Introduction to Battery Energy Storage Systems for the Grid

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Erik Norgren, P.E.

CED engineering.ca CANADA
CPD FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.ca

Table of Contents

Introduction ... 1

1. BESS History ... 2

1.1 Historical Context ... 2

1.2 Recent Growth ... 3

1.3 BESS Policy ... 6

2. BESS Technology and Chemistries ... 10

2.1 Lithium-Ion (Li-ion) ... 11

2.2 Lead-Acid ... 12

2.3 Flow Batteries ... 13

2.4 Sodium Batteries ... 14

2.5 Zinc Batteries ... 14

2.6 Other / Emerging Technologies ... 15

3. Applications and Use Cases ... 16

4. Design ... 18

4.1 Site Selection and Layout ... 18

4.2 BESS Key Components ... 18

4.3 Safety and Environmental ... 20

5. Interconnection Process Overview ... 22

5.1 ISO and Queue Basics ... 22

5.2 Detailed Interconnection Steps ... 23

6. Summary ... 25

Introduction

Battery Energy Storage Systems (BESS) are enabling the U.S. power grid to transform as intermittent energy sources like wind and solar have increased which requires other power sources to become more dispatchable and flexible. Traditional storage technologies have existed for decades, like pumped hydroelectric storage (PHS), however the evolution of BESS technology, dominated by lithium-ion-based systems, are able to offer much more rapid dispatch and ability to scale between small and large applications. A BESS system's capability to store and release energy, provide steady, sustained power flow, or rapid cycling, and its scalability in terms of both power capacity and energy storage duration make it a unique asset to complement an evolving grid and power demands.

BESS operation involves an electrochemical reaction and process. The charging cycle involves the input of electrical energy to convert to chemical energy within the battery cells. The discharge cycle reverses this process and supplies power to the grid. Several BESS technologies and chemistries exist; however, the fundamentals of this process are the same. Lithium-ion batteries are most prevalent due to generally high round-trip efficiency (exceeding 90%), declining costs, and higher volume of cell manufacturers and supplies relative to other chemistries such as vanadium redox. Section 3 of this course will explore the available chemistry and their advantages and disadvantages.

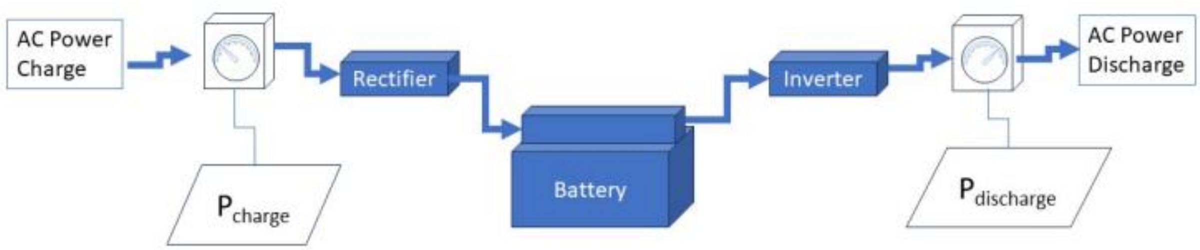

Figure 1: BESS Charge and Discharge Cycle (Source: DOE BESS Evaluation Method, December 2023)

BESS is poised to experience continued growth across the grid, with private corporations, the Federal government, Independent Power Producers (IPP), and utility companies all seeking the benefits of BESS. A primary driver for the growth has been the U.S. Inflation Reduction Act, which provides a minimum 30% tax benefit for BESS projects. This policy will be further discussed in this course. As costs continue to decrease and the need to decarbonize and manage the grid increases, the total installed capacity will continue to skyrocket up to as much as 150,000 MW by 2030.

1. BESS History

1.1 Historical Context

BESS applications are exponentially growing and becoming a critical cornerstone of the electrical grid. This section summarizes the origins of BESS, key developments in technology and general trends.

The modern era of battery storage started in the 18th century with Alessandro Volta's voltaic pile device. With this invention, Volta utilized stacks of alternating copper and zinc, separated by paper or cardboard soaked in electrolyte (saltwater). This combination produced a flow of electrical current, cementing its place in history as the first electrochemical battery. Volta's device however was not rechargeable and had limited capacity. In 1859 Gaston Planté developed the lead-acid battery which was the first rechargeable device. Lead plates were submerged in sulfuric acid, allowing current to be reversed and producing the recharging effect.

Figure 2: Alessandro Volta (Source: NASA.gov)

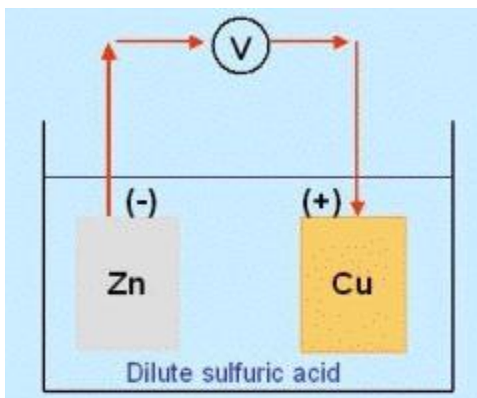

Figure 3: The Voltaic Cell (Source: NASA.gov)

In 1899, the nickel-cadmium (Ni-Cd) battery was developed by Waldemar Junger which generally offered improved energy density from lead-acid chemistry. The Swedish inventor was successful in gaining adoption and this technology saw deployment in the US by the 19040's in portable devices and initial grid experiments. Along a similar timeline, Thomas Edison invented the nickel-iron (Ni-Fe) alkaline battery. This was designed for early concept electric vehicles and several stationary applications.

The 19th century set the stage for 20th century applications on the electrical grid. The first storage applications mainly focused on mechanical storage (pumped hydro). World War II drove widespread use where lead-acid and Ni-Cd batteries were used to power submarines and offered Uninterruptible Power Supply (UPS) capabilities for critical infrastructure. In the 1960's, the Energy Storage Systems program was established at Sandia National Laboratories by the DOE. Several studies advanced early concepts for batteries to be deployed to support the electrical grid.

In 1981, Sony offered the first commercialized Li-ion battery in 1991. Li-ion offered longer life and higher energy density, and its first uses were in small electrical devices such as watches. The first applications for the grid were small, generally less than 100 kW, however in the timeframe from 2000 to 2010 saw an emergence of utility-scale storage. The need for utility-scale storage was driven by the exploding penetration of wind and solar power applications. The intermittency of these sources called for an asset class that could provide quick dispatchable energy.

Portland General Electric commissioned a 5 MW (1.25 MW-hour) in 2012, which was the first utility-scale application of its kind. This was a lithium ion based system developed as part of a Department of Energy demonstration project. The system was integrated with a distribution feeder system and controlled by a central utility dispatch system to create a high reliability zone. The system could operate in parallel with the utility grid, or support an islanded system disconnected from the utility grid. This project was deemed the first "Microgrid" application supported by a utility-scale BESS system.

Note: BESS system capacity is typically expressed first as its power capacity, usually in kilowatts (kW) or megawatts (MW). This is the rate of power flow it can provide. The second term, its energy storage duration capability, is almost always expressed in hours. For example, a 1 MW 2 MW-hour system has a 1 MW power flow capacity and a 2 hour storage capacity (i.e. it can deliver 1 MW sustained discharge over a 2 hour period). 2 MWh / 1 MW = 2 hours

1.2 Recent Growth

Today BESS technology is a rapidly expanding grid asset that complements renewables (wind, solar, hydro), traditional fossil fuel power (coal, natural gas, diesel), and nuclear power. The Energy Information Administration (EIA) reported 26 GW of operating capacity in the U.S., representing a 66% increase in 2024 alone.

