of power conversion systems.

5.2. Reliability and aging

Cell cycling leads to volumetric variations in cell components that put mechanical strain on electrodes, potentially leading to internal detachment of particles from the matrix. In many cases, this limits the number of phase transitions that can be used and reduces capacity below theoretical capacities. The SEI layer in lithium ion cells is an example of a side reaction occurring in the early stages of cell operation. A stable SEI layer is required for operational stability since the normal operating voltages lead to degradation of the electrolyte by the charged negative electrode. Ethylene carbonate is a typical electrolyte component that has been associated with SEI formation, and vinyl-carbonate has been identified as a slightly more reactive trace additive that helps form stable SEI layers. Poor SEI formation can lead to excessive SEI layer growth and impedance; lithium plating can occur over the top of excessive SEI layer growth [5].

Lithium plating can also occur at very low temperatures, and this provides a lower limit to lithium-cell operation temperatures along with limits on electrolyte phase change.

Lithium-ion cathodes are also reactive enough to oxidize the electrolyte at operating voltages and at elevated temperatures some products of the alkyl-carbonate electrolyte oxidation have been detected. This and the decomposition of the SEI layer at higher temperatures places upper limits on operating temperatures for lithium-ion cells, often in the vicinity of 60 C. Some cathode materials are also subject to undesirable phase change in the charged state that can lead to capacity loss; this is true of layered metal oxide cathodes of the class $LiMO_2$, the most commonly employed cathodes in current lithium-ion systems. Metal dissolution from the cathode into the electrolyte is also possible with dissolved metals likely reacting in the electrolyte to form passivating metal salts that might increase impedance [6].

In general, all of these side reactions lead to reduced cell capacity and increased cell impedance.

5.3. Effects of scale

Because of the susceptibility of batteries to degradation by overheating, the heat generated during cycling is a concern. For high power battery systems, the requirement to remove heat generated can be significant. Cooling removes heat from the exterior of the system or wherever cooling is installed. For large energy storage systems, the effective distance between heat generation and cooling might be significant. For example, if the volumetric power generated internally to be dissipated (i.e. Joule heating per volume) is $\dot{q}$ and the characteristic length to the surface where heat is dissipated is *l*, the effective thermal conductivity within the system is λ and the effective heat transfer coefficient between the battery pack and the cooling system or surrounding air is *h*, then the approximate temperature rise within the system is estimated as $(\Delta T_i) \approx \dot{q}l^2/\lambda,$ and the approximate temperature rise between the side of the cell and the cooling system is $(\Delta T_\infty) \approx \dot{q}l/h.$ These temperature increments are additive, and in both cases as the length scale of the system increases the temperature increment will increase.

5.4. Lithium-ion systems

5.4.1 Risks associated with batteries

Electrochemical energy storage is a safety concern because the technology is evolving rapidly at the same time applications are growing rapidly. The issue is primarily related to the increased energy density and reactivity of recent technologies, in particular lithium and sodium-based technologies, and a lack of familiarity with the changing hazards associated with evolving technologies. This is particularly true of lithium-ion cells [7], and the majority of recent work addresses these systems.

With their relatively high energy density, lithium-ion batteries are highly desirable for energy storage, but this brings challenges. First, the voltage window over which lithium operates is such that aqueous electrolytes are infeasible and alkyl carbonate electrolytes are the norm. Even with these electrolytes, passivation layers are required to reduce reactivity under normal operating conditions, and at elevated temperatures the electrolyte reacts exothermically with both the anode and cathode. Second, the energy density is high enough that the sudden release of the stored energy can bring the battery system up to temperatures where these reactions are dangerous, leading to thermal runaway. Finally, the electrolytes are flammable in air and this can lead to dramatic fires when electrolyte venting during thermal runaway is ignited.

While thermal runaway is a concern in most lithium ion batteries, there is a significant impact from the specific cathode chemistry used by the batteries. Fig. 5-1 shows Accelerating

Rate Calorimetry (ARC) data that compares the thermal runaway events of various cathode chemistries. This shows how higher chemistry cathode materials like $LiCoO_2$ have more significant runaway events compared to more stable materials like $LiFePO_4$ (LFP). However, there is also a price paid in energy density of these materials as well.

