Energy Storage Market and Technical Assessment

Rochester Public Utilities

Energy Storage Market and Technical Assessment
Project No. 112056

Revision Final
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prepared for

Rochester Public Utilities
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Rochester, MN

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EXECUTIVE SUMMARY

Batteries and energy storage have generated a significant amount of interest in the utility space over the last several years. Batteries offer solutions that are unconventional and potentially disrupting to the power industry. The main driver for the interest in batteries is the decrease in cost of lithium-ion batteries resulting from the development of electric vehicles. This decrease in cost has allowed battery storage solutions to become a viable business case for various situations. Batteries also have garnered interest from the ever-increasing number of renewable projects on the power grid. These resources are variable, inconsistent, and unreliable; however, with batteries many of those problems can be solved. Battery manufacturing is dominated by LG Chem and Samsung in Korea and China. However, production facilities in the United States have been scaling up for the past few years. Some of the noticeable plants include Tesla's Gigafactories to help meet the expected demand from electric vehicles (EVs). In a 2018 shareholder's meeting at the Nevada Gigafactory, Tesla announced an annual production of 20 GWh and is expected to approach 35 GWh as more production lines are installed. As more batteries are produced and the prices continue to decline batteries can offer different types of services and become profitable investments in more locations. Regulators have seen a rise in demand for battery energy storage and have taken measures to ensure a fair and competitive market for battery energy storage. These new regulations can allow for battery energy storage projects to receive financial benefit in many regional transmission systems in the US.

With all the excitement around batteries they are not mainstream. There are two places in the United States with the most battery penetration. One is the California Interconnected System Operator (CAISO) that has been extremely progressive in terms of having a regulatory and political landscape to incentivize renewables and battery storage. California has such a high penetration of solar that they experience over generation during the day and must ramp up dispatchable generation in vast quantities in a short time when solar resources decline in the late afternoon. This scenario creates an opportunity for energy storage to have value and solve problems. The second location with a significant portion of battery energy storage in the US is in the PJM ISO which is situated in the states of Ohio, Pennsylvania, Maryland, New Jersey, and Virginia. They have an energy landscape that rewards frequency regulation with attractive economic incentives. Batteries can respond faster than most other frequency measures and can be lucrative when using frequency response as a business case. If battery prices continue to drop, batteries can provide solutions for T&D deferral, reliability improvements, capacity, resource firming, energy arbitrage, and ancillary services.

The lithium battery industry has significant potential for continuous improvement due to the potential of hundreds of unexplored chemistry combinations, the maturating of supply chains and manufacturing processes, and efficiencies gained from battery management system operation. Batteries have historically seen marginal performance improvement and lithium-ion cost reductions. Costs could continue to decline but with high demand the cost of lithium and other elements like cobalt may alter the predictions of future battery prices. There are hundreds of potential chemistries each with their own advantages, supply chains, and performance metrics. The industry is in its infancy and economies of scale will continue to drive the price down. With each of these chemistries there are six key performance metrics to consider: power, energy, energy density, performance under sub-optimal conditions, cost, and safety. All of these factors can create a robust repertoire of available chemistries that are suited to a diverse set of battery storage solutions.

The real value from battery energy storage comes from the versatility and scalability of the system. A battery can be sized exactly to address the problem it is going to solve and placed right where the solution is needed. Many other utility assets do not have this versatility. Battery prices have declined drastically in the past decade and many industry reports expect battery prices will continue to decline. However, as raw material cost becomes a larger percentage of the battery pack cost, batteries will be further subjected to geopolitical forces.

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LIST OF ABBREVIATIONS

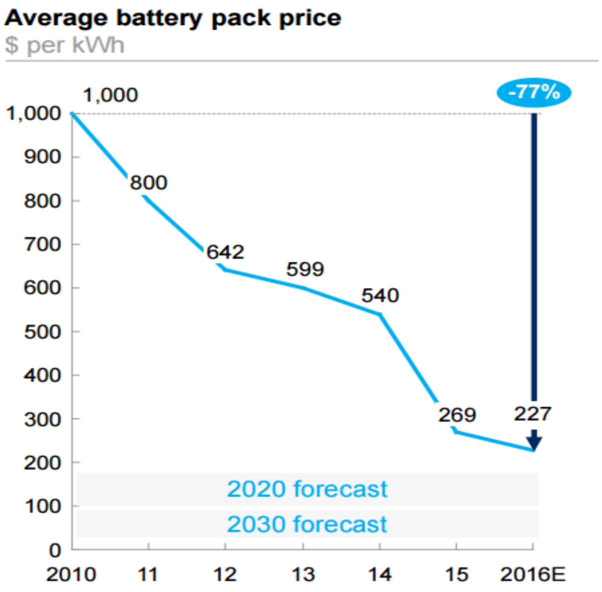
Abbreviation	**Term/Phrase/Name**
BESS	Battery Energy Storage System
BOP	Balance of Plant
CAISO	California Independent System Operator
CAES	Compressed Air Energy Storage
Burns & McDonnell	Burns & McDonnell Engineering Company, Inc.
EV	Electric Vehicle
LGIP	Large Generator Interconnection Procedure
LGIA	Large Generator Interconnection Agreement
LMP	Locational Marginal Price
MACRS	Modified Accelerated Cost Recovery System
FERC	Federal Energy Regulatory Commission
IPP	Independent Power Producers
R&D	Research and Development
RPS	Renewable Portfolio Standards
RTO	Regional Transmission Operator
PV	Photovoltaic

1.0 BATTERY STORAGE MARKET

1.1 Market Drivers

The worldwide demand for lithium ion batteries has increased dramatically with the growing presence of electric vehicles (EVs) and higher penetration of utility scale renewables. The combination of economies of scale and the maturation of manufacturing process has led to a disrupting trend in price over the past few years (Baker, 2019). While the price decline over the past decade, as represented in Figure 1-1, has generated battery demand, there are also policy incentives in the United States that are helping this trend. There are tax credits for battery systems that are paired with solar energy projects and energy storage targets for states which both make energy storage more attractive. The tax incentives move the breakeven point of battery investments lower and expand the potential uses for batteries.

Figure 1-1: Historical Trend of Battery Pack Price



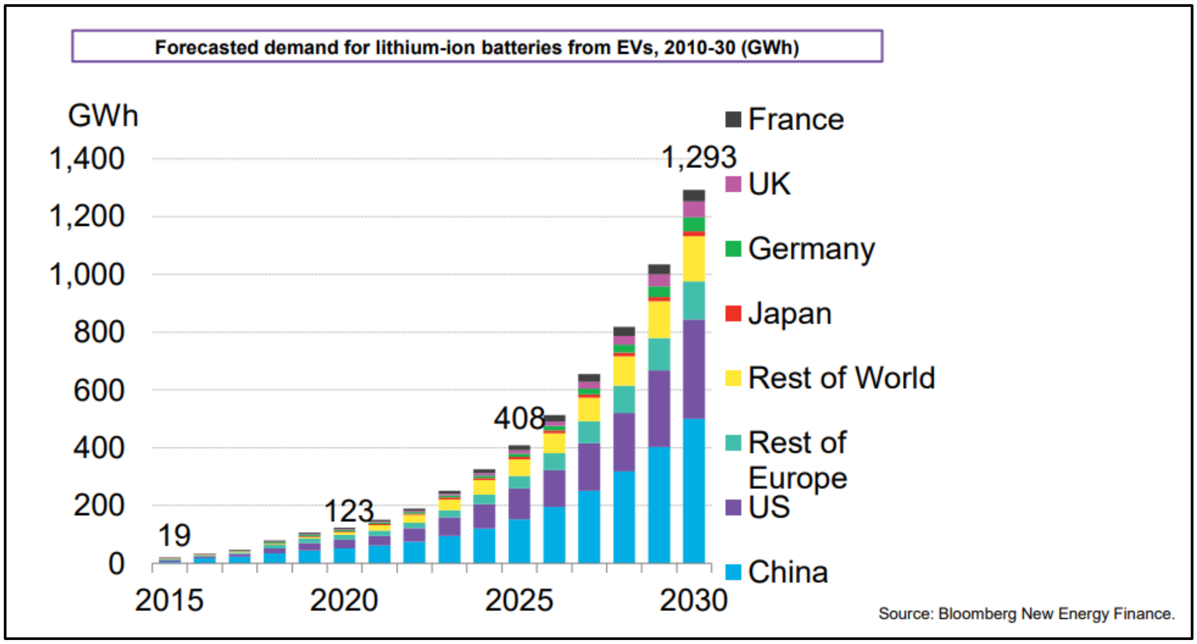
(Company, 2017)

Utility scale energy storage projects using lithium ion batteries are primarily being driven by the battery price reductions. The research and development (R&D) and capital investment is making battery energy storage a cost-effective solution for grid scale storage. Without the EV market and advances in lithium-ion technology, batteries would likely not be a viable option for utility applications. As the percentage of generation assets shifts towards renewables, the ability to dispatch and store power when needed becomes more valuable. Firming the capacity of wind and solar will continue to generate demand for energy storage. In addition to tax credits there are initiatives from the FERC to have energy storage be more competitive on the wholesale market.

1.1.1 Battery Demand

The largest driver for battery demand has come from EV growth. The volume of EVs on the market is expected to grow at a significant rate over the next 10 years. With the main cost of an EV being the battery, it is essential to reduce battery costs as low as possible. Figure 1-2 shows the forecasted demand for lithium-ion batteries due to EVs. This trend means that utility scale battery energy storage systems will become a more feasible investment as prices decline.

Figure 1-2: Forecasted Battery Demand from Electric Vehicles

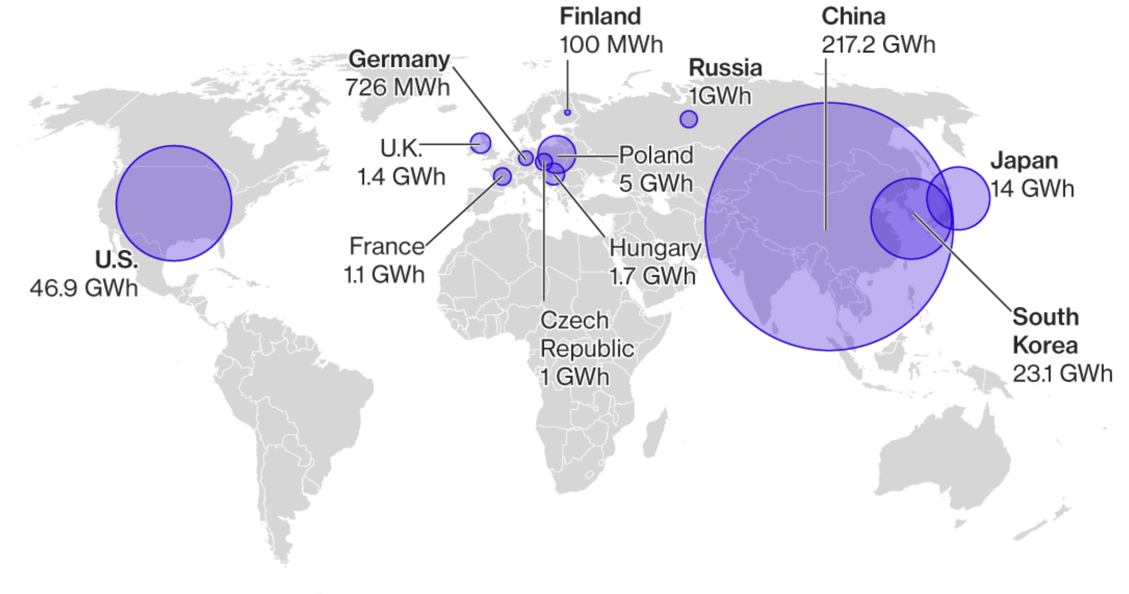


(Curry, 2017)

1.1.2 Battery Supply

Major companies like Tesla have been leading the change in the US production capacity of batteries over the past few years. Tesla’s Gigafactory 1 in Nevada is still growing into subsequent phases and Gigafactory 2 is opening in China with plans for similar factories in the future; however, this plant is dwarfed by other manufacturers abroad. Tesla will have a significant portion of the production capacity of lithium-ion batteries for electric vehicles as the Gigafactories become 100% operational. As shown in Figure 1-3, the total manufacturing capacity of lithium-ion battery production in the US is expected to nearly double over the next several years with an additional 15 GWh coming from the Tesla Gigafactory 1 expansion alone.

Figure 1-3: Planned and Existing Battery Cell Production Capacity



Source: Bloomberg New Energy Finance, CATL IPO prospectus

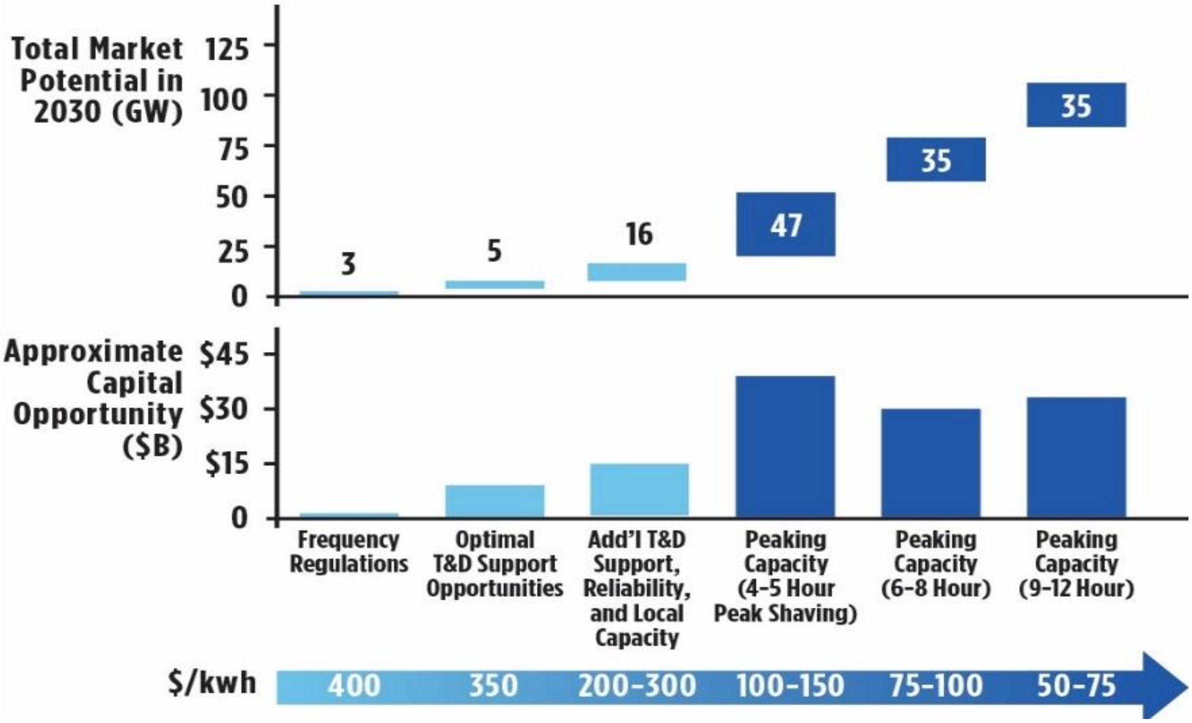
Bloomberg

(Jie Ma, 2018)

Due to the forecasted increase in demand for stationary and EV batteries, manufacturers have been investing in more production capacity. With increased production comes greater demand for raw materials, such as lithium and cobalt, both of which are essential for current battery technology. Cobalt is mostly mined out of the Democratic Republic of Congo and lithium has concentrated deposits in a handful of locations such as the Atacama Desert in South America. There are no lithium or cobalt mines in commercial operation in the United States, however, some are planned to come online by 2022. With the concentration of raw materials, supply chain reliability and abundance could be a potential issue in the future.

If the price of batteries continues to lower, the grid parity price will be met for different services in different areas. For example, batteries located in PJM have already met grid parity for grid services due to the frequency regulation market that has been created in that independent system operator (ISO). In regions higher electricity costs, parity will be met sooner. At the continued rate battery prices have declined in the past, batteries will be cost competitive with many conventional sources. The services that will reach cost parity first will be those that require relatively small capacity in terms of power and total energy storage but provide high value like frequency regulation. Batteries are versatile and have one of the fastest response times when compared to other generation assets. Batteries can respond within seconds whereas most other generation takes minutes or even hours. Frequency issues need to have quick responses for short durations making batteries an attractive solution for frequency response programs. Battery services that reach parity after other ancillary services will include T&D deferral and peaking capacity. These services require larger batteries in terms of both power and total energy storage. As demonstrated in Figure 1-4 using batteries for long durations of capacity will be one of the last services to reach grid parity.