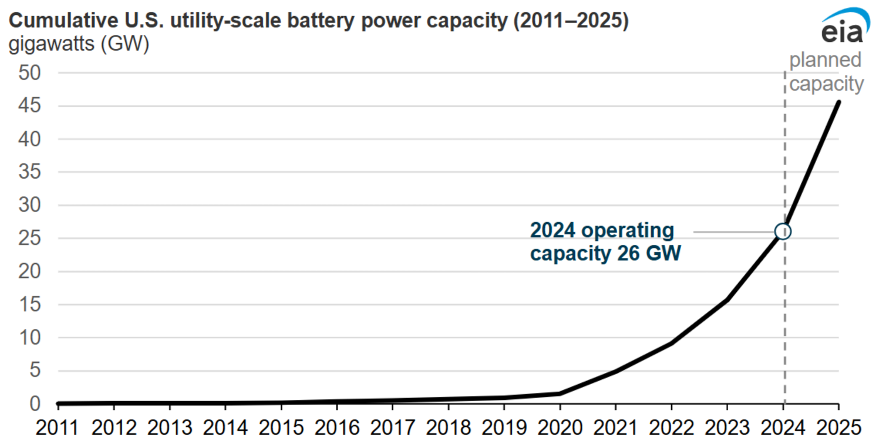

Figure 4: Cumulative BESS Capacity (Source: EIA)

For perspective, the total BESS capacity is a relatively small fraction (2%) of the total reported generating capacity in the U.S. as reported by EIA in 2024. For perspective on all generation sources, the Environmental Protection Agency provided these figures which break down the electric generation in the U.S. by source as of 2023.

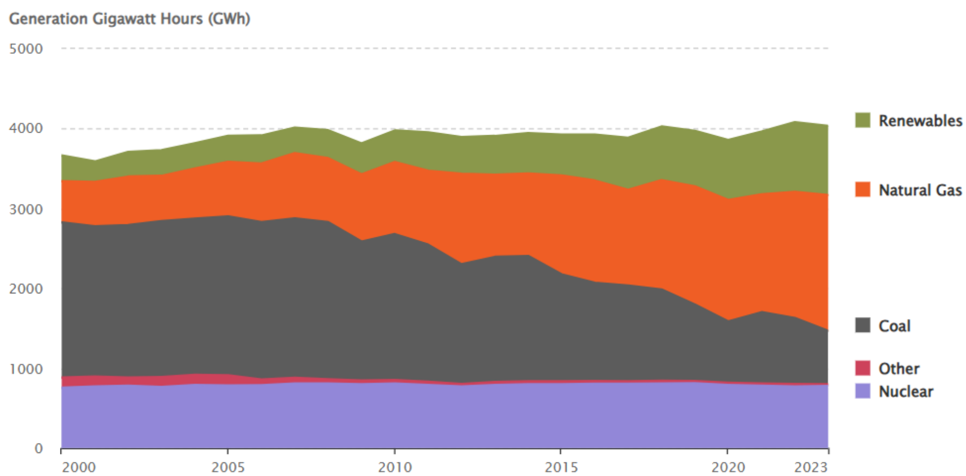

Figure 5: U.S. Generation by Source (Source: EPA)

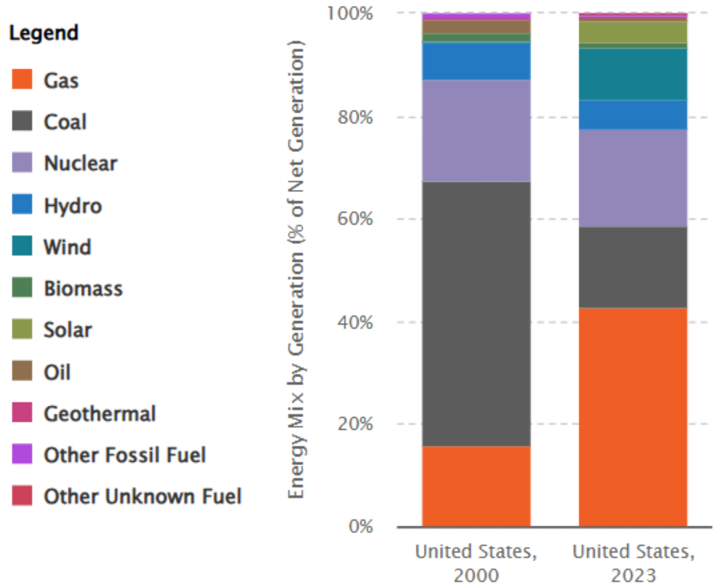

Figure 6:Generation by Source as a Percentage (Source: EPA)

It should be noted that BESS is not considered a generation source, as it does not generate its own electrical energy, but rather stores and discharges from other sources. Nonetheless, as the total capacity of BESS grows, it is expected that similar summaries conveying capacity profiles in the U.S. will begin to convey BESS as a contributing resource. As can be seen in Figure 6 above, coal has seen a rapid decrease as aging coal plants begin to retire, driven by renewable energy and emissions reduction goals across various states. From 2000 to 2023, coal decreased from roughly 45% of the total fuel mix to 15%. These retirements create the need for utility companies to replace the lost capacity with alternative resources. Although utilities are greatly increasing the amount of natural gas power to compensate, they are also showing a shift towards storage to diversify their resources.

This figure provided by the EIA gives a sense for where BESS additions in 2025 are concentrated. As can be seen, California and Texas continue to lead the country in BESS additions as they currently have the most lucrative power markets for BESS and generally have high renewable penetration on their transmission systems. As of 2025, California has approximately 16 GW of BESS capacity installed, and Texas has approximately 8 GW. The next highest state is Arizona with just under 2 GW.

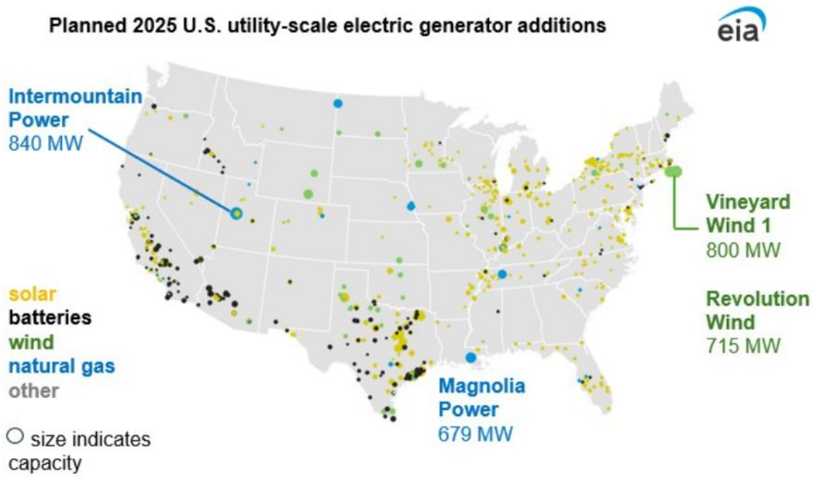

Figure 7: Planned 2025 U.S. Utility-Scale Generator Additions (Source: EIA)

Globally, energy storage is accelerating as well. The chart below displays the total storage additions by gigawatts (GW) by the leading nations. These figures exclude pumped hydro storage. China leads the way with over 50% of storage deployments, followed by the U.S., with around 15%.