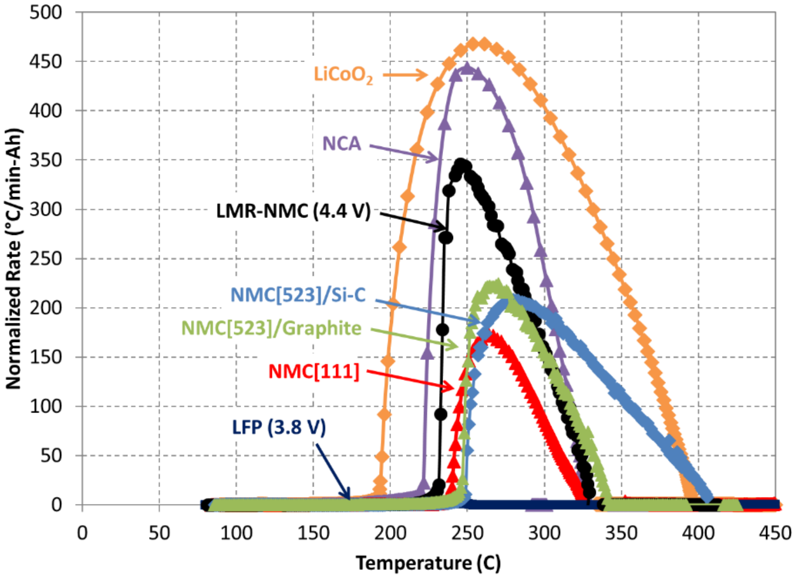


Fig. 5-1 Comparison of normalized thermal runaway curves comparing various li-ion chemistries collected using Accelerating Rate Calorimetery

While individual cell reliability is very high, generally exceeding six-sigma quality levels, the assembly of a large number of cells into module, packs and systems to provide large scale storage provides a situation where the probability of a single failure is non-negligible. With the value of system-scale investments being significant, it is important to design systems to detect incipient failure early and to be robust against these single point failures increases.

A challenge in system design exists because small variations in batteries across a coupled system can be exacerbated through operation. A cell that has an initial reduced capacity due to some variation may cycle at a deeper effective depth of discharge if it is connected to a single battery management system. Since other cells in the pack can take up small differences during cycling, it is difficult for the BMS to detect these variations. Operating at higher depths of discharge tends to accelerate cell aging, leading to a faster capacity loss. When this occurs, the cells become progressively imbalanced in their capacity. This can lead to overcharging or over discharging of cells that can lead to failure of individual cells.

5.4.2 Classification of failures

Field failures of lithium ion batteries have been well documented due to their prolific use in consumer electronic devices. Catastrophic failures of lithium ion batteries most dramatically entered the public eye in 2006 when incidents of laptop battery fires led to a widespread and costly recall, however even by that point the potential issues surrounding lithium ion batteries were known and anecdotal evidence abounded concerning the overheating of small cell phone batteries. Because of this, safety testing has traditionally focused on the response of small single cells, with the greatest concern being the potential outcome of a spontaneous field failure.

Abusive failures, in contrast to field failures, happen not during normal operation of a cell or battery, but due to the application of conditions outside the normal operating range of the battery. These can come from a variety of sources, but can generally be categorized into electrical, thermal and mechanical abusive conditions. Examples of abusive conditions can include (but are not limited to) an external short circuit, overcharge or overvoltage of a cell, overheating of a cell, and mechanical crushing. Multiple test procedures have been developed to characterize how cells and batteries might respond to abusive conditions. [8-11]

Historically battery abuse testing results for lithium ion batteries have been looked at somewhat skeptically, reasoning that in small consumer electronic devices that 1) abusive failure was unlikely and 2) that any failure that did occur would be limited to the device and its most immediate surroundings. The use of lithium ion batteries outside of small devices is changing this view, however. The use of large stationary storage platforms introduce new questions. How might these devices perform during a building fire? How would the system respond if a spontaneous field failure were to occur in a single cell and cascade to other cells within the system?