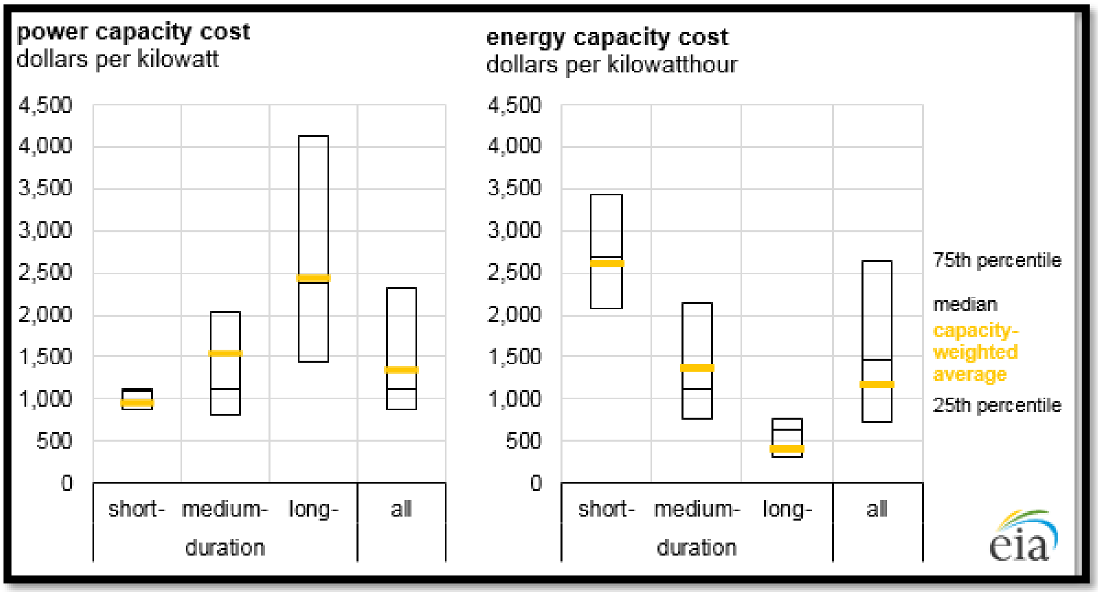
Figure 1-4: Grid Parity for Battery Services



1.1.3 Battery Price

Typically, the total cost of short duration batteries is cheaper on a per unit basis than long duration batteries in terms of a battery that is designed to provide power capacity services. The opposite is true for batteries designed for providing energy services. The $/kW and the $/kWh price are both important metrics to follow for battery energy storage. The $/kW price of a battery offers an indication on what services the battery can economically provide. Services that require a large power output, such as providing capacity, will be more cost effective as this price declines. The $/kWh metric is essential for cars and battery energy storage. The amount of energy that can be stored in a battery is essential for determining how a battery can operate on the grid. Sizing the battery to the needs of that location is essential for a good investment. At a high level a battery targeted for peak demand needs to have a high power rating output to meet the peak demand and a size large enough to withstand the duration of the peak demand. An oversized battery may sit idle longer than desired, but under the correct conditions can be used for other revenue streams. An undersized battery may not completely solve the problem or provide the solution it was intended for. With batteries being modular and having the ability to be placed in many areas, another module can be added until the problem or opportunity is sufficiently taken care of. Batteries can be designed to be cost effective for power or total energy capacity but cannot address both issues effectively. Various types of batteries and their respective costs are presented in Figure 1-5.

Figure 1-5: Total Installed Cost of Large-Scale Battery Storage Systems by Duration



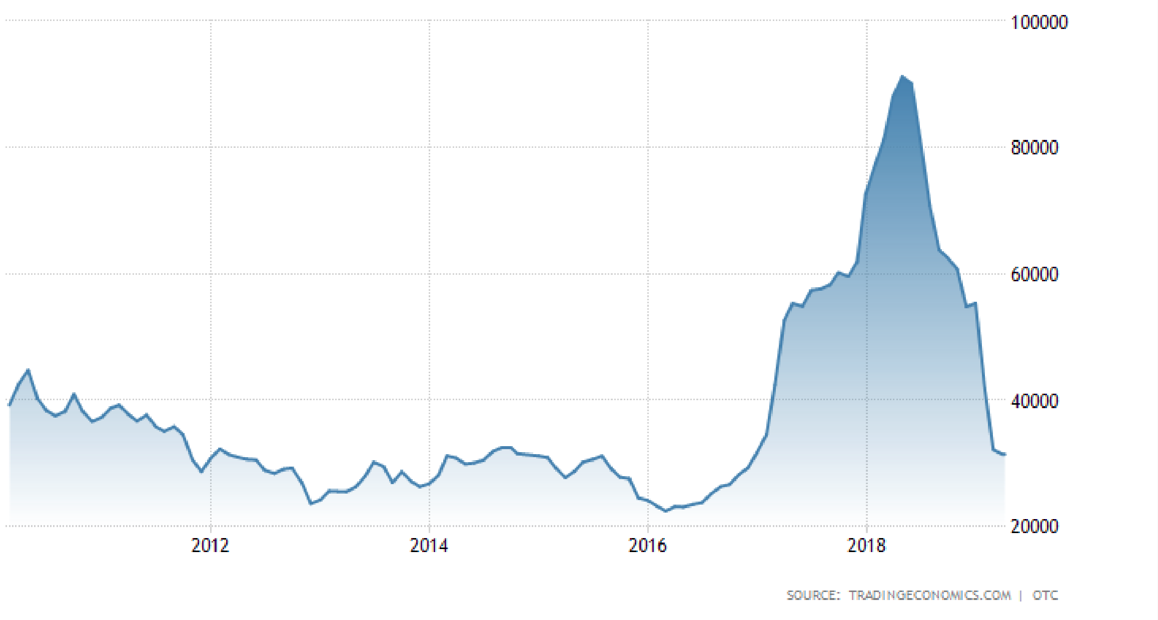
(EIA, 2018)

Tesla has announced that they believe they can produce, but not install, a battery at $100/kWh, for the before the end of 2020 (Maloney, 2018). This is a crucial milestone because $100/kWh of installed capacity is significant for numerous reasons. One reason is that at a battery pack price of $100/kWh, EVs become cost competitive with conventional vehicles which would create an incremental surge in demand for batteries. If the raw costs to make a battery are above $100/kWh then batteries cannot be manufactured for less than that. Near $100/kWh there will be areas of the country where peaking capacity for batteries is at grid parity as shown Figure 1-4. A less aggressive prediction from Bloomberg Energy Finance has a battery price of $209/kWh in 2018 with an average decline of 19% per year for the past 6 years (Curry, 2017). With this assumption that would put battery prices somewhere around $170/kWh in 2019. There are different price targets for power and capacity. Both prices are expected to change in installed costs at similar rates. Companies and reports all have different forecasts for battery prices in the future. Some of them are aggressive like Tesla's having pack costs at $100/kWh and others project no price decline at all. The reality is that because raw materials make up a large portion of the cost of batteries, the cost of those commodities will have a strong influence over the cost of the batteries when compared to efficiency gains in manufacturing. Figure 1-6 and 1-7 below show the commodity price of lithium and cobalt over the past 5 years.

Figure 1-6: Lithium Prices ($000/Metric Ton)

SOURCE: TRADINGECONOMICS.COM | OTC

Figure 1-7: Cobalt Prices ($/Metric Ton)



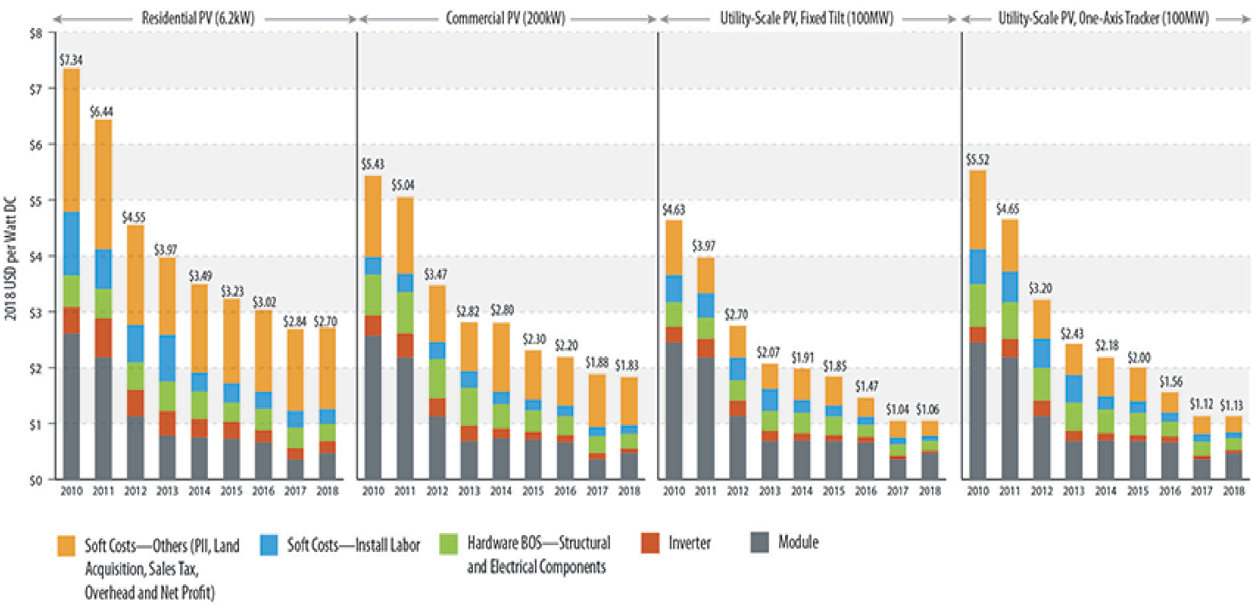
SOURCE: TRADINGECONOMICS.COM | OTC

(Trading Economics, 2019)

1.1.4 Renewable Penetration and Integration

Both wind and solar costs have dropped significantly over the past decade. The maturation of solar manufacturing while increasing the efficiency of the panel’s production has led to a steep drop in $/kW. Wind has experienced a less dramatic, but still significant drop, due to the construction of larger turbines with similar balance of plant (BOP) costs. With state renewable portfolio standards, dropping prices, and environmental concerns, incremental renewable power resources will continue to proliferate. Swanson’s law has observed that photovoltaic (PV) prices drop roughly 20% each time the cumulative shipped volume doubles. This results in a price drop by about half every decade. Figure 1-8 shows the historical cost of utility scale solar.

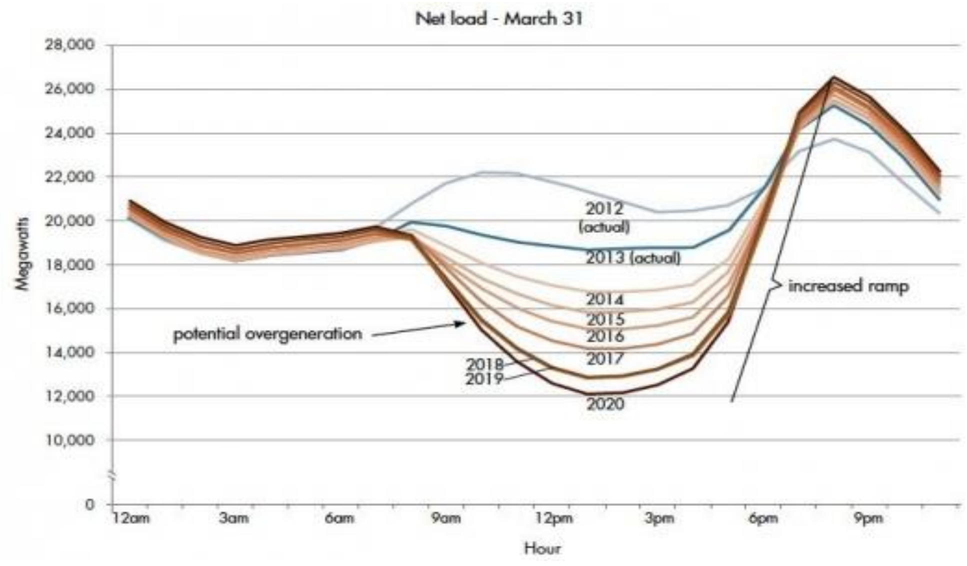
Figure 1-8: Historical Installed Cost of Utility Scale Solar



(U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018)

When the percentage of renewable energy increases in a region it creates various challenges for system operators. Solar generation only produces when the sun is shining, and wind only produces when the wind is blowing. One issue is the duck curve experienced by the CAISO where high solar penetration has created a load and generation mismatch as shown in Figure 1-9. The solar panels are overproducing which is requiring the system operator to ramp down generation early in the day and then quickly add generation as the solar stops producing and the demand realized by the utility increases dramatically. This creates a ramping problem where hundreds of megawatts of generation need to come online in a few hours. In California the duck curve is problematic, but it would be as problematic if they had a generation mix with more flexible generating units. California regulators are requiring utilities develop large amounts of battery energy storage capacity and energy to support the incremental solar generation. This problem does not exist today in Minnesota but could with greater proliferation of solar.

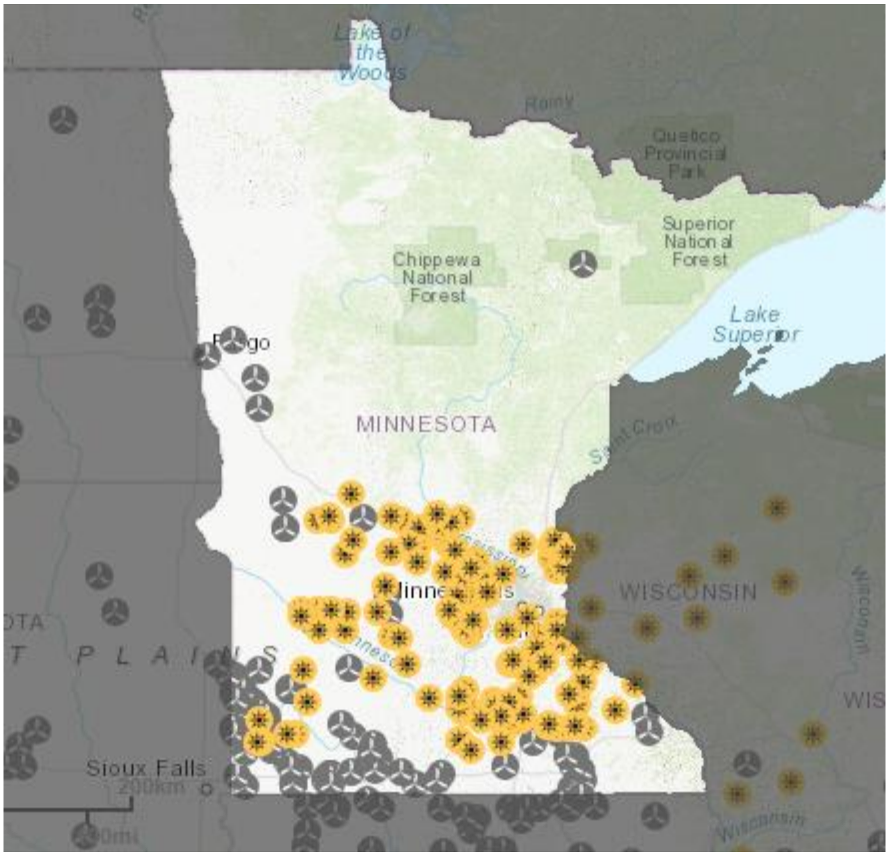
Figure 1-9: California Solar Generation and System Load Duck Curve



The load factor of the overall system gets lower along with the capacity factor of baseload generation with high concentrations of solar panels. This problem can cause baseload generation assets to become less profitable because the fixed assets have been invested in already and are not producing as much energy as expected. Not only does it create a financial problem for existing generators, but it also creates a ramping problem near the end of the afternoon for system operators. All of these factors mean that there needs to be a higher margin of supply to ensure that the electricity demand will be met. With batteries attached to solar and wind farms these problems can be mitigated. In an ideal world, anything generating over the base load requirement can be stored until needed. With prices being the main driver of action, it can be expected that as more solar is paired with batteries and added to the system, owners will store and dispatch when prices are favorable. This will help mitigate problems associated with the duck curve and reduce rapid market price increases in the late afternoon. Baseload generation will also sit idle for less time and the renewable generation assets can provide power more often at times of higher demand when paired with batteries. Under this scenario there is a relatively small margin of supply for system operators.