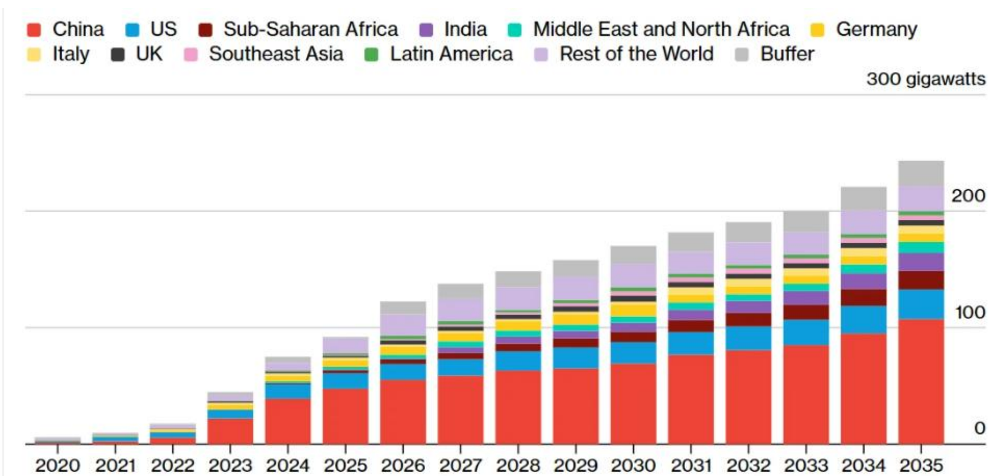

Figure 8: Generation by Source as a Percentage (Source: BloombergENF)

1.3 BESS Policy

BESS policy remains strong in the U.S. and China, the two leaders in storage additions over the last decade. In 2025, the U.S. and China have supported policy with the goal to rapidly expand storage growth with benefits to climate goals, a positive impact on energy pricing, and energy security. This section will cover the U.S. policy both at the Federal and State levels.

On the Federal level, recent growth has been greatly influenced by the 2022 Inflation Reduction Act (IRA) which had several significant benefits for BESS. This policy extended the 30%

Investment Tax Credit (ITC) to standalone storage which means the full CAPEX of the project (labor plus equipment) is ultimately returned as a tax credit to the project owner. Developers will typically sell these tax credits to larger entities, typically large banks, with large tax obligations in return for upfront cash that can be used to pay down construction debt. In addition to the 30% base tax credit, the IRA also offers ITC Bonus Zones, typically referred to as “Energy Communities”, which can boost the tax credit by an additional 10% to a total of 40%. The IRS provides these definitions for the different types of energy communities that are available:

Labor Category: Metropolitan or non-metropolitan statistical areas with a minimum of 0.17% employment in the fossil fuel industry (coal, oil, or natural gas, including extraction, processing, transport, storage. This is applicable for any year after 2009. The MSA or Non-MSA must also have an unemployment rate at or above the national average for the year prior. MSAs and non-MSAs can fall in and out of the bonus each year as their labor participation rates change over time.

Coal Closure: Census tracts, including directly adjoining census tracts, where a coal mine closed after December 31, 1999, or a coal-fired power station retired after December 31, 2009.

Brownfield Site: Real property where expansion or reuse is complicated by hazardous substances, pollutants, contaminants, or certain mine-scarred land (with exclusions like Superfund sites). These types of properties are often confirmed via environmental assessments.

Finally, the IRA offers an additional 10% bonus for storage projects that utilize domestic content. Projects can achieve a 50% total tax credit if they are located in an energy community and seek to meet the domestic content requirements. 100% of structural steel and iron has to be sourced from the U.S. and a certain percentage of manufactured product components (MPC) must also be from the U.S. Projects that begin construction after 2026 must have 55% of manufactured components sourced from the U.S. These components include battery cells, system packaging, inverters, transformers, and other elements.

Related to all tax credits described above, a developer can seek to “safe harbor” equipment to lock in the tax credits. Safe harboring means the project owner takes specific documented steps to show that either construction has started or they have executed a binding contract for equipment supply. This method provides protection against future policy changes which could impact available credits. There are two methods for safe harboring:

- **Physical Work Test:** This includes significant site work, usually in the form of laying equipment pads or foundations or trenching. The project owner needs to demonstrate a binding contract for this work.
- **5% Cost Method:** The project owner will demonstrate having spent at least 5% of the project cost, typically in the form of initial purchase contracts for long lead time equipment (transformers and breakers)

The Trump administration’s One Big Beautiful Bill (OBBB) Act accelerated the phase-out of tax credits for solar and wind projects. The bill requires wind and solar projects to be placed in service by December 31, 2027, to qualify for the tax credits. This applies to both Investment Tax Credits and Production Tax Credits (PTC). PTC’s have been around for a couple of decades and is a structure where the project will receive variable tax credits based on actual energy production. This bill has had a dramatic impact on the solar and wind industry, where projects in development that cannot meet the 2027 deadline need to have their economics re-evaluated without the significant aid of the tax credits. There have been sweeping layoffs in the solar and wind industry because of investments being reduced or pulled on projects that cannot meet the deadline.

BESS fared much more favorably under the OBBB bill, where BESS projects can begin construction before 2033. The placed in service date requirement by 2027 does not apply to BESS. Tax credits for BESS are set to fully phase out in 2036. The bill did however impose certain requirements where materials cannot be sourced from certain entities of concern, most notably China. The bill requires a minimum 55% of materials sourced from non-foreign entities of concern in 2026 and increasing to 75% by 2030. This favorable treatment under the OBBB will support continued rapid growth in BESS deployments moving forward. Many former wind and solar developers are seeking jobs in BESS.

About State-level policies, many individual states have created goals specific to energy storage capacity or created certain financial incentives. As of the date of this course preparation, there are twelve states that have implemented energy storage targets. Additionally, 23 states have 100% clean energy goals in place, which ultimately require clean generation sources such as wind and solar. Naturally, with a goal to have this type of clean energy goal, battery storage as a dispatchable asset complements a resource mix that is predominantly intermittent.

Several leading states have established energy storage targets:

- California: 1,825 MW procured by 2020 and fully installed by 2024. 2 GW of long-duration (12+ hours duration) between 2031 and 2037. It should be noted that CA has achieved more than 10,000 MW (500+%) of its goal
- Massachusetts: 5,000 MW by 2030. A minimum of 750 MW to be long duration (8+ hour)
- Michigan: 2,500 MW by 2030
- New York: 1500 MW by 2025, and 6,000 MW by 2030. 35% to be located in disadvantaged communities and 20% to 8+ hour duration resources
- Virginia: 3,100 MW installed by 2035. 10% behind the meter

New York and Illinois have taken more advanced measures to promote BESS deployment by enacting Index Storage Credit (ISC) programs. In New York, the program is administered by the New York State Energy Research and Development Authority (NYSERDA) and provides a payment incentive for utility-scale BESS that participate in the NYISO wholesale energy market. If selected under a competitive procurement, a BESS project will contract with NYSERDA under a contract-for-difference structure which provides supplemental revenue. Essentially, the BESS will participate in the wholesale market, earning revenues for energy arbitrage, capacity payments, and ancillary services. Based on an agreed-to "strike price", NYSERDA will pay the BESS project the difference between the strike price ($/kW-month) and the actual revenue earned in the market. These supplemental payments are intended to increase total revenue for the project, increasing viability and economic returns to at least the minimum criteria of the BESS project and its investors. NYSERDA conducted its first procurement cycle for this program in 2025 and plans to conduct several more procurements to meet New York's storage target goals.

Separately, Illinois is in the process of preparing to offer a similar opportunity. The Illinois Power Agency (IPA) under the Illinois Commerce Commission (ICC) will structure a similar 20-year contracting model that aims to supplement BESS revenues. This program will conduct multiple cycles of procurement and will support Illinois' storage target of 3 GW. The procurements will be split between ComEd who serves the Chicago area, and Ameren Illinois who serves the remainder of the state.

2. BESS Technology and Chemistries

Introduction

This section describes the available BESS technologies and chemistries and their advantages/disadvantages. Although Lithium-ion types dominate the market in terms of deployment volume, the other types discussed (lead-acid, flow batteries, sodium-based, zinc based, other) continue to evolve in their applications for the grid. Choosing the proper chemistry for the application is critical as it impacts energy density, power density, performance, efficiency, degradation, cost and safety.