5.4.3 Criteria for initial failure

Experience with field failures in consumer electronics has led to significant improvements in reliability against manufacturing defects and other issues that might lead to failure within the normal operating parameters. However, the gradual development of short circuits is a rare possibility. It is important to identify these developing hazards before they become an issue, and research and development efforts are underway to develop diagnostics that will detect incipient cell failure.

Batteries will generally be defined with a maximum operating temperature that is set to prevent long term degradation. At still higher temperatures batteries can undergo thermochemical processes that release some of the stored energy. Depending on the system, this can be a separator failure that leads to the release of stored energy through an internal short circuit associated with separator failure. Separator failure will lead to the release of the stored energy at a rate determined by the resistance of the internal short circuit. Separator failure depends on the material used, but typical separators used in lithium-ion batteries are designed to shutdown at temperatures in the vicinity of 130 C to prevent an external short circuit from leading to thermal runaway, while the materials themselves soften and can fail at temperatures above 160 C [12-14]

Other separator failures or inadvertent internal short circuits can also lead to heat release and be the initiating event. If the short circuit resistance is small, the heating will be rapid and the temperature rise is basically the ratio of the stored energy to the heat capacity of the system, or $\Delta T_s \approx E/mc_p$; here E is the stored energy and mc_p is the product of the mass and the specific heat of the system. For many systems with aqueous electrolytes the combined thermal capacity of water and the lower energy density of those systems can reduce dangerous temperature excursions, and hazards like hydrogen generation through side reactions become the concern. If the stored energy discharge is less fast because the resistance of the internal short circuit is not small, then cooling to the environment or to the thermal management system will reduce the temperature rise to one below the limit give above. In this case the heating is closer to that given above in our discussion regarding the effect of scale on heat dissipation: $(\Delta T_\infty) \approx \dot{q}l/h$. As noted above, $\dot{q}$ is the volumetric power generated internally by a short circuit, *h* is the effective heat transfer coefficient to the cooling system or environment and *l* is the characteristic length scale for the system between cooling surfaces. In general, the lower of the estimated temperature rises $(\Delta T_s)\ and\ (\Delta T_\infty)$ will be the relevant one.

This temperature rise described in the previous paragraph is very approximate, and can be refined with detailed numerical simulations. Such simulations are straightforward using modern finite-element thermal modeling programs given assumptions about the short circuit rate of heating (i.e. an assumed internal short circuit resistance) [15]. However, the actual resistance of an internal short circuit is generally unknown, so estimates for heating as given above can be sufficient. Lower bounds on the internal resistance can be estimated from the cell performance itself; for a hard short circuit the actual cell internal resistance can be the limiting resistance. Fortunately, hard short circuits like this are most likely in mechanical abuse scenarios that seem less probably in grid energy storage when compared to energy storage for vehicles or consumer electronics. For example, a nail puncture test is commonly considered as highly relevant for these vehicles and to some degree consumer devices and can result in short circuits with low internal resistances.

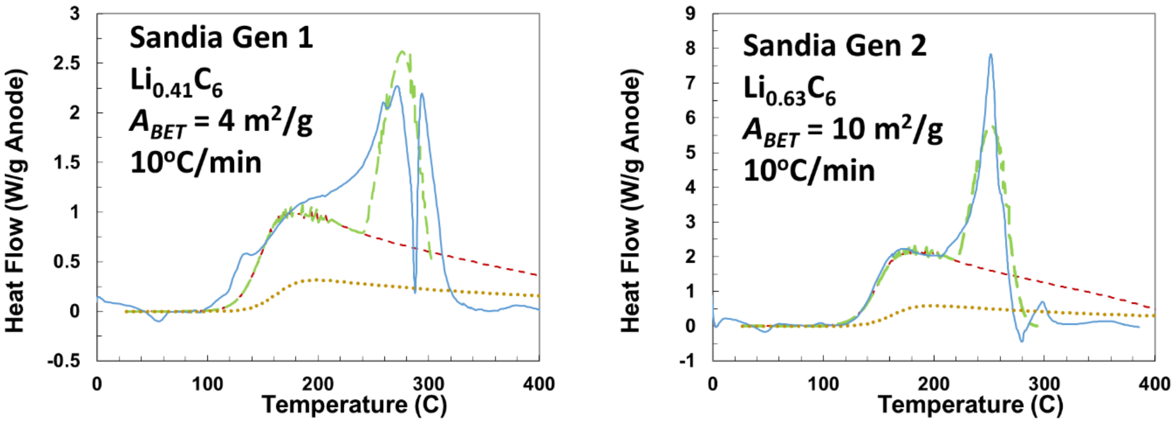
For lithium-ion systems, exothermic reactions described above can also occur. A summary of the processes is provided in [16]. Calorimetry measurements like those shown in Figure 6-1 have been made [16-20] and these can be translated into thermal sources [21-23]. The question of whether thermal runaway will occur depends on whether the heat release rates for a cell will exceed the heat losses. Since rates for chemical decomposition reactions generally increase strongly with temperature (following an Arrhenius form) there is generally an ignition temperature above which thermal runaway will occur. One characteristic test that can identify the thermal runaway condition is referred to as an oven test; a cell is placed in a heated environment and the temperature at which the cell goes into runaway is identified. This provides a representative temperature at which runaway will occur, and systems should be designed to avoid temperature excursions of this magnitude.