Due to the disparity in solar insolation between California and Minnesota, Minnesota may not experience as dramatic of a duck curve scenario. Minnesota's favorable wind resources spread variable production throughout the entire day instead of concentrated in roughly an eight-hour window. However, depending on the season and the future of Minnesota's wind potential, the wind turbines may produce excess generation at night when demand is low. With enough renewable penetration the duck curve concept will still exist; however, the problem can be turned into an advantage if solar and wind projects are coupled with storage and demand response services. Currently Minnesota has a high solar and wind penetration compared to neighboring states with Iowa being an exception for wind penetration. Future wind and solar projects planned in Minnesota are shown in Figure 1-10.

Figure 1-10: Solar and Wind Projects Planned in Minnesota



While the solar projects' production may seem small with a total output of 100 MW, the projects are significantly outpacing other resources in terms of the number of installations. There are 55 announced solar farms with an average size of 1.77 MW per facility. The total operating capacity of power plants in Minnesota is roughly 25.2 GW as of 2018. Upon completion of these solar projects, solar will make up about 5.0% of the operating capacity in Minnesota. These projects and similar facilities announced in the future will be good candidates for pairing with battery storage due to their size. Solar and battery sites can be added as they become economically viable. Dispatchable batteries can help reduce the maximum peak of the system. With rising peak demands and decreasing load factors batteries can be added as the solar grows incrementally deferring the need for additional large-scale peaking generation.

Renewable generation is second to coal generation in terms of total output in 2017 in MN as shown in Appendix A. This was not true a few years earlier. In 2010 coal and nuclear were the main sources of generation. There has been a general increase in overall electricity consumption in Minnesota and with the advent of electrification and population growth it would be no surprise to see this trend continue. These trends are represented in the figures provided in Appendix A. This trend is also not surprising as independent power producers (IPP) can take advantage of the scalability of solar and the relatively quick design to system implementation times. These solar farms can be sized to optimize profit and will continue to be built in areas where the marginal cost of a MWh is lucrative. Batteries have an advantage of utilizing surplus capacity outlined in section 1.1.5.4 and being optimized to the size of capacity compared to conventional sources. Conventional sources cannot typically be as granular in their deployment and have much longer development timelines.

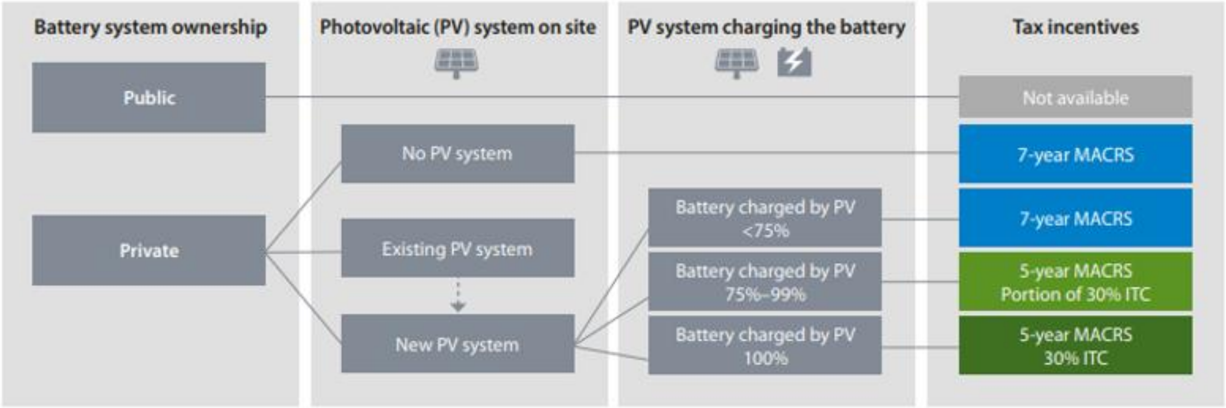
1.1.5 Regulations & Policy

There are several regulations and tax policies in place to incentivize battery energy storage. Several of these are discussed in the following sections.

1.1.5.1 Federal Tax Incentives

There are tax incentives for private developers to install batteries with their solar projects. The tax credit can be taken advantage of in various forms. Under the circumstances outlined below, these investments can obtain better depreciation schedules and tax credits. The biggest benefit of a 30% investment tax credit (ITC) can be obtained when the batteries are charged 100% of the time with solar photovoltaics (PV). This ITC does not have a value limit. Unused tax credits can be rolled over if they exceed the tax liability of the owner for that fiscal year. This benefit also includes a 5-year modified accelerated cost recovery system (MACRS) that saves the owner money by being able to deduct depreciation faster than normal on their taxes. If a battery is charged between 75% and 99% only a portion of the 30% ITC is awarded. For example, if an owner of an eligible system charged with PV 85% of the time, they would be awarded with 85% of the 30% ITC which equates to 25.5%.

Figure 1-11: Federal Tax Incentives for Solar + Battery



(NREL, 2018)

Currently, the ITC only permits eligibility to solar projects paired with energy storage under relatively stringent conditions like the percentage of battery being charged with solar. A bill was introduced in the 115th Congress to amend the tax law to make all different types of energy storage eligible for the tax credit and for pairing with all generation assets; however, it was not passed. While it did not pass in the 115th Congress it may be reintroduced in the 116th Congress and would change the energy storage landscape by expanding the credit to batteries paired with all types of generation and expanding the credit to include all energy storage technology. While RPU cannot take advantage of this tax credit as a public entity, private developers can build the infrastructure and set up a power purchase agreement (PPA) with RPU. If RPU elects to pursue solar and energy storage or wind and energy storage in the future, Burns & McDonnell recommends that RPU secure that power supply and capacity through a PPA with an IPP.

Table 1-1: Energy Storage Investment Tax Credit Phase Out Schedule

Application	2019	2020	2021	2022	2023-2027
Business Application	30%	26%	22%	10%	10%
Residential	30%	26%	22%	N/A	N/A

1.1.5.2 Renewable Energy & Storage Targets

Renewable energy and energy storage targets and mandates are also a driver for the demand for batteries, albeit less than the economic incentives. Many states have renewable portfolio standards (RPS) and cities nationwide are calling for 100% renewable energy. As the renewable percentage of the generation mix increases this will drive demand for batteries as intermittency issues may arise quicker than transmission infrastructure and generation diversification can keep up. Even if transmission infrastructure can be constructed fast enough to keep up with the proliferation of renewable energy demand will create a market for batteries where transmission is too expensive. In California, the California Public Utility Commission implemented a mandate for investor-owned utilities to procure 1,325 MW of energy storage by 2020. The total nameplate generation capacity in operation and planned as of 2017 in California is 143 GW. Assuming the mandate is met that would make energy storage roughly 1% of the generation nameplate capacity. This is a significant mandate as the cumulative battery capacity of the entire United States was less than that at the end of 2017 as shown in Figure 1-12. While the nameplate capacity metric may not be overwhelming, the rate at which it needs to be implemented to reach the mandate is significant. That rate will especially be important if battery installations continue at that rate after the mandate is met.

1.1.5.3 FERC 841

The Federal Energy Regulatory Commission (FERC) filed Order 841 in February of 2018. The purpose of this order was to have operators in the United States create market rules for battery energy storage. The filings from RTOs and ISOs include; rules to ensure that a battery energy storage system can supply services it is capable of, ensuring that the energy storage resource can be dispatched, setting market clearing prices as a buyer and seller, establishing a minimum size of at least 100 kW to participate in the wholesale market, ensuring that reselling occurs at the wholesale locational marginal price, and accounting for the physical limitations of energy storage.

These compliance filings were due to the commission December 3, 2018. Each operator will have different dates at which these filings will go into effect. The Midcontinent ISO (MISO), which is the transmission area RPU operates in, will allow energy storage resources to register as an energy storage resource after the new tariff goes into effect on March 1, 2020. If RPU elects to pursue energy storage as a capacity resource, Burns & McDonnell recommends that RPU waits for the installation of that resource until after the MISO tariff is finalized and in place respectively.

1.1.5.4 FERC 845

As of April 2018, FERC adopted reforms to the large generator interconnection procedures (LGIP) and the large generator interconnection agreement (LGIA). Generators under 20 MW must be accepted in the interconnection queue but are still responsible for all upgrades that are not qualified transmission upgrades. In general, the filing of FERC 845 benefits parties interested in installing battery storage and renewable generation as it helps provide clarity across all wholesale electricity markets. The clarity stems from the updated definition of a generating facility to include storage both in conjunction with another generating facility and as a separate project. The reform helps remove barriers for utility scale storage to participate in wholesale markets. The current interconnection process is thought to stifle competition and innovation with the barriers addressed in the new order. Taking down these barriers allows for more viable battery energy storage interconnections. For example, an interconnection request can be filed to have a lower than maximum capacity of the battery facility in order to prevent paying for upgrades to the system. This can reduce the price of battery or a renewable energy project by avoiding unnecessary costs associated with interconnection and transmission infrastructure.

Another change that FERC 845 enacts allows new generating facilities to take advantage of surplus interconnection capacity. Surplus interconnection capacity is created with intermittent and peaking resources because the capacity of transmission lines is not always fully utilized. A major perk to taking advantage of surplus capacity is that interconnection customers do not have to obtain interconnection rights through the standard interconnection process, but rather an expedited surplus interconnection process. This will create an environment where developers can interconnect relatively quick and at a potentially more attractive price.

FERC 845 also allows for the option to build. If the transmission provider cannot meet the construction timeline of the interconnection customer, the customer can elect to build it themselves. However, the customer may still run into issues with eminent domain and local laws. Under this scenario the interconnection customer would pay for all the upgrades, which was standard prior to the FERC 845 implementation, and get reimbursed for qualified transmission upgrades.

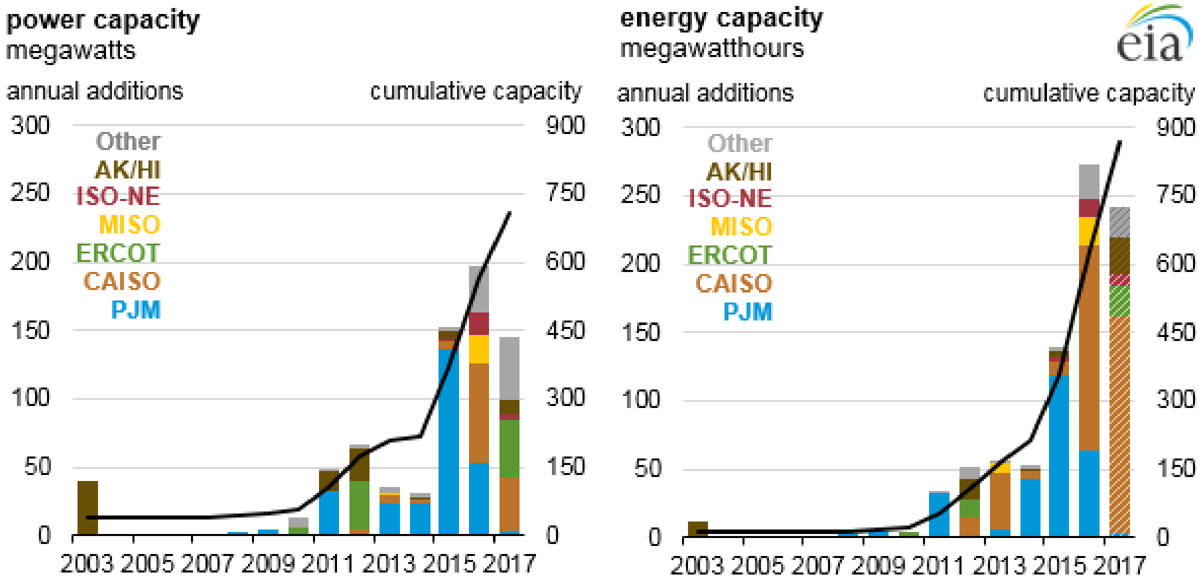
1.2 Market Overview

The battery market in the United States, as of 2017, had 708 MW of capacity with 867 MWh of energy capacity in operation. Of these installations more than 90% were in organized ISO, RTOs, Hawaii, and Alaska and more than 80% of them have lithium-ion chemistries. Just under half of these installations reside in the PJM territory and most batteries in the PJM are owned by IPPs. This is due to the creation of a frequency regulation market in 2012 which made conditions favorable for battery energy storage to be used by IPPs to provide frequency regulation services. These metrics are shown in Appendix B.

As of January 2019, there are 13 battery projects in the generation interconnection queue for a total capacity of 480 MW. Of those projects in the queue, 6 of them are in southern Minnesota for a total of

155 MW of capacity. The interconnection queue of MISO indicates some momentum in the battery energy storage space following behind the trends of other ISOs. However, when those projects come on line they will account for about 0.5% of the total 100,000+ MWs of generation capacity in MISO. Appendix B provides additional information on the location and size of current battery energy storage projects.

Figure 1-12: Annual Battery Capacity Additions in the United States



(EIA, 2018)

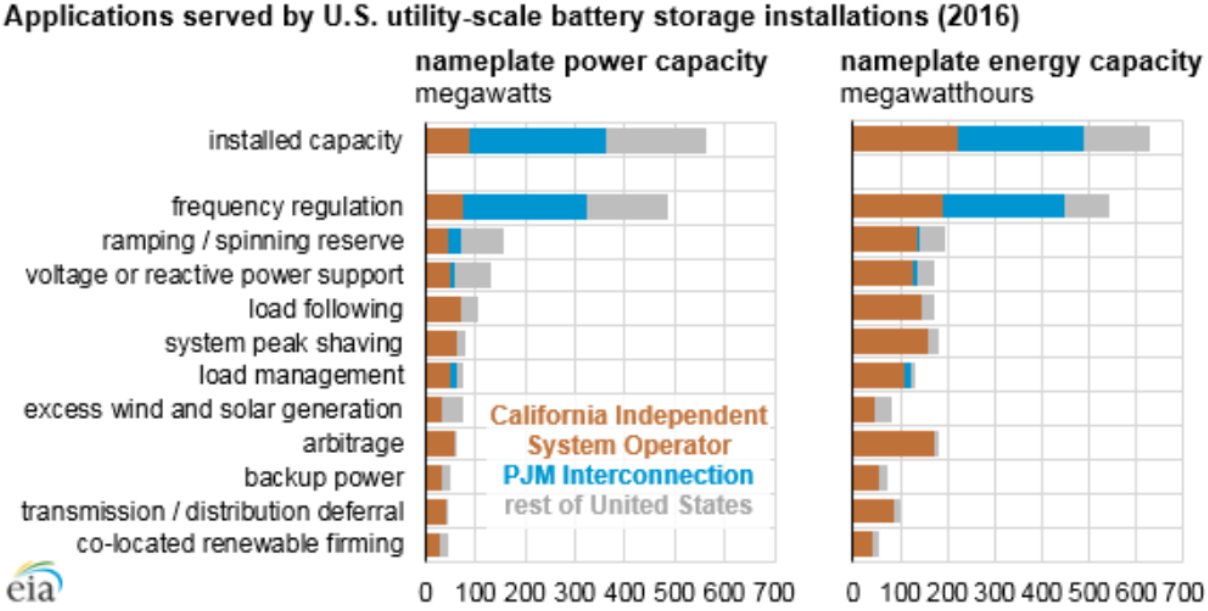
2.0 UTILITY APPLICATIONS

The battery market is still in its nascency and so are the applications that utilities use batteries. However, both are maturing rapidly as price declines. A utility-scale battery is defined as a battery that has at least 1 MW of nameplate capacity. The possible applications of utility scale battery energy storage are numerous. The main reason these applications are so broad is that batteries are modular. Batteries can be placed anywhere on the power grid and be sized according to the value stream it is attempting to address. This allows batteries to be competitive in numerous ways. They can be sized to optimize revenue and take advantage of the modularity of batteries to reduce the risk of uncertainty. Not only are batteries modular, but they can serve a vast array of different grid services. A battery can be used for frequency regulation, helping a black start, peak demand shaving, storing cheap power, and many others. A battery cannot do all these services at once. Batteries are designed for a primary task but can be utilized for different services if the primary task is not needed all the time. For example, if a battery is designed for peak demand capacity, it can be used for energy arbitrage during the off-peak seasons to add revenue without misusing the battery.