In selecting the proper chemistry, there are several trade-offs and other factors to consider:

Duration versus cost: The cost per kWh stored over the life of the installation is an important metric. Li-ion is typically deployed when the required duration is four hours or less. This is due to high energy density and maturity in the market leading to favorable economics. When the duration increases to eight hours or longer, lithium-ion becomes less cost competitive. Chemistries which are able to scale up their storage duration more effectively by decoupling energy capacity from power capacity are better suited for long duration (flow batteries).

Cycle life & degradation: Storage applications for the grid often require performing at least one cycle per day (365/yr) and in some cases thousands of cycles per year. Batteries degrade in their energy capacity as a function of the cycling rate and in terms of calendar life. Average depth of discharge also has a considerable impact on the rate at which the BESS will degrade and when the capacity needs to be augmented. These factors need to be heavily considered when choosing technology/chemistry.

Safety: Storage systems for the grid have very large energy volumes and thus present many safety considerations. Fire risk, thermal runaway, and failure modes must be designed for and managed. Generally, the LFP type lithium-ion chemistry and flow batteries have better thermal stability.

Supply chain: Availability of materials, potential policy risks, and recycling/disposal are other important considerations. Technologies that have abundant materials such as zinc or sodium base chemistries may be more attractive than chemistries like lithium-ion which contain lithium, nickel and cobalt.

Space requirement vs energy density: The footprint of the project can have a considerable impact on project cost, permitting and environmental factors. Solutions that have higher energy density require less footprint, so chemistries like lithium-ion may edge out flow batteries.

Application & Use Case: The intended application will also influence what chemistry can be selected. For services that require fast dispatch/response, such as frequency regulation or ramping support, lithium-ion may be best suited. For applications requiring longer discharge cycles, such as smoothing renewable (wind, solar) output or providing backup power, flow batteries, sodium-based or zinc-based solutions may be optimal. For smaller back-up power applications that require less duration, lead-acid could be the obvious choice. Also, future technologies such as aluminum-air or liquid-metal could be the ultimate solution for projects requiring 12 or more hours of discharge.

2.1 Lithium-Ion (Li-ion)

Lithium-ion batteries are based on a reversible interaction between a cathode and an anode. Cathode chemistries will often be lithium iron phosphate (LFP) or lithium nickel manganese cobalt (NMC), although other much less common chemistries do exist. The cathode and anode are separated by a "separator" and contained in a liquid electrolyte. These components are combined in stacks and packaged together to form "battery cells".

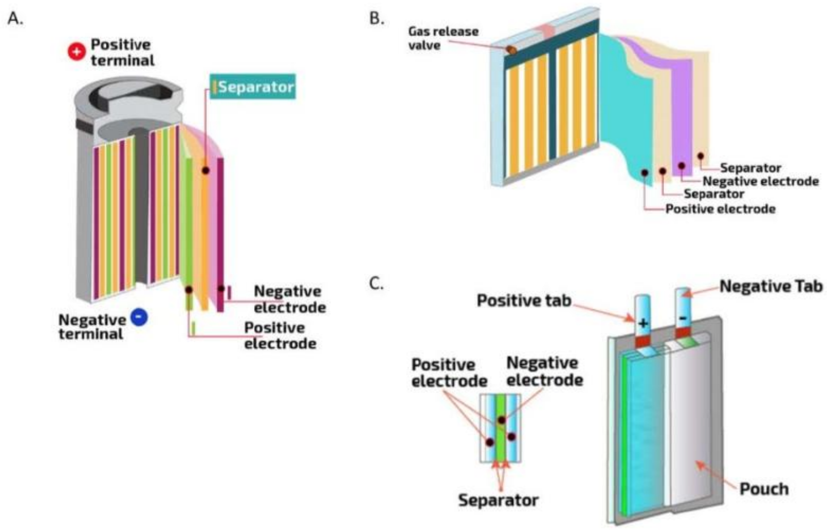

Figure 9: Lithium-Ion Chemistry (Source: DOE)

Lithium-ion is by far the dominant choice for electric grid applications. The DOE suggests Li-ion accounts for 99% of the market share primarily due to high energy density, long lifespan and continually decreasing cost. Figure 9 below provides a display of the Li-ion battery imports to the U.S. with China accounting for 88% of the supply.

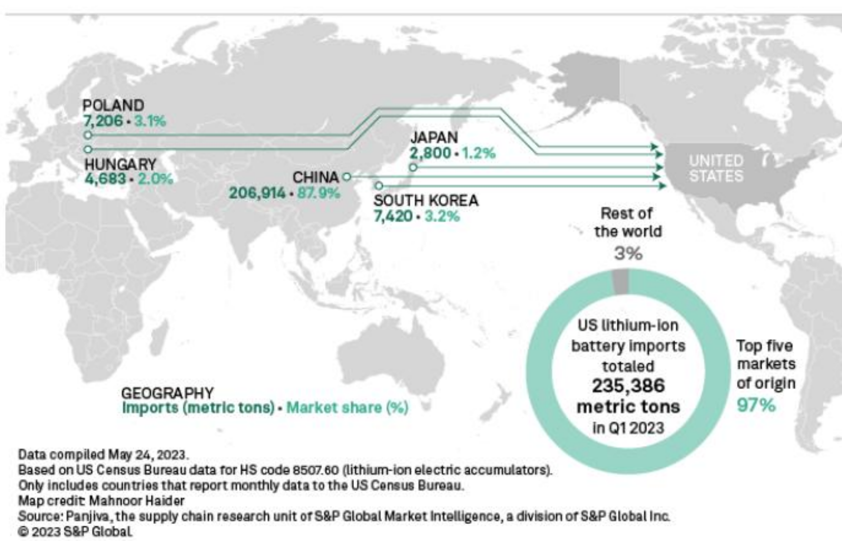

Figure 10: Lithium-Ion Supply Chain (Source: DOE via S&P Global, Ferguson, Mark, "Infographic: The Big Picture 2024 – Energy Transition Outlook", 12/6/2023)

<u>Advantages:</u>
- High energy densities versus other chemistries
- High round trip efficiency often exceeding 90%
- Large number of vendors to choose from. Chinese vendors have been the dominant supplier in the market however the supply chain is beginning to diversify
- Supports rapid response applications such as frequency regulation and ramping support

<u>Disadvantages:</u>
- Degradation as the system cycles and also calendar life. The system is continually losing energy storage duration, which either requires the system to be upsized initially or battery cells need to be augmented (replaced or added to) at certain intervals
- Safety considerations related to fire risk and thermal runaway. Poor management greatly increases the risk
- Raw material constraints related to the supply chain. Common raw materials include lithium, nickel, and cobalt. At times there are ethical considerations for how these materials are extracted and supplied
- Strict thermal management specifications leading to heating and cooling system design requirements. These requirements add complexity and cost to the system
- Less optimal for long-duration applications (8+ hours) as the system size and physical footprint becomes very large

<u>Subtypes of Li-Ion:</u>
- LFP (Lithium Iron Phosphate): Provides greater safety element with improved thermal stability and higher thermal runaway temperature. The stationary storage industry for the grid has made a shift to LFP as the predominant sub-type.
- NMC: Noted for higher energy density, however higher cost. Also, more safety risk of thermal runaway given lower runaway temperature.

2.2 Lead-Acid

Lead-acid chemistry is the most traditional and mature with components that include lead anode, lead-dioxide cathode and sulfuric acid electrolyte. They have been used for more than a century in motor vehicle applications and stationary systems. Lead-Acid is most commonly used for backup power applications with short duration requirements. They have short cycle life and low energy density, generally limiting grid applications.