For most lithium-ion systems in use today, the limiting reactions that determine whether thermal runaway will occur are reactions between the cathode and the electrolyte. This is true of most metal oxides of the form $LiMO_2$ including the $LiCoO_2$ and the mixed metal oxides where M is a combination of nickel, cobalt, manganese or aluminum. For most of these materials thermal runaway will occur for temperatures above a critical value that ranges from around 150 C to the low 200's C. Lower heat losses that might occur in larger grid-scale storage systems might lead to lower temperatures for thermal runaway as discussed in the section Effects of

Scale, above. Lithium-ion chemistries based on $LiFePO_4$ cathodes are an exception to cathode driven thermal runaway.

For $LiFePO_4$ the cathode-electrolyte reaction seems to be negligible, reducing somewhat the total heat release but mostly reducing the rate of heat release, as reflected in the curve for $LiFePO_4$ cathodes in Figure 5-1. Heat release associated with lithium in the anode reacting with the electrolyte does still occur in $LiFePO_4$ batteries and any stored energy can be discharged through a short circuit if the cell separator fails. Fortunately, the reaction rates between the anode and the electrolyte are limited, probably by the SEI layer, especially for temperatures up to around 200°C.

The prevalence of the cathode heat release around 150 to 200°C in determining the occurrence of thermal runaway has led past calorimetry studies to focus on that cathode-electrolyte system and in that temperature range. The increasing interest in $LiFePO_4$ batteries and also the needs to better understand high temperature heat release rates needed to understand cascading failure discussed in the next section has led to recent work at Sandia better characterizing the anode-electrolyte reaction. Recent results considering a range of experimental measurements both at Sandia [24], from the Bar-Ilan University group [25] among others suggest that the anode reaction rates are strongly dependent on the anode particle surface characteristics and the probably breakdown of passivation layers at higher temperatures. A newly developed model has had some success in matching a wider range of calorimetry measurements; some results using this new model are shown in Figure 5-2 [26]. There model predictions are compared with selected differential scanning calorimetry measurements available in the literature beyond those for which the original model by the Dahn group was developed [20, 23]. Accounting for the area dependence seems to allow a better prediction of the heat release occurring below 200 C while the incorporation of a model for the breakdown of the passivation layers allows a prediction of the spike in heat release rates observed above 200°C. While the original model set assembled by the Dahn group [22] has been exceptionally useful for initial thermal runaway in the $LiCoO_2$ system, the evolution of technology to new material systems necessitates a revisiting of the models and an extension to more general capabilities as is underway.