An important concept to take into consideration when thinking about utility scale battery energy storage when compared to conventional generation assets are the metrics that they are defined by. Typically, power plants are described by the maximum instantaneous power that they output in MW. With baseload generation it is assumed that they can operate almost continuously at or around those power levels with consistency. With the advent of renewables, this paradigm began to shift as the maximum power output cannot be controlled nor the timeframe at which it occurs. With batteries there is another variable, energy capacity. Batteries do have a maximum power output, but it also comes with a duration at which the battery can operate without having to pause to recharge. Therefore, battery systems are defined by their maximum power output in MW and the maximum energy stored in MWh. When looking into a battery solution it is important to note that batteries can have a high-power capacity or a high energy capacity, but not both. Batteries cannot effectively be designed for power and capacity due to the way the modules are connected to maximize power or capacity. Batteries can also be designed to maximize lifetime, but this configuration will negatively affect the maximum power output and duration of operation. The price of the battery will be contingent on the desired maximum power and energy.

In general, the battery market is predominantly in PJM and CAISO with PJM’s ancillary services market driving battery installations and capacity driving installations in CAISO. The way utilities are using batteries is shown in Figure 2-1.

Figure 2-1: Applications of U.S. Utility-Scale Battery Storage Installations (2016)

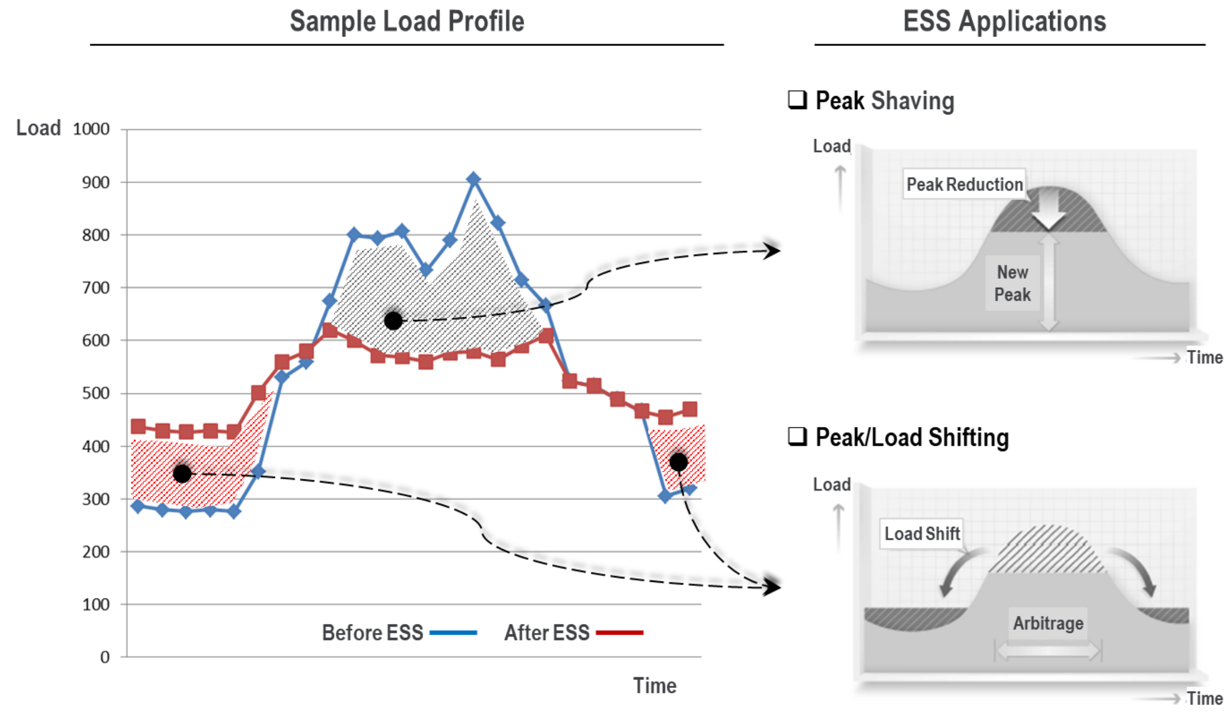


2.1 System Peak Demand Management

Peak demand can be costly and difficult to prevent for a utility. Every extra MW that needs to be provided at a peak time that normally isn't provided, can be offset by battery energy storage. Batteries can be a cost-effective alternative solution compared to other peak capacity resources. Batteries used for this purpose will also add value to the grid during off peak times through secondary value streams. High capacity factors and scalability give batteries a two-fold advantage over other peak demand resources like large natural gas peaking plants. The battery can be optimized so the resource has a desirable capacity factor.

Batteries can also be used to shift load daily as well. Batteries can fill in the dips during the night time and help during higher loads. The batteries can help shave daily peak load or help smooth out the ramping period as demand surges or solar production ramps down. Depending on the cost structure, it may even help disperse demand or congestion charges on the transmission systems. This value add can be used during the off-peak season to help make a business case for a battery more robust.

Figure 2-2: Conceptual Peak Demand Management with BESS



2.2 Energy Market Arbitrage

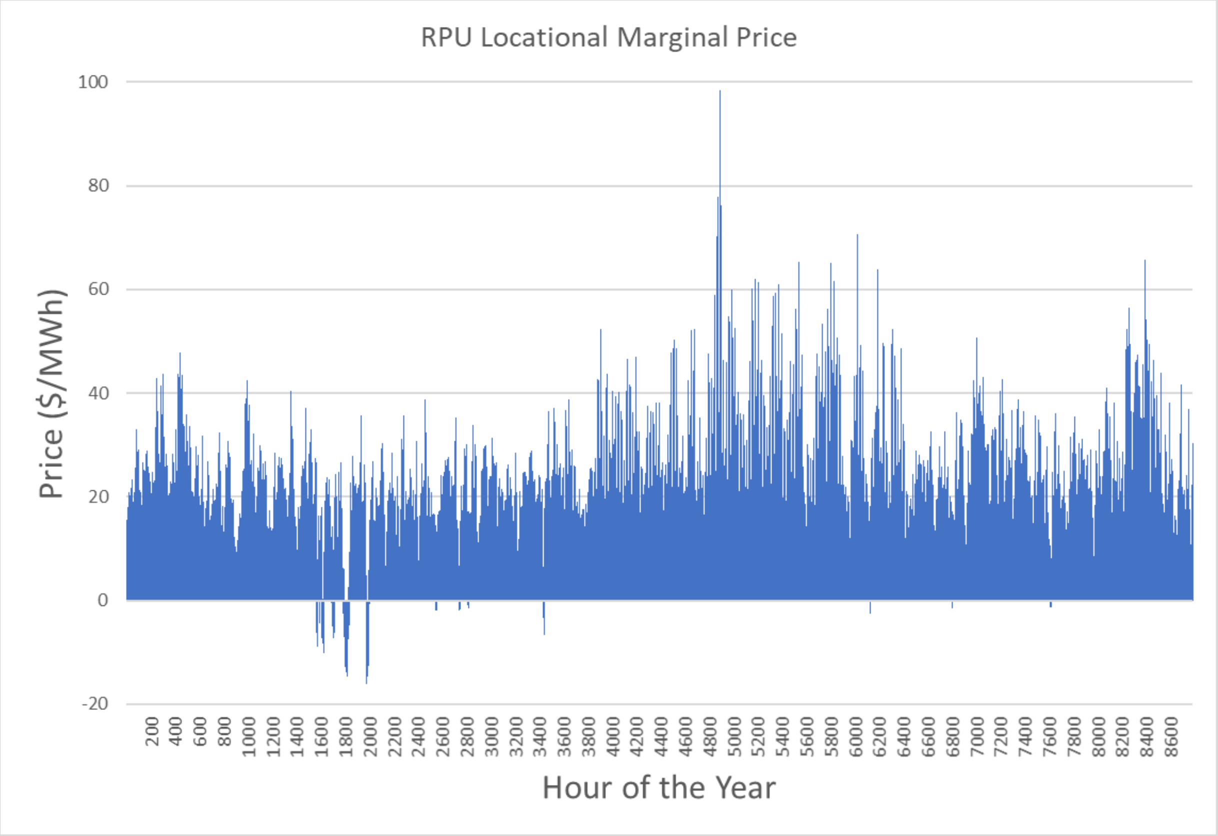
Energy arbitrage can build a business case for a battery by taking advantage of the disparity between the prices that were bid the day before and the real time prices in the market. While it can be difficult to predict the value stream of this method, the basic concept is simple. When the real time price of electricity exceeds the original bid, the battery can expend itself and the and charge when prices are relatively low. Energy arbitrage can be used in conjunction with many other value streams if it does not impede the primary focus of the battery. For example, if a battery was built for the purpose of back-up power or shifting load to a later portion of the day, the battery needs to have enough charge to fulfill the task it was given. Energy arbitrage can be a difficult business proposition due to the infrequent or unpredictable events in which the batteries will be able to charge at low prices and discharge at high prices.

Another nuance to take into consideration is the length of time it takes to charge and discharge the battery. Batteries are designed to have a certain charge rate and the life expectancy can be affected if the battery is charged at inappropriate levels. With energy arbitrage being contingent on acting on price spikes and declines there will be a tradeoff between the profitability during an event and long-term lifetime of a battery. For example, if there was a price surge for 30 minutes and there was a decaying price point for the next few hours the battery would want to expend all of its energy in the 30 minute window when prices are high. After the event the battery can recharge when the price is low. This would enable the battery to have a greater profit margin for that cycle; however, there is some finite and expedited battery degradation due to it being discharged or charged above the recommended range of charge rates. Battery manufacturers will provide a maximum continuous charge current and a maximum pulse current, which lasts 30 seconds, to prevent excessive damage to the total capacity of the battery. The battery can also take the decaying marginal profits over the next few hours and experience a more appropriate discharge rate for the value of not unnecessarily reducing the life of the battery.

The charge rate of a battery design will be crucial in determining how much value energy arbitrage can add to a business case. The energy arbitrage business case is like the peaking capacity business case due to price spikes being correlated with spikes in load. As more renewables come onto the system there may be opportunities in specific locations to take advantage of locational marginal prices for both overloaded transmission lines or improbable events of multiple renewable generation assets going offline congruently. Batteries with higher charge rates, decreased initial prices, the frequency of events where the real time prices significantly differ from day ahead prices, and the cost to charge the battery are all factors that can impact decisions on battery investments now and in the future.

At RPU’s MISO load node for locational marginal price (LMP), shown in Figure 2-3, roughly 26% of the hours are above the breakeven point for energy arbitrage assuming that the battery is charged with the average electricity cost. To have a net benefit from this model the battery would need to be charged at lower than average prices. Figure 2-3 shows the infrequent and clustered negative price points. This business model is difficult to enact because the battery needs to be charged and ready for price spikes but it is only lucrative when charged below a certain price threshold. The battery can seldomly be used for anything else because it needs to have capacity for price spikes. There can also be multiple days in a row that arbitrage does not make economic sense. Additionally, batteries will also have a maximum round trip efficiency of approximately 90% which further impairs the business case for energy arbitrage on a standalone basis.

Figure 2-3: RPU Locational Marginal Price



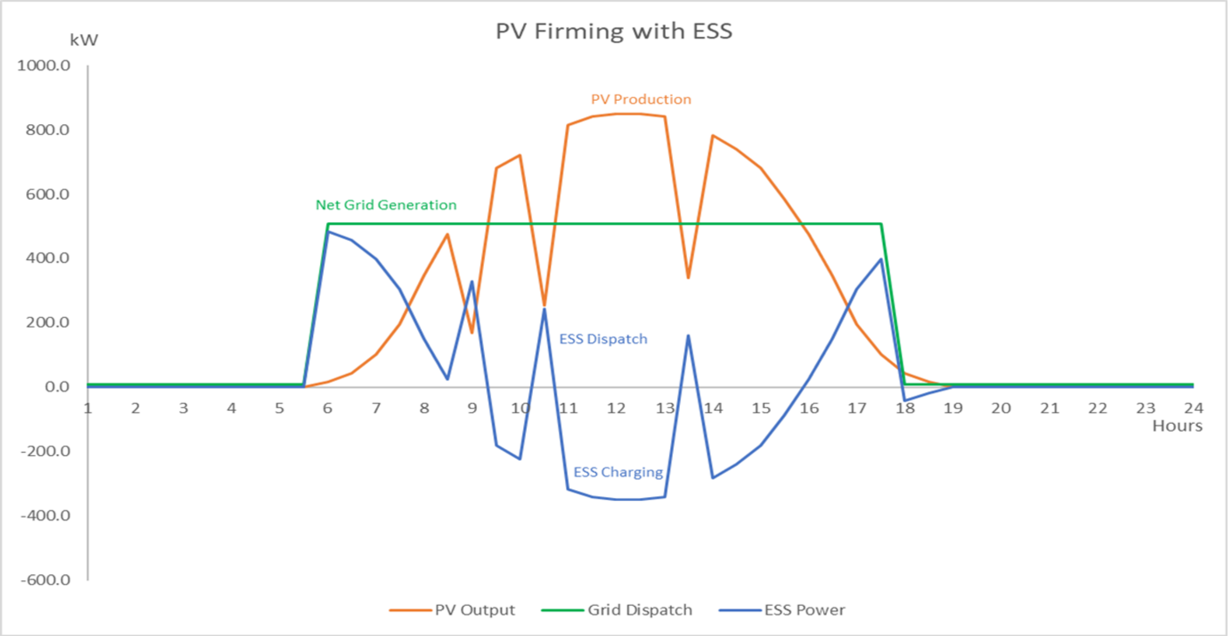
2.3 Renewable Integration

As more renewables interconnect to the grid the value of the generation goes down while the value of firm capacity goes up. This is due to the margin of supply for generation assets going down. As more resources entering the grid are unpredictable, there must be enough back up generation if a multitude of generation assets stop producing when it was predicted that they would be generating. This creates the need for idle generating assets. Firm capacity value can be added by placing energy storage at a solar or wind facility. However, this may not be lucrative under scenarios where back up generation is plentiful and renewable penetration is low. As conventional coal and gas units continue to retire and non-dispatchable assets come online, energy storage will be a more viable and attractive option.

2.3.1 Renewable Resource Firming Capacity

Solar farms can also have sporadic spikes and dips due to cloud coverage and other environmental variables. Batteries can help smooth out this generation by stepping in during dips and preventing unwanted spikes. This smooth generation facility can be more manageable for owners and system operators. This non-dispatchable firming helps provide stable net generation to the grid. If RPU pursues solar and wind, it should consider pairing that resource with battery energy storage to obtain firm capacity.

Figure 2-4: PV Non-Dispatchable Firming



2.3.2 Renewable Resource Storage and Management

In scenarios like the duck curve described earlier, renewable resource storage and management can be crucial to a solar or wind investment. While the duck curve is an extreme case, every unit of solar added decreases marginally in value because the power is not being produced when needed. Under this scenario the battery would act more similarly to the energy arbitrage business case or peak capacity. The battery can store production when the market is saturated with solar and discharge at a higher price point.

Storage can be utilized to smooth out the big ramp up in production that is needed in the late afternoon. This makes the solar more valuable because it is being dispatched under higher price points and is valuable to system operators by allowing for more predictable ramping needs and putting less strain on their assets. With significant energy storage penetration this ramp can be continually mitigated as more energy can be stored and used later. With a flatter load profile, utilities will see fewer demand peaks from a conventional generation perspective. By the end of 2018 battery energy storage has helped mitigate the disparity between minimum and maximum generation during the duck curve by less than one percent. One percent may seem insignificant, but with the amount of energy storage in CAISO that is planned to be added, the percentage will continue to rise. Recurrent Energy announced a 150MW solar farm paired with 45 MW and 150MWH of lithium battery storage for the purpose of providing dispatchable solar in

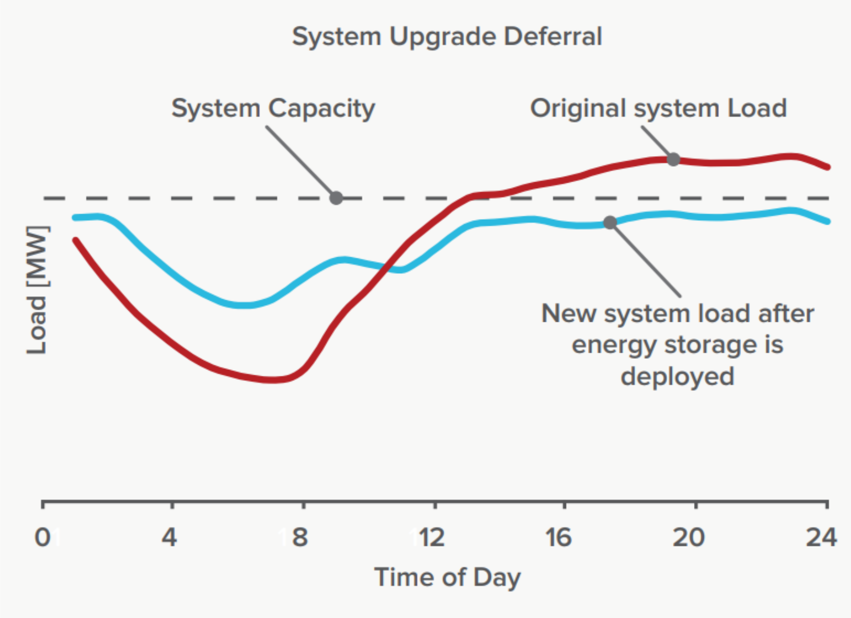
2018. The project is expected to begin operation in 2021. The purpose of this project is to curtail daily peak demand when solar resources are waning in the late afternoon.