<u>Advantages:</u>
- Generally low upfront cost relative to newer chemistries
- Robust supply chain and availability
- Less safety concerns, making suitable for installations in occupied buildings (such as UPS systems)

<u>Disadvantages:</u>
- Short lifetime and more frequent maintenance intervals
- Toxicity concerns related to lead
- Low energy density equating to a larger space requirement for a given capacity
- Slow charge and discharge capability compared to newer chemistries

- Poor performance in applications that require deep depth of discharge

2.3 Flow Batteries

Flow batteries are unique in that they store energy in liquid electrolytes, which are typically held in tanks. Pumps are used to move the fluid through a stack of cells where a redox reaction occurs. The most developed technology is the vanadium redox flow battery. Flow batteries are becoming increasingly attractive as they can offer long duration storage of 8 hour or more. Lithium-ion applications, on the other hand, are often limited to 2 or 4 hour systems. To achieve longer durations, the catholyte and anolyte tanks simply get bigger. There are some commercial flow battery applications, however these facilities use expensive minerals such as vanadium that limit the cost effectiveness and are generally difficult to obtain. Continued research is occurring to identify alternate and more effective fluids that will reduce costs and allow flow batteries to scale across the industry.

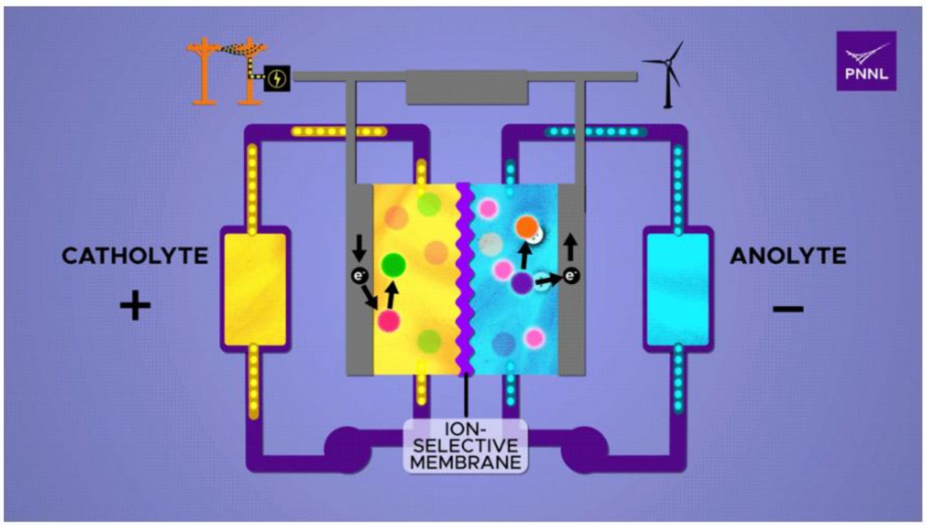

Figure 11: Flow Battery Diagram (Source: DOE – Pacific Northwest National Lab)

Advantages:

- Long-duration applications can be achieved of 8 hours or greater. Energy capacity can be scaled up independently of the power capacity side
- Decreased safety risks compared to lithium-ion systems that have thermal runaway risk
- Very little degradation and requiring only routine maintenance. Systems are often designed for a minimum of 10,000 cycles and a 10+ year life

Disadvantages:

- Typically lower "round trip efficiency" versus lithium ion. Round trip efficiency refers to the complete charge and discharge cycle and is a measure of energy output versus energy input
- Generally requires a larger footprint per unit of energy density compared to other technologies
- Many components and high complexity. The systems include tanks, piping, pumps, membranes and many auxiliary parts to support fluid movement
- High upfront cost
- Limited maturity in the market which can detract investments and can be viewed as a risk

2.4 Sodium Batteries

Sodium battery chemistry typically refers to Sodium-Sulfur (NA-S) or Sodium-Ion. The design of these batteries is quite similar to lithium-ion but uses sodium instead of lithium. There is high interest in this solution given the very abundant and cheap supply of sodium, however they require high operating temperatures and offer less energy density. At this time, sodium batteries have not been widely adopted in the market, however any long-term disruption to the lithium supply chain could highlight this solution as a good alternate. Sodium-sulfur is likely to be the choice for any near-term applications, and research continues on sodium-sulfur which may be better suited for long duration (8+ hour) applications.

Advantages:

- Sodium as a replacement for lithium can lead to reduced cost and reduced supply chain risk
- Most cost competitive for long duration applications

Disadvantages:

- Requires high operating temperatures which can exceed 300 °C. This increases safety concerns and requires high cost items for containment and temperature control
- Lower energy and power density compared to Li-ion
- Low maturity in the market and few large-scale projects completed. This leads to limited investment opportunities

2.5 Zinc Batteries

The use of Zinc as a negative electrode (i.e., Anode) dates back to the 1800's when Alessandro Volta created the voltaic pile. Zinc battery chemistries will typically refer to Zinc-Air, Zinc-MnO_2, Zinc-Nickel, and Zinc-Bromine. Z-air and Z- MnO_2 are widely used today to power small portable devices. Z- MnO_2 has seen early adoption in grid-support applications with a good example being Urban Electric Power's backup power project in San Diego which uses a 1 MWh battery to backup a datacenter. Zinc-Br is also early in its deployment for grid support where a first deployment of a 35 MWh system by EOS is planned by Indian Energy in Southern California. Zn-Ni batteries are seeing development for stationary applications to support the data center and telecom industries. There are certain developers, such as ZAF Energy, advancing the technology as a potential replacement for lead-acid and lithium-ion in industrial applications and relatively small grid support projects.

Advantages:

- Generally low materials cost and low environmental impact
- Zink is an abundant material
- Low safety risk profile and reduced fire risk
- Zinc BESS can be offered in flow-type systems for longer durations. Duration can be decoupled from power capacity by increasing tank size

Disadvantages:

- Low maturity in the market. Very few utility-scale installations
- Technical issues such as slow kinetics associated with using air as a cathode, electrolyte flow management issues (passivation, water loss, formation of dendrite)
- Lower efficiency and energy density compared to lithium ion and other chemistries

2.6 Other / Emerging Technologies

- Aluminum-air: very high energy density (up to ~400 Wh/kg) and aluminum is a very abundant resource. This tech is still in the R&D stage and aluminum corrosion is currently a primary bottleneck in early designs.
- Liquid-metal batteries / high-temperature chemistries: An example is molten-salt chemistry which can offer long duration and long cycle life. However, this technology is in the R&D stage and high operating temperature is one of the main challenges.

These chemistries may play a significant role in future long duration applications for the grid and compete with Li-ion.

To summarize all points across chemistries, the following table provides a snapshot.

Chemistry	**Duration/Use-case**	**Advantages**	**Disadvantages**
Li-ion	Short to mid duration (1-4 hours), peak shaving, frequency reg, ramping, renewable smoothing	High power and energy density, mature in market, high efficiency	Safety risk, supply chain risks, considerable degradation
Lead-acid	Short duration, backup power	Mature market, low cost	Low energy density, short life, smaller scale applications
Flow batteries (Vandium Redox, other)	Mid to long duration (4+ hours), renewable or grid smoothing	Long cycle life, scalable duration, reduced safety risks	Low energy density, high system complexity, high upfront cost
Sodium-based (Na-ion, Na-S)	Mid to long duration, cost-sensitive projects	Abundant materials, lower costs	Low maturity in market, high operating temps
Zinc-based	Longer storage durations, early in grid support development	Potentially lower upfront cost, generally safe materials	Low power density, lower efficiency
Emerging (Al-air, liquid-metal, etc.)	Very long duration (12+hour to multi-day)	Very high theoretical energy, abundant materials	Early stage development, complex systems

Figure 12: Summary of BESS chemistries

3. Applications and Use Cases

BESS can be used in several ways to benefit the electric power industry and electricity consumers. This section summarizes the use cases for grid support.