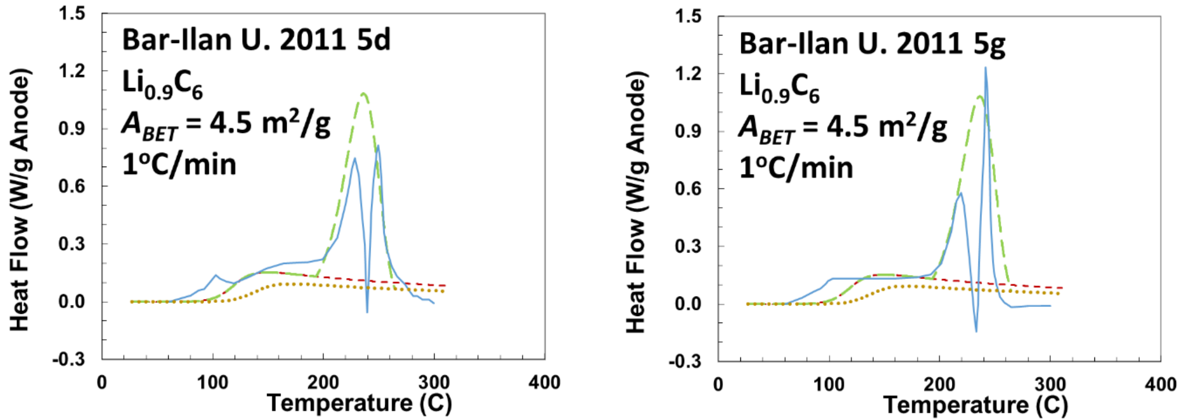


Fig. 5-2 Anode + electrolyte DSC data from Sandia [24]and Bar-Ilan University [25] compared to the original anode model (brown dotted line) [27] and to the proposed revision incorporating surface area effects (red dashed line) and the extension of this model to account for higher temperature breakdown of the SEI layer (green dashed line) from [26]. The SEI decomposition step (small peak at 100 C) has been neglected for simplicity for both models shown.

5.5. Criteria for cascading propagation

To date, much research on safety has focused on preventing the initial thermal runaway. While this is an important objective, the possibility of a thermal runaway, including from external sources, does exist and some limited work has addressed cascading failure from a single cell to a larger number of cells. This is a significant concern for large-scale storage systems since the cost of a complete facility is orders of magnitude greater than the cost a single cell failures.

Fig. 5-3 [28] shows how a single cell failure can propagate through a module or pack. In this test, a nail penetration failure was used to fail a single cell within a 5 cell series string (5S1P). The initial runaway is severe enough and the cells in close enough thermal contact to trigger thermal runaway in neighboring cells, which in turn triggers the next cells in the pack eventually consuming the entire battery over the course of several minutes. This both increases the intensity and prolongs the duration of the failure.

Some measurements of thermal runaway propagation from cell to cell have been conducted recently [29, 30], but the analysis of these results is still in its early stages. The authors here will draw on premixed flame propagation theory to interpret the results. This theory suggests that the propagation speed, *s*, for an exothermic reacting front can be estimated as $s \approx \sqrt{\omega/\alpha}$; here ω is the heat release rate in units of inverse time and α is the effective thermal diffusivity of the pack [31]. The heat release rate is not well measured under higher temperature conditions characteristic of cascading propagation, and this is a current research challenge. The role of thermal properties is easier to identify, though. The cited measurements show that the heat transfer between cells plays an important role in inhibiting propagation [27, 28]. For example, an air gap that might exist between packs of cylindrical cells can, in some of the measured scenarios, prevent cascading failure. This can be understood by the reduction in the thermal diffusivity through the air gap that slows the propagation and heat release, giving time for heat dissipation to occur. Heat dissipation cooling the system will reduce the rates of propagation further because the heat release rates, while not quantitatively known generally increase strongly with temperature. The fact that reasonable configurations lead to a failure to propagate suggests that this problem is surmountable with some additional research. Other configurations with less of an air gap, for example with pouch cells closely packed, are more prone to propagation [29, 30].