2.4 Transmission and Distribution Infrastructure Deferral

A viable business case can be made for batteries under the right circumstances for infrastructure deferral. Many T&D projects take multiple years to complete and must be started many years before the new capacity is needed. Not only do they have long lead times, but they also have inherent risk. The risk is that the projected demand is not going to be needed or fully utilized at the completion of the T&D project. The risk of projecting load is that it may not materialize in the way it is predicted. The prediction may assume that the upgrade is needed too soon or may never be needed. Batteries can help extend the life of T&D assets and prevent unnecessary upgrades. The other major motivator behind T&D deferral is shifting an upgrade to the end of the useful life of the current assets. Figure 2-5 shows a conceptual scenario where the load is expected to exceed the system capacity. For example, if a 115kV line is heavily loaded for a small percentage of the year, but still requires an upgrade, a battery can help prevent an upgrade until the transmission line has reached the end of its useful life. The congestion relief can still be a viable business case if the congestion is not enough for a transmission line upgrade. The value of batteries in this business case is reducing the risk of stranded assets, extending the life of existing assets, and providing a cheaper and quicker solution.

Batteries for T&D deferral are typically designed between 2 MW and 10 MW. While transmission system use cases can be made for most of that range, distribution solutions should be less than 5 MW.

Figure 2-5: Conceptual Asset Deferral



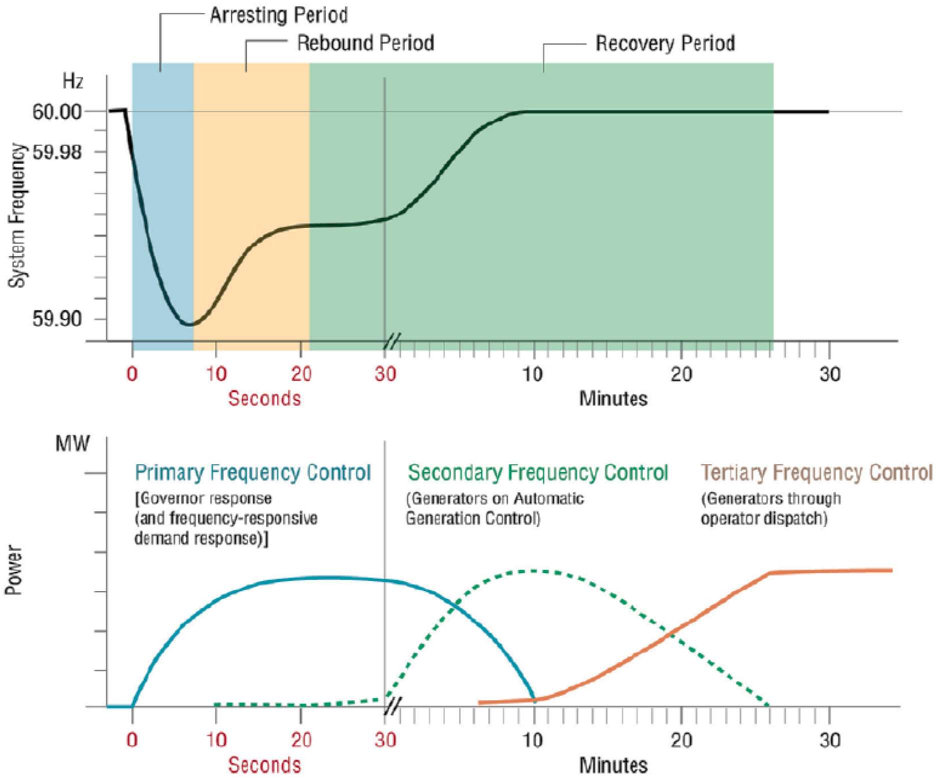
2.5 Frequency Regulation

The AC power system is sensitive to fluctuations in frequency and typically operates at frequency of 60 Hz. If the system experiences frequencies +/- 0.3 Hz outside of the normal frequency, the system's protective devices will trip or equipment will begin to be damaged. Frequency deviates from 60 Hz when generation does not meet demand. If a power plant unexpectedly goes offline it can cause a significant dip in frequency as generation has gone offline while demand remains relatively the same. The same principle applies for massive unexpected added load. If there is excessive generation or a massive decrease in load in a short period, the frequency can become too high. These frequency issues are typically dealt with by the methods outlined in Figure 2-6.

Batteries can respond within seconds giving them a significant advantage when attempting to deal with frequency issues on the power system. Frequency issues are short in duration because they can be mitigated by adding generation, using the nearby power plants' auto generation reserves, or turning on a new unit. These methods help return the frequency to normal conditions, but they take longer to respond. Batteries can help return the frequency back to normal operation and prevent under frequency violations while waiting for the secondary and tertiary frequency control measures to come online. Batteries add another quick, primary response to frequency issues without needing to cut demand.

Since 2012, PJM has had a frequency regulation market favorable for batteries. PJM has a regulation service that compensates resources that respond to their automated signals. MISO does not have similar incentives for batteries. The automated signals accurately adjust output or consumption to regulate frequency. Under this lucrative scenario, batteries are dispatched under frequency disturbances to prevent over frequency and under frequency trips, equipment damage, and frequency disturbances by mitigating the issue within the time correction period. To have frequency regulation be part of the business case the owner of the battery needs to ensure that the state of charge (SOC) is always at a level where it can accept or inject power into the system at any given time by PJM's automatic signal. This allows the batteries to have limited opportunities for secondary value streams. Participating in frequency regulation will reduce the lifespan of the battery significantly due to the harsh operating conditions it will respond under. This should be taken into consideration when analyzing a business case.

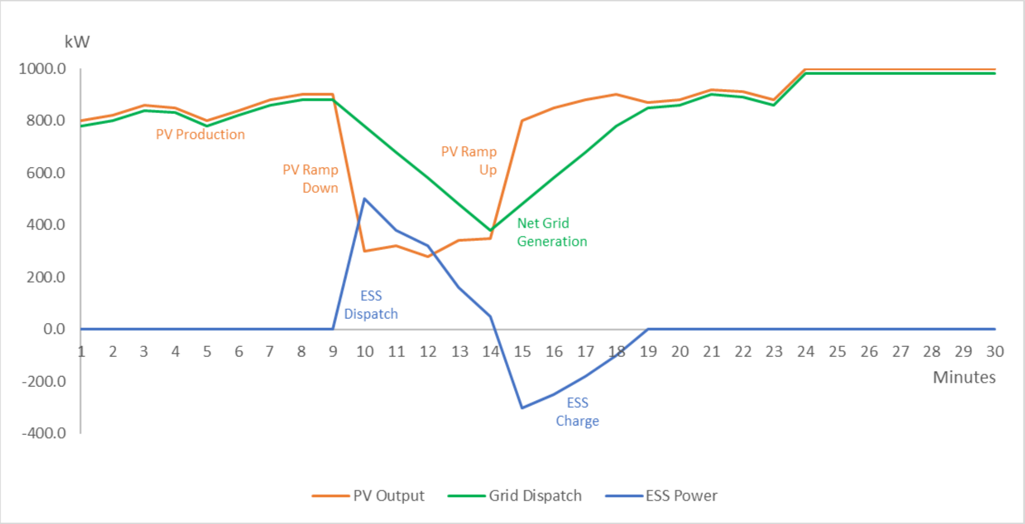
Figure 2-6: Frequency Regulation



2.6 Ancillary Services

Batteries can provide ancillary services other than frequency regulation such as VAR support, voltage support, spinning reserves, and ramp rates. All generation assets can assist with ancillary services. The main advantage of batteries in this space is the scalability and location diversity. However, ancillary services may be used to supplement a business case. These services are desired much more in PJM territory than in MISO. With regulatory changes ancillary services can add to the value stream of a battery. Figure 2-7 shows how batteries can help with ramp rate control under a high solar penetration scenario.

Figure 2-7: PV Ramp Rate Control with BES



2.7 Reliability Improvements

Batteries can help improve reliability from numerous standpoints. Customers can install them to prevent blinks. Utilities can install them on the distribution system to enhance their reliability metrics like SAIDI and SAIFI. Batteries also have an opportunity to help restore power in major outage events like storms. These metrics can be enhanced, but only marginally since the batteries would be placed at the distribution substation. Customers can implement batteries to enhance their own reliability metrics, but this is out of the utility’s direct control. Where reliability can come into consideration for a business case is if it is paired with ancillary services at the distribution level. Areas with high rooftop PV penetration would make more worthwhile locations. The batteries would not be able to keep the power on forever, but it can help reduce the amount of time customers are without power. With the expectation of high-quality power in the United States batteries can make a difference in the duration of outages. Most areas of the United States experience a reliability rate above 99% and it is unlikely that a battery can recover costs by operating for less than 1% of the year. A business case made primarily from distribution level reliability is unlikely; however, showing the benefits of reliability improvement may help get the battery investments funded by regulators. There are a multitude of ways to achieve similar reliability results so batteries may not be the best solution to address that problem in isolation. A business case analysis would need to be done to determine whether batteries are the correct solution for the problem.

3.0 BATTERY TECHNOLOGY

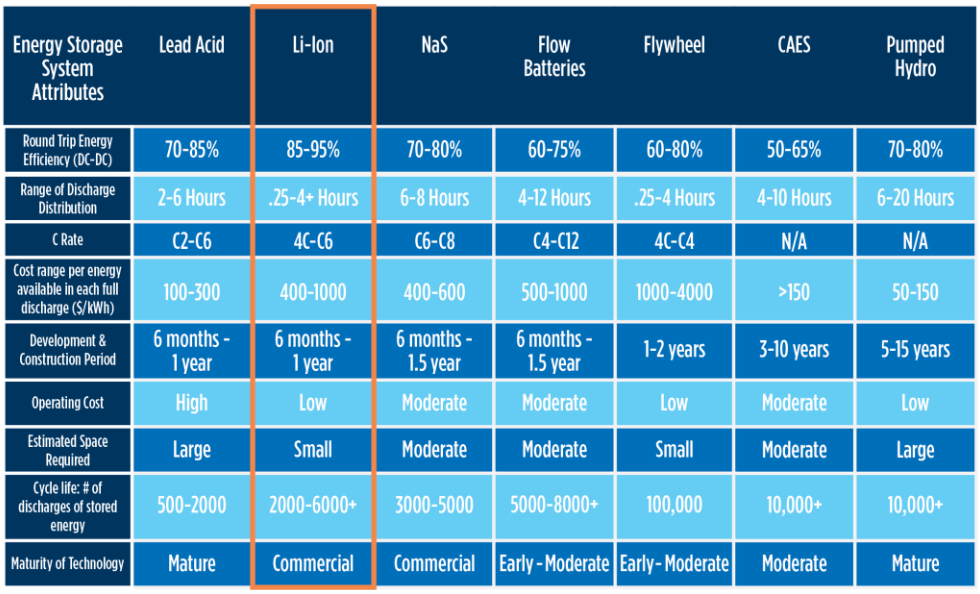
3.1 Energy Storage Technologies

This paper has discussed the broad applications of lithium-ion batteries from a utility perspective. This analysis has assumed that lithium-ion batteries were in use. However, there are hundreds of potential chemistries for lithium-ion batteries with a broad range of characteristics along with other available energy technologies. Other energy storage technologies can have viable utility scale applications, but many of them are lagging in price reduction due to not having a distinct price reduction driver or are already a mature technology. Some of these technologies have notable presence in the current operating energy storage market like lead acid batteries and compressed air storage. Even with the disruptive addition of lithium-ion batteries to battery storage systems, these technologies will continue to operate and be added because the technology is mature.

Other battery types like lead-acid have been around for decades. The major setback for lead-acid batteries is the energy density. The energy density of lead-acid batteries can be as much as 33% of a lithium-ion battery. Energy density is measured by energy per volume or Wh/L. Batteries with a lead-acid chemistry do not have a sufficient energy density to fit into vehicles and still maintain the desired range of all electric vehicles. However, it is less of an issue for stationary storage. Lead-acid batteries are a notable amount of the operating batteries in the United States and hold a portion of the market due to their ability to be deep cycled. The main perk of lead-acid batteries is the cost as they are cheaper than lithium-ion batteries. Lead-acid batteries can have a better business case for energy storage applications that are not inhibited by the size of the infrastructure or power density characteristics.

Even though space is less of an issue for a utility scale production, the cost reduction of a more energy dense battery poses a few advantages. These advantages include but are not limited to; smaller footprint, flexible chemistry options, and the forecasted price reduction with more R&D. Sodium sulfur batteries are also commercially available; however, the characteristics like lower round trip efficiencies and their costs are rarely an attractive option. Sodium sulfur batteries are not popular in the United States, but have a presence in Asia. Figure 1Figure 3-1 provides characteristics of various energy storage technologies.

Figure 3-1: Energy Storage Technologies Characteristics

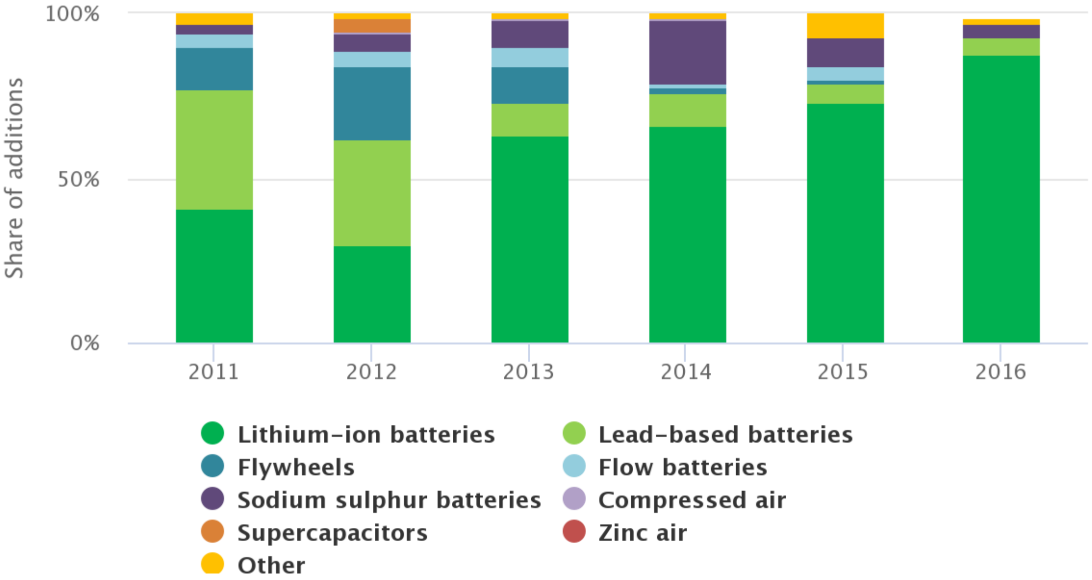


Energy Storage System Attributes	Lead Acid	Li-Ion	NaS	Flow Batteries	Flywheel	CAES	Pumped Hydro
Round Trip Energy Efficiency (DC-DC)	70-85%	85-95%	70-80%	60-75%	60-80%	50-65%	70-80%
Range of Discharge Distribution	2-6 Hours	.25-4+ Hours	6-8 Hours	4-12 Hours	.25-4 Hours	4-10 Hours	6-20 Hours
C Rate	C2-C6	4C-C6	C6-C8	C4-C12	4C-C4	N/A	N/A
Cost range per energy available in each full discharge ($/kWh)	100-300	400-1000	400-600	500-1000	1000-4000	>150	50-150
Development & Construction Period	6 months - 1 year	6 months - 1 year	6 months - 1.5 year	6 months - 1.5 year	1-2 years	3-10 years	5-15 years
Operating Cost	High	Low	Moderate	Moderate	Low	Moderate	Low
Estimated Space Required	Large	Small	Moderate	Moderate	Small	Moderate	Large
Cycle life: # of discharges of stored energy	500-2000	2000-6000+	3000-5000	5000-8000+	100,000	10,000+	10,000+
Maturity of Technology	Mature	Commercial	Commercial	Early-Moderate	Early-Moderate	Moderate	Mature

[1] C2 is a C rate of 0.5 (i.e. slow) and 2C is a C rate of 2 (i.e. fast).