Grid Supply and Demand Balancing:

BESS can be used to balance the supply and demand of electricity in short durations (seconds or minutes) or on a longer timescale (hours). For utility-scale applications, BESS can provide fast response times to assist during the ramp-up period of slower dispatching assets such as natural gas or coal-fired power plants. Fast responses also include frequency regulation, where BESS can be charged and discharged on a second-by-second basis to inject power into the transmission system to maintain near 60 Hz frequency. The transmission system frequency can dip below 60 Hz when generation sources fail to meet demand or increase above 60 Hz when generation exceeds demand. These functions help maintain power quality on the system which is critical to ensure other electrical equipment on the grid is not damaged and load receives steady supply.

Energy Arbitrage and Peak Shaving:

Energy arbitrage typically refers to charging a BESS when electricity prices are low and then discharging when prices are high. This produces a daily net revenue stream for the project, which, if conditions are right, can be repeated each day or in some cases twice per day. BESS is typically operated remotely from a dispatch center where operators monitor the energy market to evaluate when pricing is advantageous to make money. This scenario usually involves "in front of the meter" connections where the system is connected to the high voltage transmission system. The BESS will operate in an ISO/RTO wholesale market, such as ERCOT or CAISO. ISO/RTOs are entities that manage the reliability of a regional transmission system and administer an electric wholesale market. ISO/RTOs are covered in detail in a separate course.

BESS can also perform "peak shaving" and this term typically applies to behind-the-meter projects. Behind-the-meter means the project is typically located to serve a single facility or grouping of facilities at 35 kV or less. In this scenario, the battery will be discharged when the facility has its maximum or "peak" electrical load. This will reduce the metered electrical demand during peak pricing periods, thus saving the customer money on their utility bill.

Renewable Smoothing:

Energy storage can be used to optimize the output of solar or wind energy resources. By pairing or "co-locating" with BESS, solar or wind resources can temporarily store their energy output in the BESS, which can then be used to serve supply requests when the solar or wind would not be otherwise available. Additionally, BESS can be used to store solar or wind energy during periods of curtailment. Curtailment periods refer to times when the transmission system demand is less than the total generating resource supply, thus an oversupply condition occurs. Regional grid operators will call for solar or wind resources to reduce their output to match supply with demand.

Deferred Electrical Infrastructure Investment:

When a particular region on the electrical system sees increased demand, a utility company can strategically place a BESS near the increased load to aid in serving the new load. This can be a more cost effective approach than paying for expensive investments in new substations and transmission or distribution lines.

Back-up Power and Microgrids

BESS can be used to provide backup power during a utility power outage. This is typically done for behind-the-meter applications at the facility level. A BESS may be a strategic asset that's included in a Microgrid concept. A Microgrid acts as an islanded grid temporarily disconnected from the utility grid during an outage. During the outage period, the Microgrid is served by its own generation and/or BESS and is controlled by a central Microgrid controller. When the utility power is lost, the isolation and transition to Microgrid operation may be automatic with automated distribution switches, or it may be a more manual process.

4. Design

Developing and constructing a BESS system can span several years and involves site selection, equipment sizing, equipment selection, permitting, environmental studies, financing, stakeholder engagement and construction. This section will focus specifically on the design of a utility-scale BESS systems.

4.1 Site Selection and Layout

Site selection is a critical piece of BESS design. The sitting process typically prioritizes locating BESS adjacent to substations that can support the power injection and withdrawal of the BESS. If a BESS can connect directly to an existing substation, this can eliminate added costs associated with building a new substation to accommodate the project. Typically, utility-scale BESS projects are >20 MW and are connected to 69 kV or higher. Usually, projects are connected at 69 kV, 115 kV, 138 kV, 230 kV or 345 kV. Typically, the higher the voltage, the greater the project size can be supported however there are other factors. Also, the electric prices, available capacity revenue, and/or ancillary service programs in the electricity market must be able to support the project's financial viability. Finally, another electric system consideration is what interconnection queue the project will enter, how many projects are in line to get studied, and how long this process will take before the project will be allowed to connect by the utility.

Related to the land available, the terrain should typically be 10% slope or less, otherwise, the cost of grading/leveling could become substantial. Developers will typically try to avoid wetland areas as there are Federal regulations that prohibit disturbing land features that are already registered as wetlands. Wetland studies can also determine certain features to protect wetlands. Floodplain will also try to be avoided, otherwise, insurance companies will typically require that equipment be elevated above a minimum base flood elevation.

Developers will often try to locate in areas with ease of permitting which often includes locating outside city limits, if possible. In unincorporated county regions, only county jurisdiction applies and generally all that is required is construction-related permits. Within city or township limits, permitting can often include re-zoning a property or passing a discretionary approval process with a city development council.

4.2 BESS Key Components

Core components of the BESS system include the battery cells organized into packs/modules and placed within racks. These racks are placed within the BESS enclosure, which is typically a steel outdoor-rated enclosure. These enclosures resemble a shipping container and have similar dimensions (20ft high x 8 ft wide x 8ft deep). The enclosures are placed on concrete pads and or alternatively in some cases supported by pile or pier foundations. A geotechnical drilling exercise conducted early in the design process to sample the soil characteristics will help engineers determine what type of foundation is required.

Figure 13: BESS Enclosures (Source: DOE)

Each enclosure will typically be held in the range of 2 to 5 MWh. So, for a typical utility-scale project size of 100 MW / 2 hour (200 MWh), the project might require 70 separate enclosures assuming each holds roughly 3 MWh. The total project footprint including the BESS enclosures, control building, transformers, inverters, access roads and fencing is typically in the range of 20 MWh per acre, so a 100 MW / 2 hour system (200 MWh) would require 10 acres as a conservative estimate.

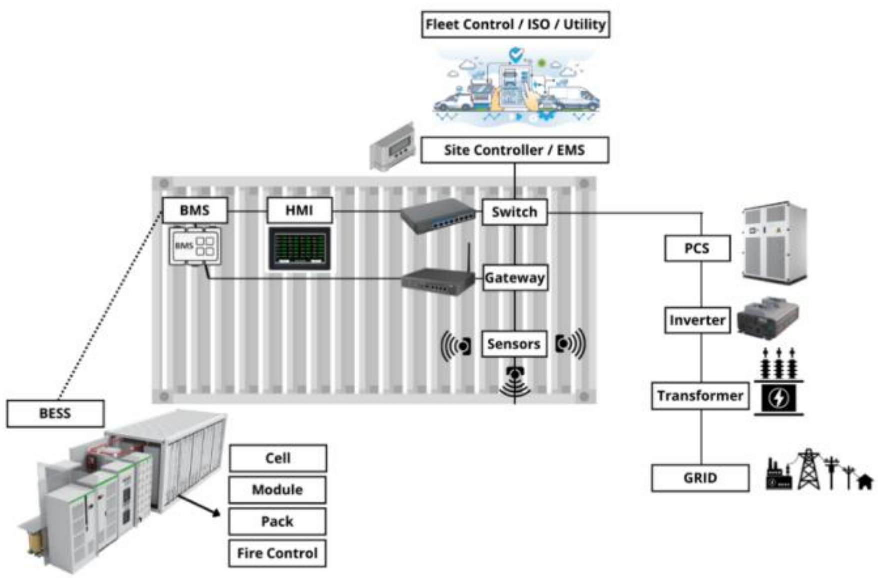

Figure 14: BESS Components (Source: DOE)

The Power Conversion System (PCS) is often a separate enclosure that includes controls and an inverter. The PCS is used to "invert" the power from DC from the battery cells to AC for injection to the grid. The direction of power flow is reversed for period when the BESS is charging. The PCS is also responsible for managing harmonics, reactive power support and fault ride-through. Depending on the design, the PCS system may contain many "string" inverters paired with individual BESS containers or small groupings. Alternatively, the design may have just a couple "central" units that serve the majority of the entire system.