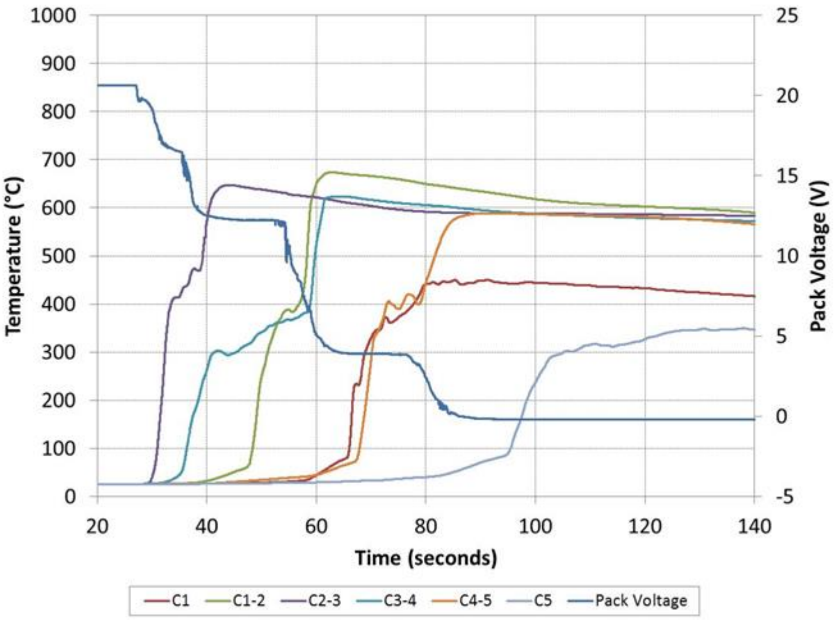


Fig. 5-3 Failure behavior of a 5 cell series (5S1P) pack after failing the central cell in the stack. This test was performed on 3 AH $LiCO_2$ cathode pouch cells. For more detail please see Lamb et al. [28]

A topic of current investigation is the role of the heat capacity in mitigating propagation since the heat capacity occurs in the denominator of the thermal diffusivity. Increasing the heat capacity is expected to reduce propagation rates and lead to a failure to propagate with a modest increase in heat capacity as has been observed in some recent experimental work at Sandia. In grid scale storage systems, if battery packs can be thermally connected to structural systems that might provide additional heat capacity, this might provide a beneficial increment in safety, though quantitative numbers are still to be determined through additional research. Some of these aspects have been investigated recently by the authors through computational models, though validation is still ongoing [32].

Another factor that will be significant in large-scale energy storage systems is the electrical connectivity of cells in the pack. When cells are connected in a manner that allows energy from multiple cells to discharge through a failed cell, as when cells are connected in parallel without any other protection, lead to more severe failure [29].

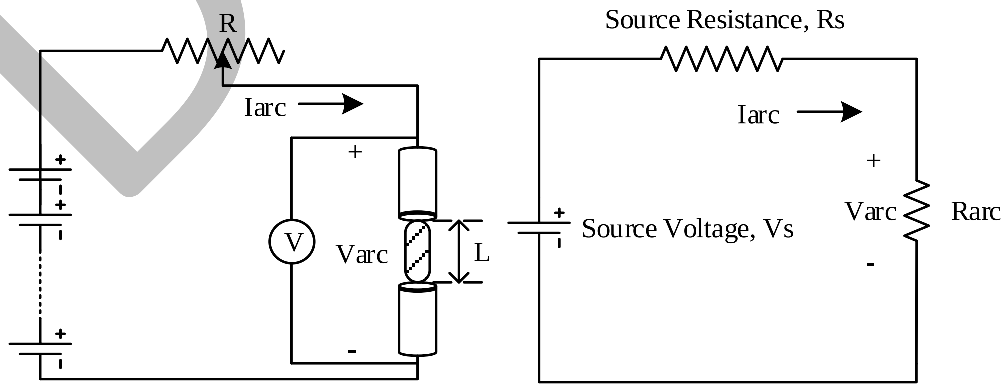
5.6. General battery hazards and other chemistries

All forms of stored energy create a potential hazard if that energy is discharged in an uncontrolled fashion. This is of particular concern with batteries, as there is no way to fully remove the stored energy in a charged electrochemical cell other than the discharge of said energy. Stranded energy is a specific problem created when a system is damaged beyond the point of operability, but individual cells within the battery still hold significant stored energy. This creates a stored energy hazard that will be continually present within the damaged system. Typically, this hazard is largely unmitigated for low voltage batteries, due to the limited hazard posed by low voltage systems. Electric vehicle and stationary storage systems, however, may be capable of hundreds of volts or more. The presence of uncontrolled high voltage increases the risks related to arcing (described more fully below).