Even though these energy storage options may seem like attractive solutions, lithium-ion batteries have dominated battery deployments recently. Figure 3-2 shows the dominance in deployment statistics up to 2016. This is due to the massive increase in deployments of energy storage overall and most of those energy solutions being lithium-ion. If battery energy solutions start to trend to larger batteries in terms of energy, then redox flow batteries can be expected to be deployed in greater quantity.

Figure 3-2: Battery Deployment Percentages by Type



(Energy Storage: Tracking Clean Energy Progress, 2019)

Lithium flow batteries are competitive with lithium-ion batteries in solutions that are longer in duration. These batteries have the same operation principles. The difference is that the anode and cathode of the flow battery are in a liquid state instead of a solid state. This provides numerous advantages and disadvantages in terms of application. The price differential and the range of acceptable charge rates usually favors lithium-ion, but with a big enough application a redox flow battery can be advantageous. A comparison of Li-ion and flow batteries is provided below in Table 3-1.

Table 3-1: Comparison of Li-ion and Li-flow Batteries Capabilities and Costs

	Li-ion (4 hour)	Li-ion (8 hour)	Flow (8 hour)
Nominal Output, MW	50 MW 200 MWh	50 MW 400 MWh	50 MW 400 MWh
Net Plant Output, kW	50,000	50,000	50,000
Net Plant Output, kWh	200,000	400,000	400,000
Overbuild Percentage, %	17%	17%	0%
Roundtrip efficiency	87%	87%	73%
Discharge Time, hours	4.00	8.00	8.00
Charge Time, hours	4.65	9.30	9.30
ESTIMATED CAPITAL AND O&M COSTS			
Project Capital Costs, 2018 MM$ (w/o Owner's Costs)	**$64**	**$122**	**$120**
EPC Cost Per kW / kWh	**$1290 / $320**	**$2450 / $310**	**$2400 / $300**
Variable O&M Cost, 2018$/MWh	$14.50	$14.50	

Some different approaches to energy storage are pumped hydro, compressed air energy storage (CAES), and flywheel storage. This is not an exhaustive list of options, but for a broader view of energy storage these are the technologies that will be explored.

Pumped hydro uses gravitational potential energy and has been commercially operating for years, but the major setbacks for pumped hydro are the massive alterations it can cause to the local environment, niche implementation locations, and the time that it takes to implement the system. Only locations with demand for energy storage that have water and a significant disparity in elevation over a small distance can make viable locations for pumped hydro.

Compressed air energy storage is like pumped hydro energy storage in that the storage solution is partially limited by niche geographic locations. CAES can be implemented where cavernous geographic characteristics are in place or in air storage tanks where there is demand for energy storage. Compressed air is a mature technology that has notable operating capacity; however, there does not seem to be any trend of adding more compressed air energy storage capacity.

Flywheels are similar to batteries in the fact that they get charged up and are scalable. The difference is that the energy is stored in angular momentum. Low speed flywheels are essentially a rotating mass on an axle that spins and works well for frequency response. Fast speed flywheels are rotating magnets that have less friction. This technology has not been fully developed, but with a developing storage market these could have some advantages over batteries. These advantages can include the lifetime of the energy storage unit and precious metal availability. Spinning magnets do not degrade over time like batteries do because they do not over heat; however, the force exerted on them causes them to expel shrapnel eventually. This degradation limits the number of cycles in the lifetime of a flywheel.

3.1.1 Battery Lifetime

The longevity of a battery is predetermined by the type of battery chemistry and can be prolonged or shortened based on how the battery is utilized. Every battery has a unique charge rate, ideal depth of discharge (DOD), loading capacity, and operating temperature impact. Battery life is typically measured in battery cycles, or one charge and one discharge. This metric is used; however, it is not the most consistent as there is no clear definition on what constitutes a cycle. In testing solar panel efficiency every panel is exposed to 1000 $\frac{W}{m^2}$ so that efficiencies can be compared effectively between different panels. There is no set precedent like there is for measuring the efficiency of battery cycles. This means that there is no set precedent to test battery life with a discharge rate, charge rate, operating temperature, discharge depth, and many other variables. This is important to note because different battery chemistries will perform better and have longer life in terms of cycles based on all of these variables. It is important to note that there is a general trend that the deeper the average discharge the fewer number of cycles a battery will have in its lifetime.

Lithium-ion batteries work by trading ions back and forth between the cathode and anode. Theoretically this process should never break down. However, the capacity of a battery does degrade over time. Ions are stored in the anode when there is a charge. The anode is typically made of graphite that allows one lithium-ion for about every six carbon atoms. Graphite is a repeated sequence of a hexagonal carbon structure that builds off each other. When the battery gets overheated this repeated structure can be damaged. If the structure is damaged to the point where a section is broken, a dendrite is created and the ion can no longer be stored in that part of the structure. This process happens thousands of times as the battery is used. This process will eventually lead to a noticeable decrease in battery capacity. The anode will degrade naturally with normal use. Minimizing the anode degradation is the key to prolonging the life of a battery.

3.2 Charging and Discharging

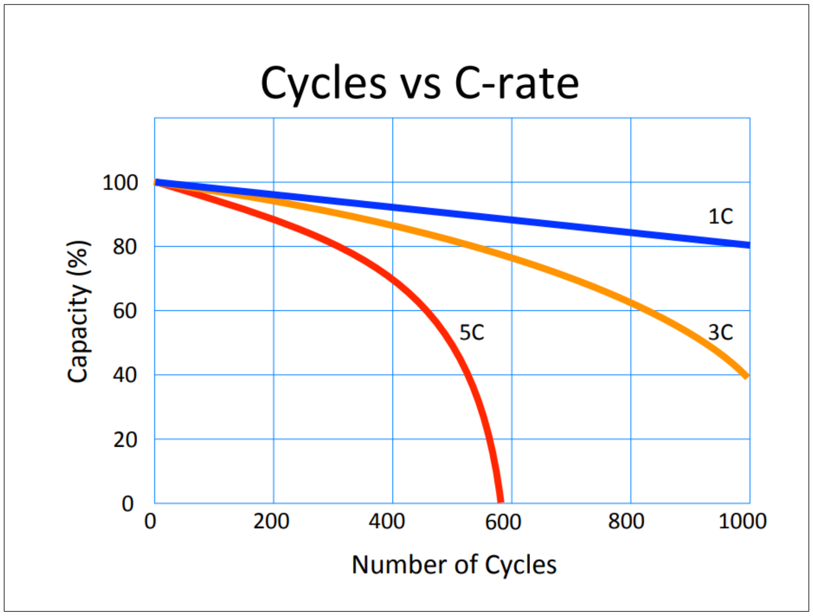
Every type of lithium-ion battery will have a unique C rate. The C rate determines the charge and discharge rate characteristics of a battery. A rate of 1C means that the battery will be completely charged in 1 hour. Each C rate is dependent on the rated amp-hours. This means that a fully charged battery rated for 1 Ah can supply 1A for 1 hour, 500mA for 2 hours or 2A for 30 minutes. A battery with a 40Ah capacity that is charged at 1C would take 40 A for 1 hour. If it was charged at 0.5C, it would charge at 20 A and take 2 hours or twice as long to charge due to being charged with half of the current. If the same battery was charged at 2C it would take 80 amps for 30 minutes due to the doubling of current. Charge rates can significantly affect how much capacity a battery will have over several cycles as shown in Figure 3-3. Batteries can be charged or discharged at different C rates between sessions and even in the same session. As the battery approaches maximum capacity the charge rate should be reduced to minimize reduction in battery capacity. The general practice is to follow the recommended charge current given by the manufacturer until achieving a SOC of about 70%. After reaching that capacity the battery will transition into a constant voltage charging scheme to prevent degradation. This constant voltage scheme allows the battery to be charged with a current that tapers as the battery gets closer to 100% capacity. This has severe implications for battery applications like energy arbitrage and outlines limitations in performance.

Research is being conducted to maximize the charge rate without degrading the battery. Machine learning paired with battery management systems can lower the C rate, with the granularity of fractions of a second, to prevent damage to the battery while allowing the C rate to increase again when the battery can withstand a higher charge rate.

Charging and discharging have similar characteristics. The internal resistance a battery will exhibit is different. The difference between the internal resistance of the battery and the typical load rarely alters how fast a battery can be charged and discharged. The differences in resistance creates a discharge rate that is referred to as the E rate. This E rate is like the C rate because of the similar resistance experienced in charging and discharging.

As mentioned previously, batteries are typically designed for high power scenarios or long duration applications. However, both of those qualities can be sacrificed to maximize number of life cycles. Figure 3-3 is a conceptual graph showing degradation in cell phone batteries over different consistent charge rates. Utility scale batteries are designed and maintained to last for more cycles than shown in Figure 3-1. Figure 3-1 also shows that different technologies have various ranges of potential operational C rates. The most notable difference is the ability for lithium ion to perform above a 1C rate compared to all other battery options.

Figure 3-3: Conceptual Cycle Degradation for Phone Batteries



3.2.1 Temperature Exposure

Temperature of a battery can significantly impact the permanent loss of capacity over time. Not all chemistries react to temperature in the same way, however, most chemistries have a drastic reduction in overall capacity if exposed to high temperatures for long durations. Batteries that experience constant temperatures of above 30°C/86° F are in an elevated temperature state. Being in this elevated state, especially at full charge, can be much more damaging to the capacity of a battery than cycling. Batteries are best suited to operate near 20°C/68°F. The same is true for extremely cold temperatures. Near -20°C or -4°F the battery can lose as much as half of its capacity for that cycle. The capacity at this temperature is reduced due to the slowing of the electrochemical reaction in the battery. Many people have likely experienced this when their phone dies from experiencing cold temperatures but is able to turn back on after it has warmed up in their pocket. Exposure to extreme temperatures can reduce the overall capacity of a battery and should be avoided. RPU should consider this temperature performance penalty during the winter months in the selection and design of future battery energy storage projects.

3.3 Battery Chemistries

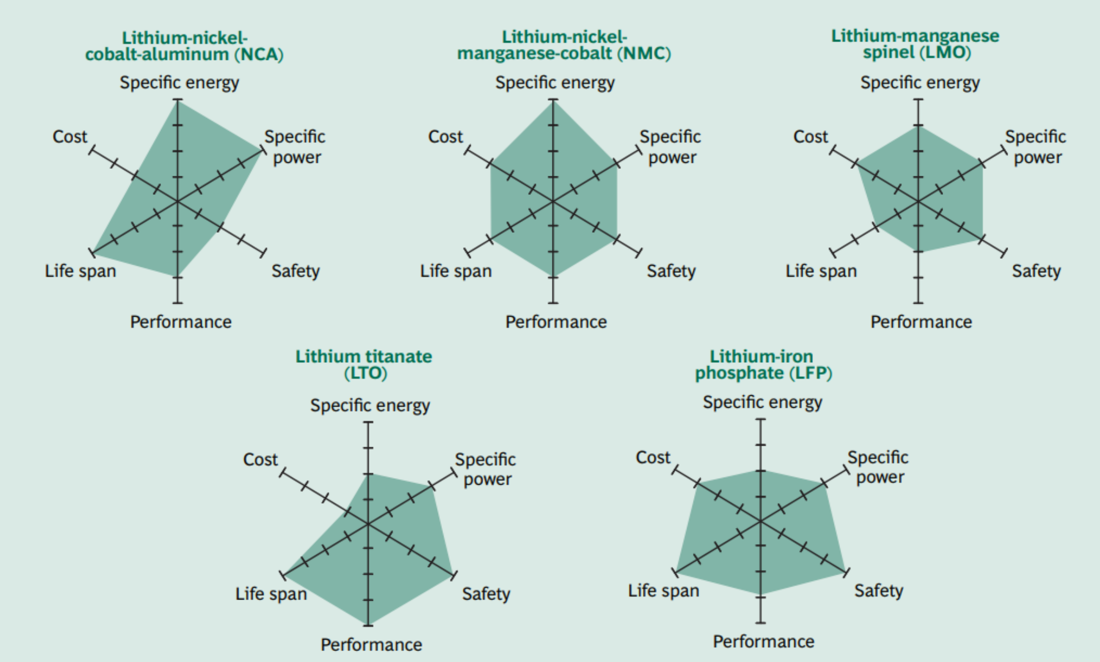
The chemistry of a battery will determine the performance of a battery in six main categories: specific energy, cost, life span, performance, safety, and specific power. Specific energy is defined as how much energy a battery can store per unit of mass ($\frac{Wh}{kg}$). Specific power is a similar metric defined as how much power a battery can achieve per unit mass ($\frac{W}{kg}$). Performance standards consider owner expectations of being able to operate under a myriad of conditions like temperature fluctuations. Batteries can be designed to perform better under certain climates, so this metric is less important if the battery choice is compatible with the climate.

For locations with extreme temperature disparities this metric may be important. For example, a battery in Rochester, Minnesota might want to be designed to operate under cooler temperatures when compared to a place like Arizona. However, it should have the performance metrics to be able to perform under extreme cold as well.

The life span metric takes into consideration the total number of cycles a battery can operate effectively under and how long a battery can be installed and still perform even if it sits idle most of the time. This metric usually measures how long a battery can maintain 80% or above the initial capacity and can be difficult to standardize because degradation varies with different use patterns and higher ambient temperatures.

Figure 3-4 shows the variability in metrics for a variety of different lithium chemistries. IBM’s Watson has identified more than 500 potential battery chemistries that should be researched and developed. While these chemistries are known this effort could take decades to completely fulfill, but it could only take a few good chemistries to significantly reduce the cost for certain battery applications. With an enormous selection of chemistries being tested there is not a clear standard of what chemistry to use for BESS. However, the anode of a battery is almost always carbon. NMC or nickel manganese cobalt is a commonly used as cathode material. NMC is a good candidate because of the versatility in the performance metrics and cost reduction when paired with cheaper lithium compounds. Another common chemistry is LFP or lithium iron phosphate because it is reliable and safe. It is expected that there will be multiple chemistry standards for different applications and regions. These standards are expected to fluctuate as cost reductions and innovation takes place. The standard may not always be the best fit for the desired application, but a standard battery may be the cheapest option for accomplishing the task because of economies of scale. It is important to note that batteries have not followed similar curves of transistor density or solar panel costs. These technologies have an extraordinary rate of technological advancement and cost reduction. Battery capacity has a more linear rate of advancement seeing single digit percentage increases in capacity and similar decreases in cost.

Figure 3-4: Li-ion Chemistries and Varying Performance Metrics



Source: BCG research.
Note: The farther the colored shape extends along a given axis, the better the performance along that dimension.

3.4 Battery Storage Project Design

Batteries are modular due to the way they are designed. One battery is made up of many modules that consist of cells. These modules will have an indicator like 16s2p which stands for 2 sets of 16 cells in series connected in parallel. Adding these modules in parallel give you a larger battery with more capacity and if connected in series will create a higher terminal voltage. Modules can continue to be added in parallel and series until the design requirements have been met.

Every battery system will have a battery management system. The purpose of this device is to protect the cells by managing the C rates, monitoring the state of charge, making sure each cell is evenly charged and discharged, communicating with external signals, and logging performance metrics.

One of the major differences in battery energy storage sites is whether it is in an enclosed structure or free standing. Each option has advantages and differing costs. The free-standing container designs have a shorter construction schedule and built in fire safety inherent with the design. The cost reduction can be given credit to the shipping container style deployment on prefabricated pads. The enclosed building structure has an easier maintenance protocol but is only cost effective at a larger scale. The breakeven point from a cost perspective is roughly 40MWh.