The Energy Management System (EMS) controls the interaction with the grid and provides dispatch signals to the BESS. It controls what mode the BESS is in (discharge or charge), what service it provides to the grid, the discharge or charge rate (MW), and other high level functions. The EMS will be set up with remote telemetry to both the BESS operator, typically off-site, and the electric market coordinator. The Battery Management System (BMS) is responsible for monitoring the battery cell performance. It monitors cell temperature, voltage, balance and overall estimate of cell health.

The BESS enclosure will typically include a Human Machine Interface (HMI) that allows operators or maintenance personnel to check system status and health. The HMI will also include access to a data historian which keeps detailed records of performance.

Grid connection equipment will include switchgear which collects all medium voltage cabling from the BESS enclosures and associated PCS's. Switchgear includes breakers and controls which can isolate cabling circuits and trip open breakers for system protection. Power flow is then directed to a step-up transformer which transforms the voltage from medium to high voltage. For a utility-scale application, the most common medium voltage on the low side (system side) is 35 kV while the high side (grid side) is 69 kV, 115 kV, 138 kV, 230 kV, or 345 kV (most commonly). The high side voltage is simply designed to match the voltage of the grid. On the high side of the transformer, power cabling will then make a final termination to a POCO structure which stands for "Point of Change of Ownership". The POCO serves as the demarcation point between the project scope and the utility's scope and will typically be a new electrical pole structure.

4.3 Safety and Environmental

Safety design for BESS systems includes considerations for fire/thermal runaway, electrical shock, chemicals, mechanical energy, and cybersecurity. Thermal runaway is often considered the most significant hazard which includes an exothermic reaction that is self-sustaining. The battery cell will overheat and degrade, leading to decomposition of materials, generation of gas fumes, and ultimately can lead to a fire or explosion event. The thermal runaway can begin with a short circuit, certain defects in cell manufacturing, or extreme temperatures due to failure in cooling systems. These events will typically start in the range of 90°C to 120°C depending on cell chemistry. Gases emitted can include carbon monoxide, methane and hydrogen which leads to a toxic and flammable environment that can ignite into a fire or explosion. The thermal runaway event can propagate between racks of cells, increasing the hazard and eventually impacting the entire enclosure. It should be noted, however, that BESS system design will typically include a minimum separate of enclosures in attempt to prevent the event from propagating between different enclosures.

Electrical hazards will include electrical shock, arc flash, and current faults from high voltage equipment. Short circuits can arise from design flaws or often insulation failures due to aging. These systems also can pose chemical risks from leaks of electrolytes which are toxic or air emissions during failures. Air emissions can include carbon monoxide, hydrogen fluoride and volatile organic compounds (VOCs), all of which are harmful to the environment. Other hazards include mechanical failures due to vibrations or impacts with the enclosures. Environmental factors like corrosion and humidity can speed up system degradation and lead to failures as well. Finally, cybersecurity can pose a considerable threat, with potential hackers gaining control of system components or downloading sensitive private content from owners or operators.

Key engineering standards related to safety design include UL 9540 which covers fire protection, shock protection, fault and thermal runaway management. UL 9540A provides a standard test for thermal runways and BESS vendors will seek 9540A certification to show the market they are compliant. NFPA 855 is becoming the nation-wide standard and covers many aspects including installation, fire detection and suppression, explosion protection, ventilation, emergency access and spacing. Other codes include NFPA 70 and the International Fire Code (IFC) which provide additional regulations for fire safety, cabling/wiring, grounding systems and protection devices for overcurrent.

Mitigation strategies are implemented at the cell level, enclosure level, and overall system level. To address the cell level, the introduction lithium-iron-phosphate (LFP) chemistry has reduced incidents dramatically due to a high trigger temperature for thermal runaway as compared to the previously most popular nickel-manganese-cobalt (NMC) chemistry. Protection systems within the enclosure also include pressure relief valves and current interruption devices.

At the enclosure level, the BMS system will continually monitor temperature, state of charge, and other parameters related to overall system health. The BMS can force a shutdown should certain parameters exceed established operating limits. Thermal management will include liquid cooling delivered to the cells or air-side HVAC systems attached externally to the enclosure. Fire suppression can include water or mist delivery, CO_2, or aerosol-based systems inside the enclosure. More recently, the industry has begun to shift towards a let it burn approach. Because the layout is designed to eliminate flame propagation between adjacent enclosures, fire responders will simply let a single enclosure burn out.

5. Interconnection Process Overview

This section discusses how a BESS project moves through an interconnection process with an ISO and/or utility prior to receiving an interconnection agreement. This is such a critical process in BESS project development and can impact the size of the project or its financial viability.

5.1 ISO and Queue Basics

The interconnection process refers to submitting your project application to the electric utility company for study and to seek an interconnection agreement with the utility that allows the project to be connected to the grid. This is a critical process that has a significant impact on project development timelines and can also influence the size and design of the project. This section focuses on utility-scale projects which submit their interconnection applications to the Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs).

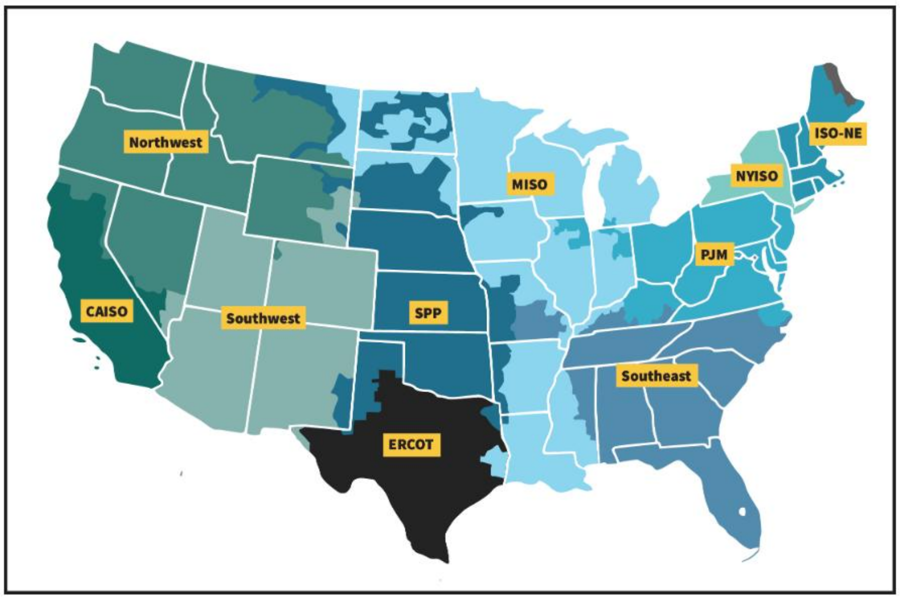

Figure 15: ISO map by region (Source: Federal Energy Regulatory Commission – FERC.gov)

This map displays the ISO's across the U.S. It should be noted that Northwest, Southwest, and Southeast are not ISO regions. In these three regions, the individual utility companies across the system are primarily responsible for managing their network and load. In the various ISO regions, the ISO (e.g. CAISO, ERCOT) manage the overall system and the associated electric supply pricing market.

When a generator or BESS project submits their project application for interconnection, typically if the project is greater than 20 MW, the ISO will handle the application and manage the overall process. The electric utility company associated in this case with performing the studies and ultimately offer the generation or storage project an Interconnection Application (IA). In the case of smaller projects (≤20MW), the ISO will typically not be part of the process, and the project will work with their respective electric utility companies directly.

The interconnection (IX) process will differ slightly by ISO, but generally it follows the Federal Energy Regulator Commission's (FERC) Large Generator Interconnection Procedures (LGIP) for projects greater than 20 MW. FERC also provides the Small Generator Interconnection Process (SGIP) for projects of 20 MW or less. Additionally, FERC Order 841 in 2018 mandated that BESS be included and accommodated in ISO wholesale markets. It dictated that storage projects be treated as non-generation resources (NGR) with specific parameters established such as state-of-charge and ramp rates.