Some aqueous cell chemistries are subject to hydrogen evolution. Hydrogen is particularly hazardous because of its wide flammability limits and the likelihood that a deflagration will transition into a detonation. Hydrogen evolution is well-known in lead-acid cells. Valve-regulated lead-acid cells are constructed in a way that hydrogen evolution is mitigated through subsequent reaction with oxygen within the system. This has significantly improved the safety of lead-acid systems when they are properly installed and operated.

5.7. Risk assessment of arcing

The potential arcing hazards of DC is a mounting concern with the recent development of battery storage system, electric vehicles, DC tracking system, photovoltaic arrays, and DC buses. Though the first commercially operation DC system was established in 1882, modeling and testing for DC arc hazard assessment have been limited. Table 1 summaries four common DC arc models used to estimate the DC arc flash in power systems, where V_{arc} is arcing voltage in volts, I_{bf} is bolted fault current in kilo-amperes, I_{arc} is arcing current in amperes for (2) and kilo-amperes for (3), and L and G are the gap width in millimeters and inches respectively. The typical DC arc test circuit and equivalent circuit are shown in Fig. 5-4, where L represents the gap width between two electrodes. The detail review of these DC arc models can be found in [33].



(a) DC arc test circuit (b) DC equivalent circuit

Fig. 5-4 DC arc test circuit and equivalent circuit [34].

The theoretical mode, referred by the latest National Fire Protection Associate (NFPA) standard 70E [34], is derived based on the maximum power transfer theorem, which may provide an arc flash estimation on the relative conservative side. Besides, this model cannot be used with nonlinear systems such as photovoltaic (PV) systems due to its nonlinear I-V characteristics [35].

Ammerman's DC arc model, the mathematical model of Stoke and Oppenlander [36], is also cited by the latest NPFA 70E 2015 edition. It can be considered as the most complete DC arc model because it covers broader ranges and provides more accurate estimations than other DC arc models. Similarly to other DC arc models, Ammerman's DC arc model considers arcing voltage to have almost linear relationship with gap width; however, practically, the arcing voltage is determined by the arc length [37-39]. A commercial software package [40], mainly for AC arc analysis, has been modified to include DC arc study based upon the assumption that it exists 1D temperature field inside the arc and using finite difference method to solve electric field and temperature. Its results were verified based on arc flash tests performed in Bruce Power [40]. However. The 600-V open air DC arc model is derived based on 125V and 250V DC systems [41].

In order to provide more accurate estimations of DC arc flash in modern power systems, a new DC arc model is necessary to overcome the limitations of previous models. Recently, researches have been performed by using Code Saturne® to simulate the DC electric arc to develop a new model based on the 3D Magnetohydrodynamic (MHD) modeling of a DC electric arc [42-45].

Table 5-1 Commonly used DC Arc Models

DC Arc Model	*Description*
Theoretical Model [42,43]	$V_{arc} = 0.5V_s$ $I_{arc} = 0.5I_{bf}$ (1)
Ammerman's Model [44]	$V_{arc} = (20 + 0.534L)I_{arc}^{0.12}$ (2)
Commercial Software [40]	A commercial software, verified by Bruce Power arc flash tests
600-V open air [42]	$I_{arc} = 0.9063 \bullet I_{bf}^{0.8927} - 0.1051 \bullet e^{0.1093 I_{bf}} \bullet (G-1)$ (3)
3D Magnetohydrodynamic (MHD) DC electric arc model [49]	$V_{arc} = (13.11 + 0.287L^{1.238})I_{arc}^{0.154}$ (4) $R_{arc} = (13.11 + 0.287L^{1.238})I_{arc}^{-0.846}$

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Appendix

Recommended Standards/Regulations/Government Policies*

Energy Storage System Components	**Standard**
Molded-Case Circuit Breakers, Molded-Case Switches, and Circuit-Breaker Enclosures	UL 489
Electrochemical Capacitors	UL 810A
Lithium Batteries	UL 1642
Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources	UL 1741
Batteries for Use in Stationary Applications	UL 1973