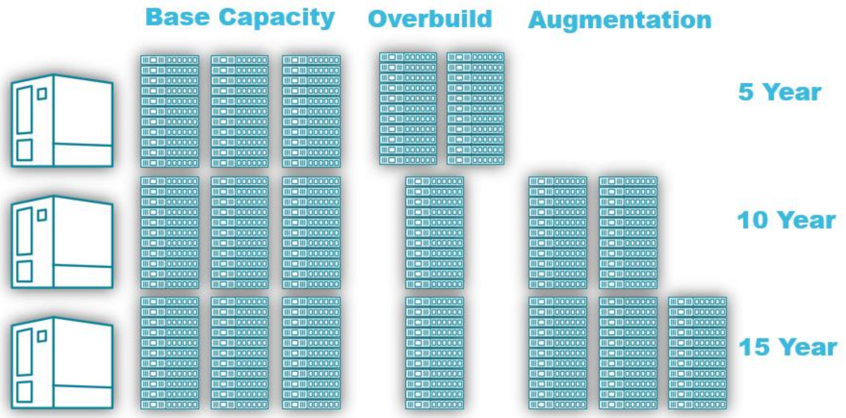
Since batteries must be charged with DC power and the grid operates on AC, a power conversion system, PCS, needs to be selected to pair with the battery system. The PCS consists of an inverter coupled with a transformer. There is a string design for increased redundancy and quicker maintenance. String inverters allow for modular approaches and more granularity in the power output. A battery system with 10 inverters is more reliable because if one of them fails, only 10% of the capacity is offline. The other main option is a central design that is more cost effective. This option is more cost effective because you have less hardware, but if that central inverter fails the entire battery goes offline. Large, phased, and impactful battery sites should consider paying for the string inverter approach for the increased functionality and reliability.

The PCS and HVAC system losses create a round-trip efficiency for the battery plant. The HVAC system takes power to maintain the desired temperature and there are losses associated with the conversion of AC to DC and back to AC again. This round-trip efficiency varies between project sites due to differing HVAC needs. Most projects fall between 85% and 95% efficient.

3.4.1 Sizing and Degradation

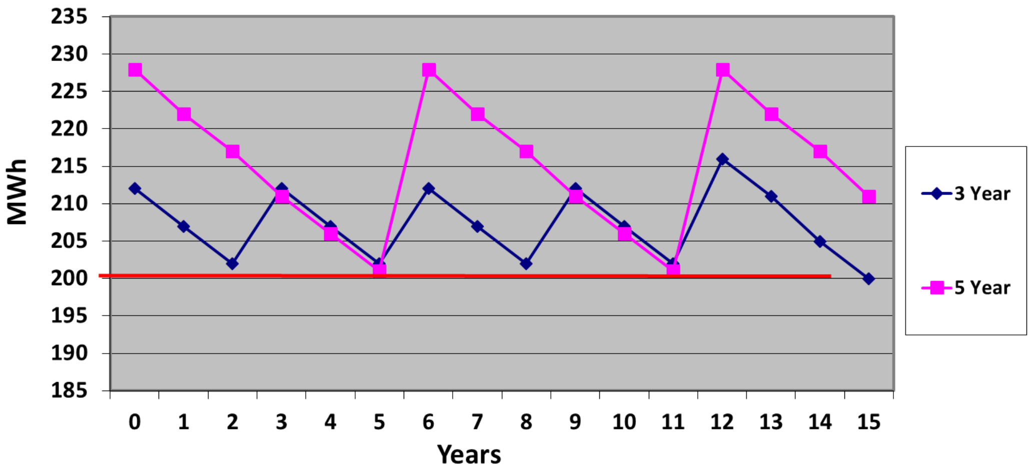
Sizing a battery is one of the biggest considerations when designing a battery facility. With battery degradation a battery site needs to be designed to operate effectively a decade from the initial commissioning date. This means that the system needs to be overbuilt to account for degradation at the facility while still maintaining the appropriate outputs or that there needs to be space available to augment battery production. Each method has different advantages and costs. A battery system that has modular outdoor units and string inverters is much easier to expand on later compared to a system with a central inverter and a center building. Overbuilding also does not require any construction or updates for a few years. However, it also does not allow for the most efficient use and sizing of the battery. Figure 3-5 shows conceptual examples to a battery sizing approach for 15 years.

Figure 3-5: Building Options for Dealing with Degradation



An augmentation approach has multiple possibilities as shown in Figure 3-6. The actual capacity of a battery cannot dip below the capacity that it needs to provide. This example shows an approach that does not allow the battery to go below 200 MWh of capacity. This approach gives varying excess capacities throughout the lifetime of the project.

Figure 3-6: Actual Capacity vs Rated Capacity



The sizing of the battery will determine many of these variables for the project. A 1 MW/ 1 MWh battery does not need an entire building or multiple inverters since it is small. The figures below show several examples of batteries that do not need excessive infrastructure to implement a battery solution.

Figure 3-7: Tesla (3) 1MW / 2MWh Batteries

Figure 3-8: Southern California Edison 20MW/ 80 MWh

Another component to degradation is the increased need for HVAC. As the battery degrades it will generate more heat. The HVAC system must be designed to accommodate this. This can be done one of two ways. The system can be overbuilt to handle the maximum heat towards the end of the life the battery or the temperature and flow of air over the battery can be increased to accommodate the extra heat. The HVAC needs will vary greatly not only with respect to battery degradation, but to seasonal temperature changes as well. In Minnesota, heating measures would also be needed for extreme low temperatures. Even though it does get extremely cold, one exposure to extreme temperatures could ruin the overall capacity of a battery. There are simple additions to the HVAC system that can keep the battery warm under these conditions especially in a building. An analysis should be done on the heating needs required for peak low temperatures.

3.4.1.1 Operation and Maintenance

Lithium-ion batteries have one of the simpler maintenance routines when compared to other energy storage options and even other grid assets like substations. Battery systems are operated remotely. The biggest maintenance cost will be the battery cell replacement every few years depending on the design. The remaining maintenance for battery systems includes periodic inspections of the battery system, fire safety, and HVAC system. The variable O&M costs capture the battery cell replacement cost over the life of the project as depicted earlier in this report.

3.4.2 Decommissioning

Lithium batteries that reach the end of their usable life need to be repurposed, recycled or disposed of. Lithium itself is not a hazardous pollutant, but the chemistry of the battery usually has enough trace elements that they are considered mildly hazardous. With lithium batteries being considered mildly hazardous they cannot be incinerated or thrown into a landfill. This means that they must be recycled.

Batteries begin the recycling process by having all combustible material removed such as casing. The remaining cells are then grinded into little pieces and melted down. This metal is either separated in the liquid or gaseous state since they are separated by different densities. Otherwise they are solidified and sent to metal recovery plants to utilize these resources. This process can be close to an order of a magnitude more intense than mining new material and should be taken into consideration when doing a life cycle analysis of environmental footprints and financial analysis.

The major issue is that there is little economic incentive to recycle lithium batteries. All battery types and chemistries are currently thrown together. There are claims that if batteries could be sorted by similar chemistries the recycling process could turn a profit. With a larger volume of batteries leaving the market from cars and other applications in the coming decades this seems like a viable solution.

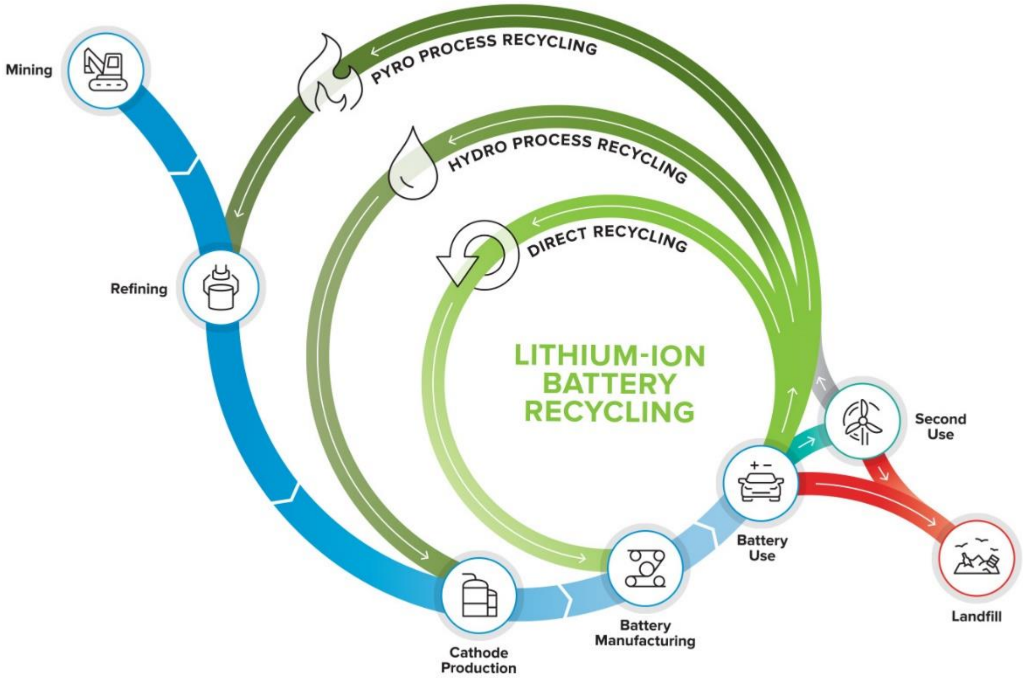
There are many reasons recycling batteries have a net cost. One of the main reasons that recycling lithium is not profitable is because the refined lithium is not pure enough to be turned into second generation batteries. The precious metals like cobalt are desirable enough to retrieve. Second generation lithium must be used for other types of products like ceramics and glass. A technological breakthrough in the recycling process of lithium is required to reuse the material to make batteries. This would create a positive feedback loop in reducing the overall price of battery systems.

Figure 3-9 shows the desired future of lithium recycling with a focus on batteries from EVs. The industry is currently in the pyro process recycling phase; however, the lithium cannot be converted to new cathodes yet. The R&D facility working on these processes has only been around for the last year. This facility will hopefully accelerate the innovation needed for recycling lithium. When the industry can mature to the hydro process or direct recycling it will drastically change the outlook for batteries after they reach their end of life and the costs of disposal.

At the end of 2018 the Department of Energy announced a $5.5 million-dollar prize for the acceleration of lithium recycling processes and the Lithium Battery R&D recycling center continues to investigate recovering battery materials (Staub, 2019). This initiative is fueled by a presidential executive order to be less dependent on foreign sources for these critical resources. Batteries are often bottlenecked by the cost of the precious metals required to make them. For example, a popular battery chemistry includes cobalt. This metal is essentially only available to mine in the Democratic Republic of Congo. If there is a supply chain interruption or a bottleneck these batteries become temporarily more expensive.

Currently, recycling lithium batteries is around $0.80/lb. Depending on battery density this comes out to roughly $14,300 for each 1,000 kWh of capacity or approximately 2 to 3 percent of the project cost. This cost is expected to go down and possibly have negative value as the lithium recycling industry becomes more mature and the volume of lithium battery recycling increases.

Figure 3-9: Battery Recycling Processes



(Kunz, 2019)