Each ISO will offer a generator interconnection website that provides information on the interconnection queue and instructions for the application. The figure below displays the Southwest Power Pool's (SPP) interconnection dashboard as an example. As can be seen, there are over 500 projects totaling 135 GW in the queue. Battery storage represents 28 GW or 21% of the queue which is considerable. "In the queue" means these projects have submitted their projects to SPP and are at some study of the study or interconnection agreement process.

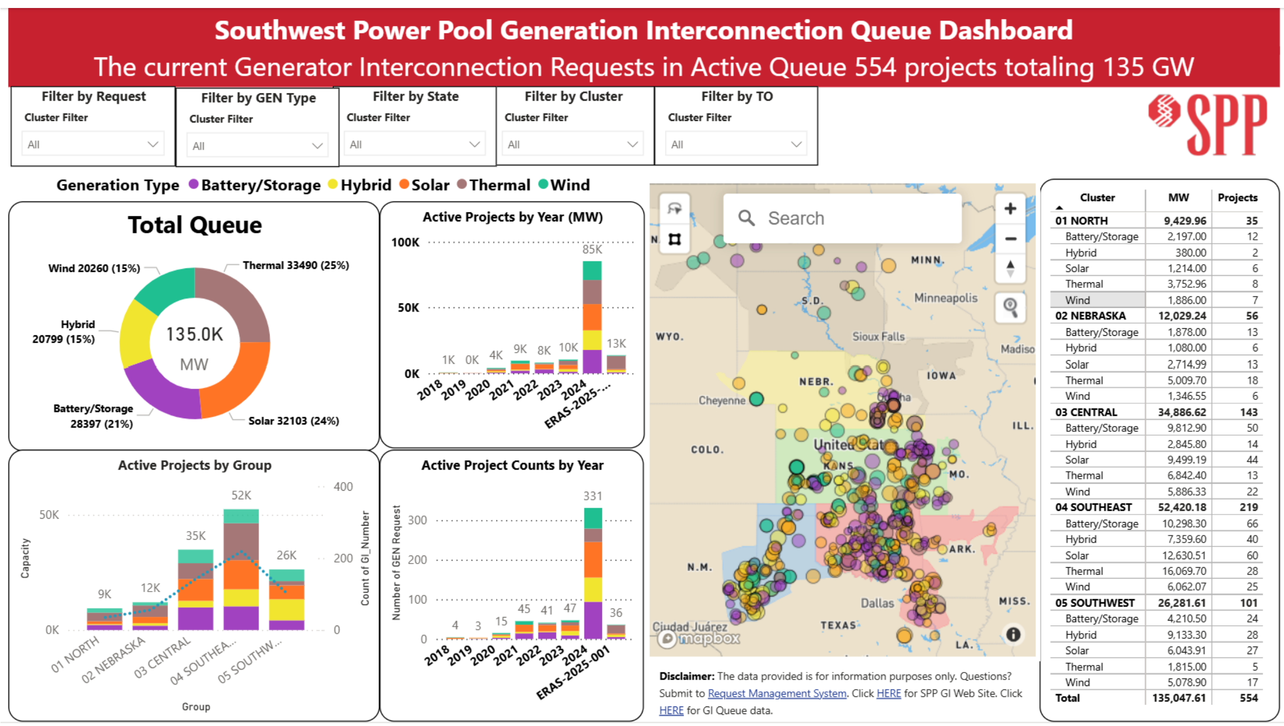

Figure 16: SPP Interconnection Dashboard (Source: https://www.spp.org/engineering/generator-interconnection/)

5.2 Detailed Interconnection Steps

1. Application and Queue Entry:

After a project owner/developer has secured a site and is comfortable making financial commitments related to the interconnection process, they can begin preparing an interconnection application. Typically, an application submission will require an application form, preliminary site plan, electrical single line diagram, equipment specifications, cash study deposits, financial security, and evidence of site control. The ISO and the utility will review the application materials and once deemed sufficient the project will be assigned a queue number. Financial securities that are required upfront and after study completions are intended to make each developer/owner put skin in the game. If the developer/owner chooses to drop out of the queue, there are financial penalties that are triggered based on which stage of the IX process the project is in.

2. Scoping Meeting and Feasibility Study:
After the application is accepted and the project is assigned a queue number, the electric utility and the developer/owner will conduct a scoping meeting to review the intended point of interconnection and project assumptions. The utility will discuss their timeline for each study that will be conducted. Following the meeting, the utility will perform an optional feasibility study. This study evaluates preliminary system impacts, alternative points of interconnection and conceptual level design. For BESS specifically, the utility will look at impacts in both the discharging and charging moves.

3. System Impact Study (SIS/SRIS):
Should the project decide to move forward, the utility will next perform a system impact study. This study performs power flow evaluation, short-circuit, stability and protection. The result of this study is a detailed look at how the BESS project will impact the system at its intended capacity. If power flow issues exist and its determined the project will have operational risk, the utility and project developer/owner can discuss project alternatives including potentially downsizing the project.

4. Facilities Study and Class Year (if applicable):
The facility study determines in detail what facilities will need to be provided by the utility to connect the project to the intended point of interconnection. In the case of a project intending to connect directly to an existing substation, the utility's scope will typically include one or more new breakers, controls & relays, a length of new transmission line over to the BESS project, and a new point of change of ownership (POCO) structure. If the project is intending to tap into an existing transmission line in the case of a utility-scale project, a new substation will be required and new circuits that loop into and out of the existing line. The facility study will also provide a cost estimate for the new facilities as well as a schedule for the utility's work.

5. Interconnection Agreement and Construction:
Following the facility study, the utility will present the developer/owner with an interconnection agreement. The interconnection agreement lays out the terms and conditions under which the BESS project will be allowed to connect with the utility's local grid. The interconnection agreement is a binding agreement that covers both commercial terms and technical requirements, and reflects the required utility facilities and schedule from the facility study. Typical schedule from the utility is 18 to 36 months although it can vary from that range.

When the developer/owner decides to move forward and execute the interconnection agreement, they are making a significant commitment to the project. The utility will typically require a form of security either cash or letter of credit. This ensures the developer/owner is committed to the project and the utility can draw upon the security to recover funds should the developer/owner cancel the project. The interconnection agreement will remain in place through construction and through the life of the BESS project.

6. Summary

BESS will continue to play a crucial role for the grid as renewable energy increases, fossil fuel plants continue to retire, and energy demands explode with AI data center growth. It's a high flexible asset that can serve several key functions from rapid short duration response to regulate frequency on the grid, mid duration applications (1 to 4 hour) like energy arbitrage to create a revenue steam, or long duration (6+ hours) to provide power when wind/solar isn't available.

U.S. utility-scale storage capacity has increased dramatically with approximately 10 GW of storage added in 2024 and 20 GW in 2025. 2024 alone was a 65% increase in storage capacity added compared to 2023. BESS will be poised to experience continued growth as it received very favorable treatment in the One Big Beautiful Bill Act, which essentially left the Investment Tax Credit for battery storage unaffected. The solar and wind market, on the other hand, has been severely impacted with their tax credits to sunset by 2027. Solar and wind projects must be placed in service by December 31, 2027.

Various BESS technologies are available in the market or under R&D research. Chemistry selection will influence energy density, power to energy ratio, footprint, cost, lifespan and other parameters. Lithium-ion systems remain the dominant choice across the industry primarily driven by high energy density, relatively low maintenance requirements, and continually reducing costs. Within the Li-ion category, Lithium-iron-phosphate (LFP) has exploded in popularity, representing 85% of the li-ion BESS market, due to improved safety profile and higher cycle life. Other chemistry types make up about 1% of storage applications for the grid with flow batteries show more advancement towards a larger market share. Flow batteries are gaining traction in the long duration market with products offering 8 hours or more.