Energy Storage System Type	**Standard**
Stationary Energy Storage Systems with Lithium Batteries – Safety Requirements (under development)	IEC 62897
Flow Battery Systems For Stationary Applications – Part 2-2: Safety requirements	IEC 62932-2-2
Recommended Practice and Requirements for Harmonic Control in Electric Power Systems	IEEE 519
Standard for Interconnecting Distributed Resources with Electric Power Systems	IEEE 1547
Recommended Practice and Procedures for Unlabeled Electrical Equipment Evaluation	NFPA 791-2014
Outline for Investigation for Safety for Energy Storage Systems and Equipment	UL 9540
Modular Energy Storage Architecture (MESA) Standards Alliance	SunSpec

Energy Storage Installation	**Standard**
Transportation Testing for Lithium Batteries	UN 38.3
Safety of primary and secondary lithium cells and batteries during transport.	IEC 62281
Shipping, receiving and delivery of ESS and associated components and all materials, systems, products, etc. associated with the ESS installation.	DOT Regulations
Worker safety	Federal and state OSHA
Competency of Third Party Field Evaluation Bodies	NFPA 790

Fire and smoke detection	NFPA 1, NFPA 101, NFPA 5000, IBC, IFC, state and local codes
Fire suppression	NFPA 1, NFPA 13, NFPA 15, NFPA 101, NFPA 850, NFPA 851, NFPA 853, NFPA 5000, IBC, IFC, state and local codes
Fire and smoke containment	NFPA 1, NFPA 101, NFPA 5000, IBC, IFC, state and local codes
Ventilation, exhaust, thermal management and mitigation of the generation of hydrogen or other hazardous or combustible gases or fluids	NFPA 1, IEEE/ASHRAE 1635, IMC, UMC, state and local codes
Egress (operating and emergency)	NFPA 1, NFPA 101, NFPA 5000, IBC, IFC, state and local codes
Access (operating and emergency)	NFPA 1, NFPA 101, NFPA 5000, IBC, IFC, state and local codes
Working space	OSHA 29 CFR 1910.305(j)(7) and OSHA 29 CFR 1926.441 (if applicable), NFPA 70E, Article 320
Physical security	NFPA 1, NFPA 101, NFPA 5000, IBC, IFC, state and local codes
Illumination (operating and emergency)	NFPA 1, NFPA 101, NFPA 5000, IBC, IFC, state and local codes
Fire department access	NFPA 1, NFPA 101, NFPA 5000, IBC, IFC, state and local codes
Anchoring and seismic protection	NFPA 5000, IBC, state and local codes
Buildings, enclosures and protection from the elements	IEC 60529, UL 96A, NFPA 5000, IBC, state and local codes
Signage	ANSI Z535, IEEE C-2, NFPA 1, NFPA 70E, NFPA 101, NFPA

	5000, IBC, IFC, state and local codes
Emergency shutoff	IEEE C-2, NFPA 1, NFPA 101, NFPA 5000, IBC, IFC, state and local codes
Spill containment, neutralizing and disposal	NFPA 1, IPC, UPC, IFC, IEEE1578, state and local codes
Electrical safety	IEEE C-2 (National Electrical Safety Code), NFPA 70E, FM Global DS 5-10, DS 5-1, DC 5-19
Communications networks and management systems	IEC 61850

Energy Storage Commissioning	**Standard**
Recommended Practice for Commissioning of Fire Protection and Life Safety Systems	NFPA 3
Building and Systems Commissioning	ICC 1000

Energy Storage Operations and Maintenance	**Standard**
Hazardous materials storage, handling and use	NFPA 400
Standard on Maintenance of Electrical Equipment	NFPA 70B

Incident Preparedness	**Standard**
Standard for Technical Rescuer Professional Qualifications	NFPA 1006
Standard for Fire Fighter Professional Qualifications	NFPA 1001
Standard for Fire Department Occupational Safety	NFPA 1500
Standard System for the Identification of the Hazards of Materials for Emergency Response	NFPA 704
Guide for Substation Fire Protection	IEEE 979
Fire Fighting	EPCRA
Fire and Explosion Investigations	NPFA 921
Fire Safety Concepts Tree	NFPA 550

* The information of the appendix is mainly extracted from: David Rosewater, “Energy Storage System Safety – Codes & Standards”, EMA Energy Storage Workshop, Singapore. August 2015