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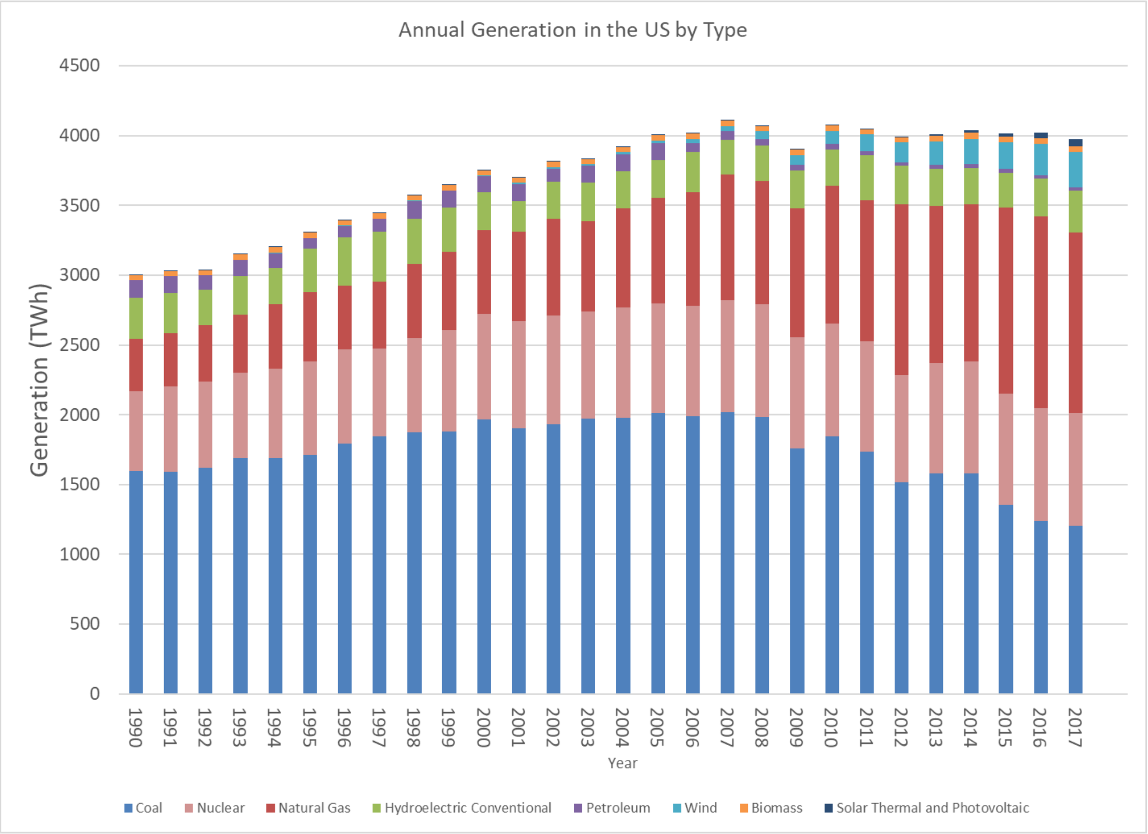
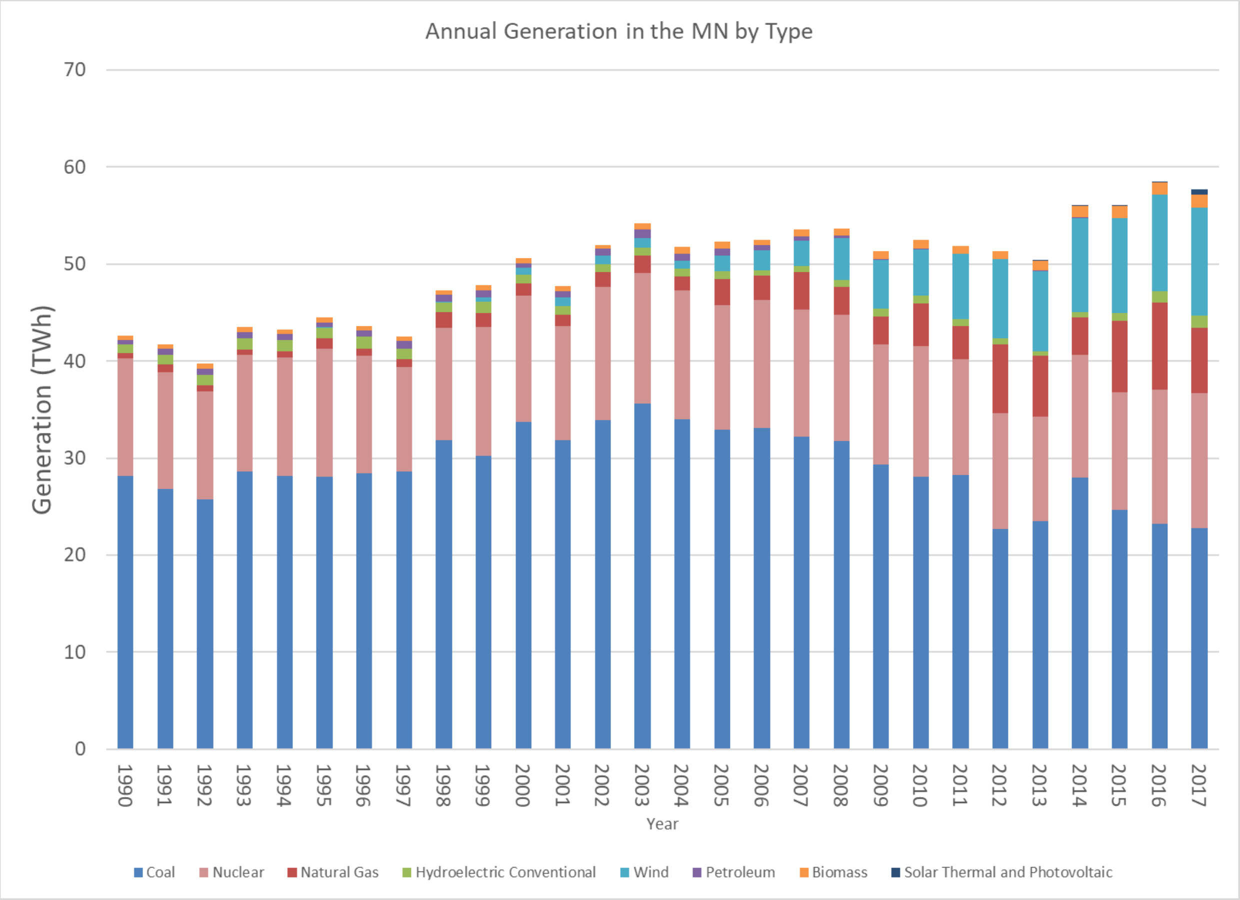
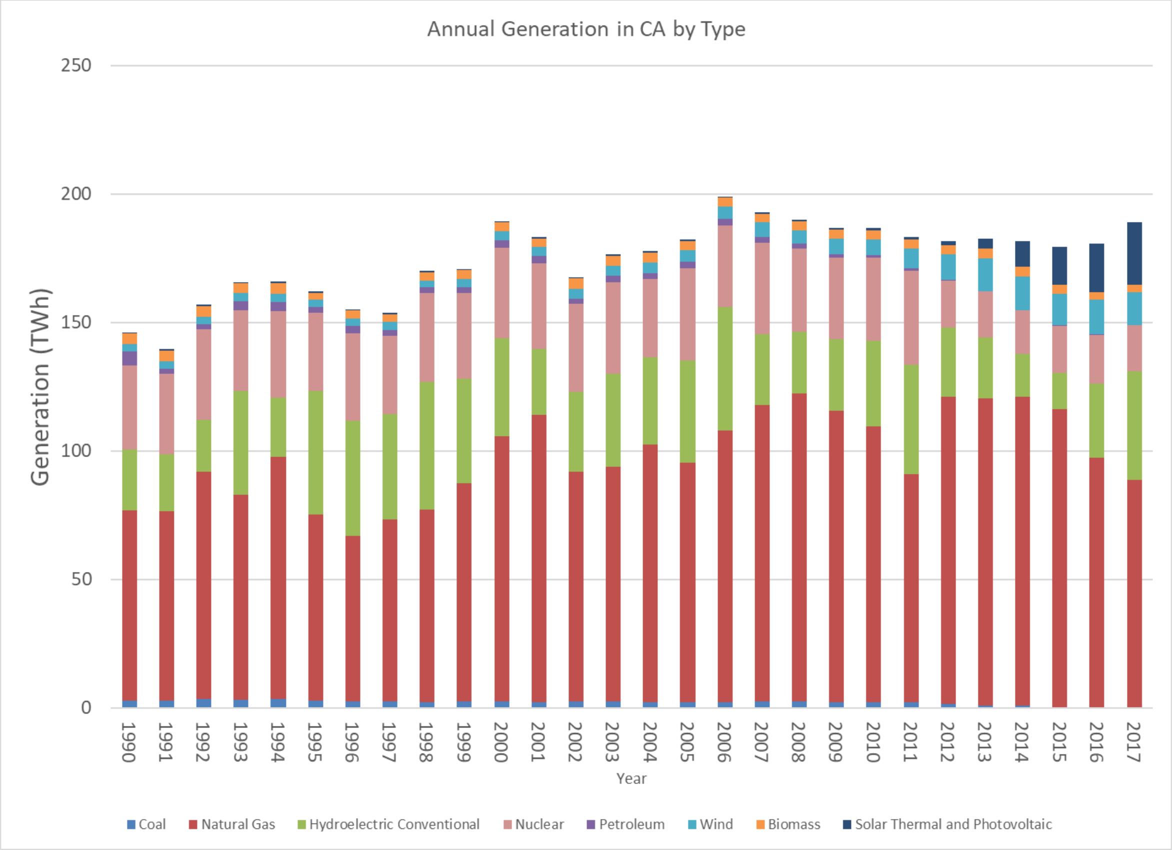
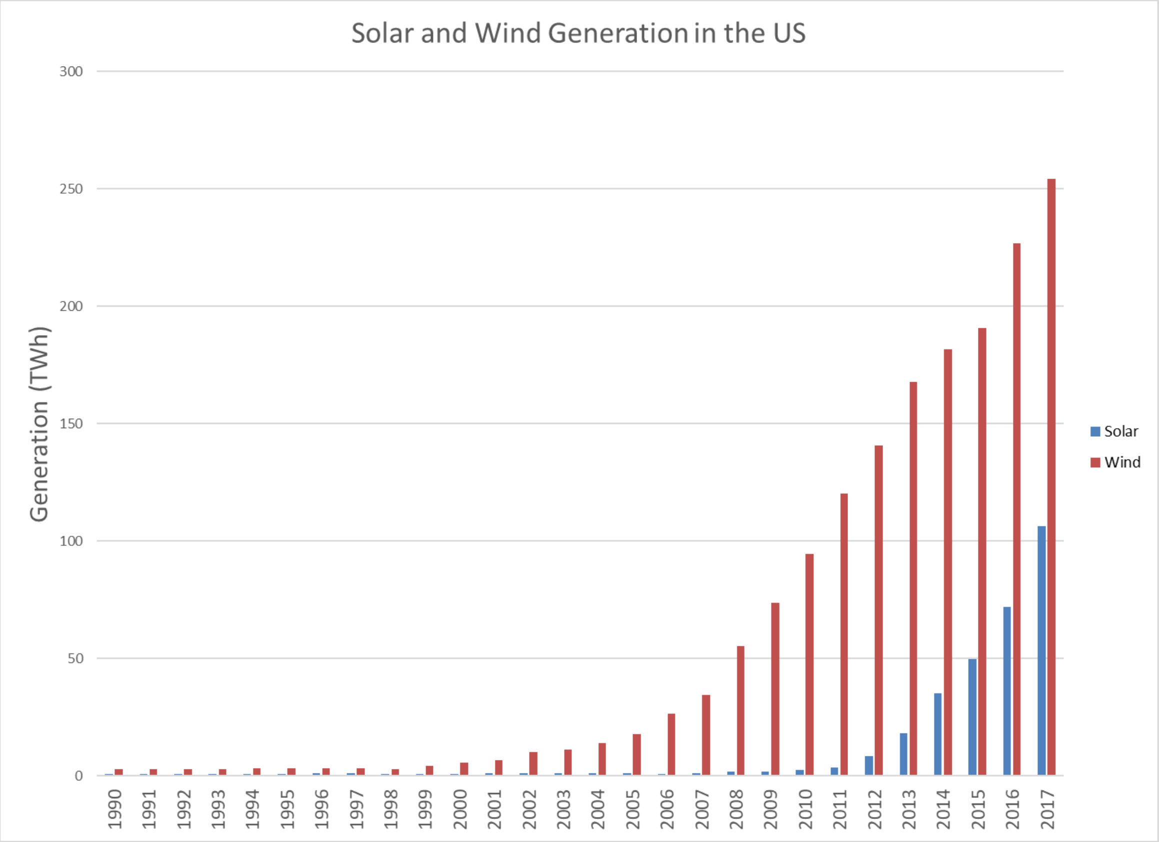
APPENDIX A - ANNUAL GENERATION STATISTICS




Annual Generation in the MN by Type
Generation (TWh)
70
60
50
40
30
20
10
0
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Year
Coal
Nuclear
Natural Gas
Hydroelectric Conventional
Wind
Petroleum
Biomass
Solar Thermal and Photovoltaic

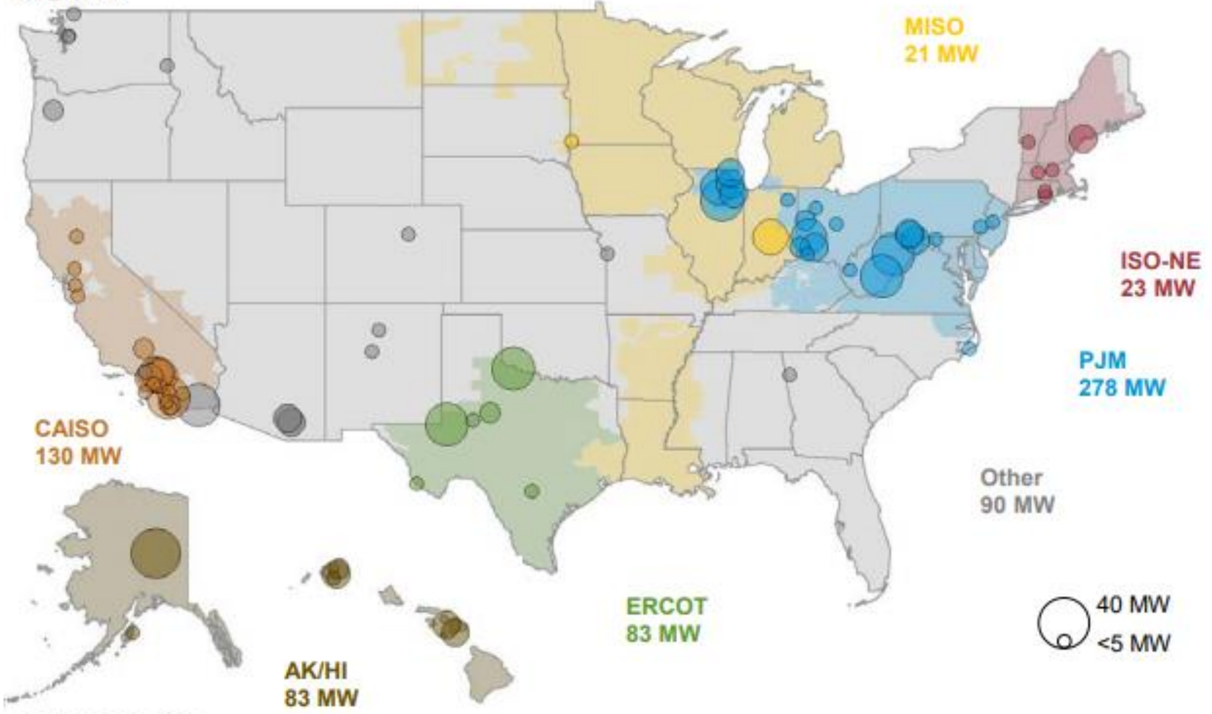


Annual Generation in CA by Type
Generation (TWh)
250
200
150
100
50
0
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Year
Coal
Natural Gas
Hydroelectric Conventional
Nuclear
Petroleum
Wind
Biomass
Solar Thermal and Photovoltaic

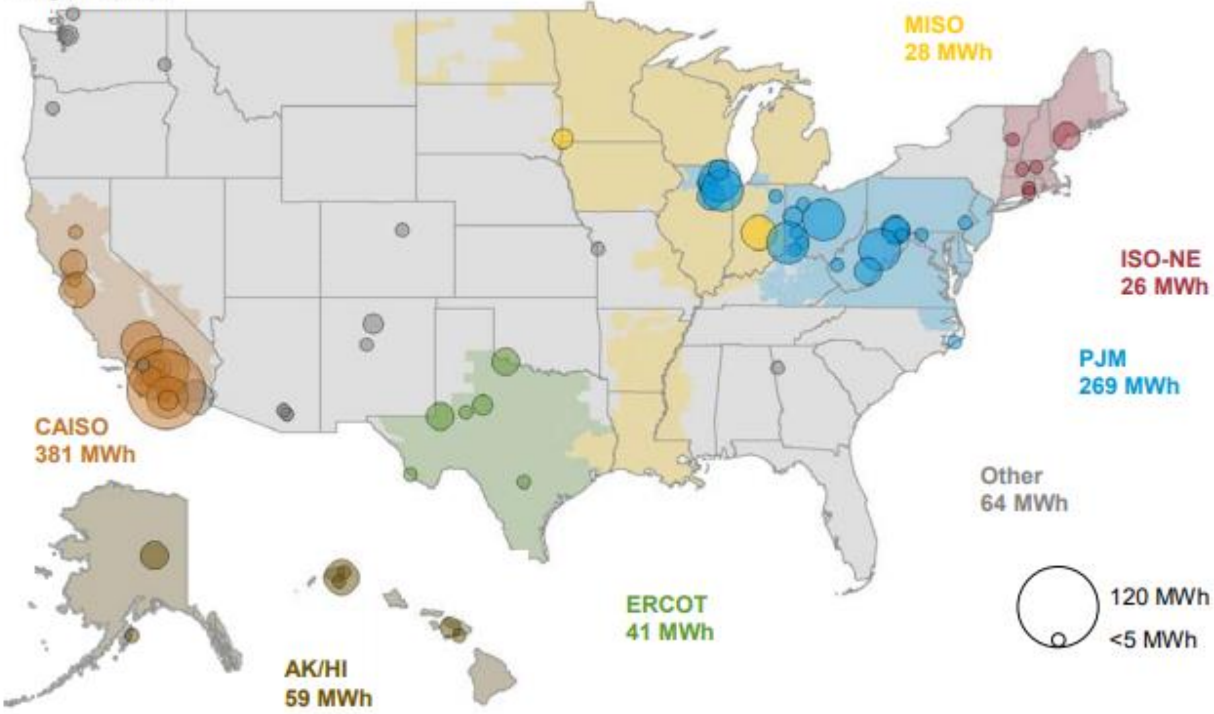

Solar and Wind Generation in the US
Generation (TWh)
300
250
200
150
100
50
0
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Solar
Wind

APPENDIX B – BATTERY ENERGY STORAGE

Battery Storage Installations by Region (2017)

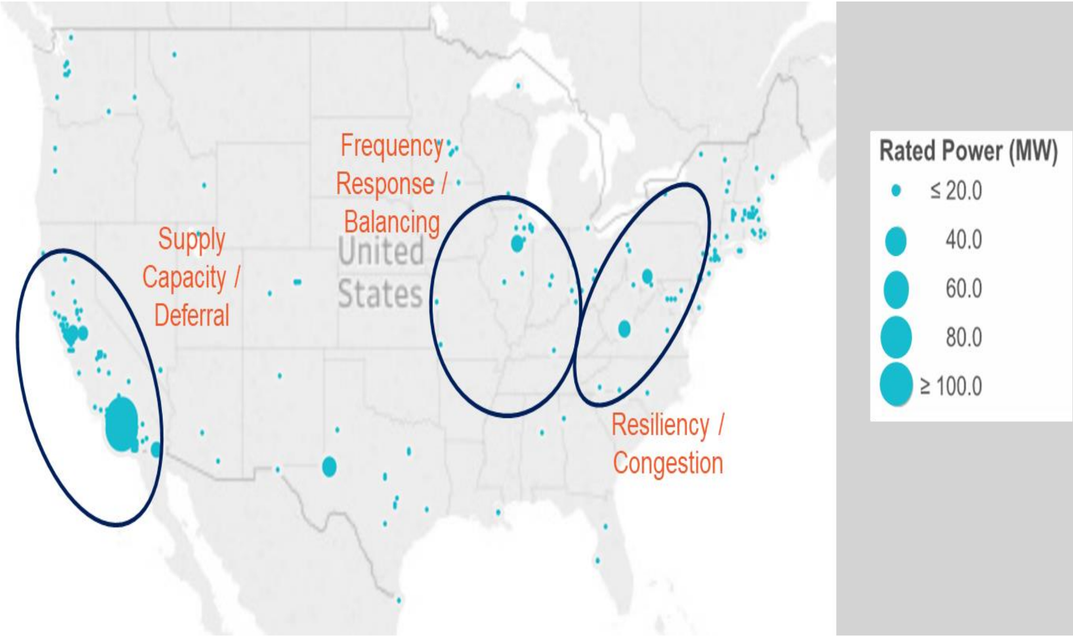


power capacity
megawatts



energy capacity
megawatthours

Battery Storage Interconnection Queue – MISO (Jan 2019)



Location of Battery Energy Storage Projects by Capacity (MW)

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