Energy Storage Roadmap Report

ESN®
ENERGY SYSTEMS NETWORK

Building an Energy Ecosystem®

ABOUT ENERGY SYSTEMS NETWORK

ENERGY SYSTEMS NETWORK: BUILDING AN ENERGY ECOSYSTEM®

Energy Systems Network (ESN) is a non-profit organization focused on growing the advanced energy technology sector. ESN is building an energy ecosystem that integrates all aspects of the energy landscape: energy generation, distribution, the built environment, and transportation. We leverage our network of Fortune 500 and global companies, academia, national research laboratories, and other non-profits to develop integrated energy solutions to increase quality of life for today and tomorrow. Our collective focus is to: reduce costs, emissions and waste; influence policy; and advance technological innovation.

ESN and our network of subject matter experts have decades of experience in energy storage technologies. We have worked on a wide range of projects that include energy storage applications for transportation and the electric grid. ESN led the formation and launch of the Battery Innovation Center (BIC) – a $20 million R&D and prototype manufacturing facility – which aims to accelerate the advanced energy storage market by linking manufacturers, government agencies and research labs, and academia. The BIC also is home to Underwriters Laboratories' (UL) Battery & Energy Storage Technology (BEST) Test Center, UL's North American testing and validation center.

For more information, contact info@energysystemsnetwork.com.

ABOUT THE ANALYSTS

PAUL J. MITCHELL, *PRESIDENT AND CEO, ENERGY SYSTEMS NETWORK*

Paul has been President and CEO of Energy Systems Network (ESN) since just after ESN's launch in 2009. During his tenure with ESN, Paul has led the organization to lead collaborative projects, offer consulting services, and provide strategic planning efforts for its partner organizations.

Prior to joining ESN, Mr. Mitchell served in the Office of Governor Mitch Daniels where he was Policy Director for Economic Development, Workforce and Energy. In this capacity, he oversaw legislation, policy, and program development for the Indiana Economic Development Corporation, Indiana Department of Workforce Development, and Indiana Department of Labor, and acted as Governor's liaison to the Indiana Utility Regulatory Commission and Office of Utility Consumer Counselor. During his tenure with the Governor's Office, Mr. Mitchell also led the formation of and directed the Indiana Office of Federal Grants and Procurement.

A native of West Lafayette, Ind., he holds a Master of Public Affairs from the Indiana University School of Public and Environmental Affairs (SPEA) in Bloomington, Ind. where he graduated as valedictorian.

JOHN E. WATERS, *CTO, ENERGY SYSTEMS NETWORK*

John is the Chief Technology Officer at ESN and has over 25 years' experience in energy storage research, design, building, testing, producing, and warranty of energy storage systems. Having invented the first battery packs for electric vehicles (General Motors), John has also led global initiatives in integrating energy storage to the electrical grid – inside the automotive vehicle or outside the vehicle. He has deep knowledge of various lithium battery formulations, performance capabilities, supply chain and product portfolios, having led the first-in-the-U.S. large-format lithium battery production at Delphi and EnerDel.

While at the Rocky Mountain Institute, John initiated the (battery) vehicle-to-grid (V2G) thesis with Google and Pacific Gas & Electric (2006) and eventually launched a V2G plug-in automotive OEM with strategic support from Alcoa, Coca-Cola, Cox Enterprises, Duke Energy, Google, and Johnson Controls.

As an energy storage industry expert, John has provided global insights to multiple corporations including 3M, Alcoa, A.T. Kearney, Boston Consulting Group, Booze & Co., GE, Goldman-Sachs, and the United Nations. He has nine U.S. and international patents, holds two defensive papers in battery pack designs, and has received numerous industry awards. He is a graduate of the University of Arkansas with a Bachelor of Science in Mechanical Engineering and a member of Pi Tau Sigma Mechanical Engineering Honorary Society.

CONTRIBUTORS

DAN ESPOSITO

Dan currently serves as an Analyst at the Indiana Office of Utility Consumer Counselor. He earned his Master of Public Affairs and Master of Science in Environmental Science at Indiana University's SPEA in Bloomington, Ind. in 2016, where he focused on energy policy. Previously, he earned his Bachelor of Science in Physics and Mathematics at the University of Dayton in 2014.

During his time at Indiana University, Dan provided research support for a forthcoming report providing recommendations for the midterm reviews of the federal Corporate Average Fuel Economy (CAFE) standards and the California Zero Emission Vehicles program. Dan worked at the White House Council on Environmental Quality to assist with the Obama Administration's Mid-Century Strategy for Deep Decarbonization. Dan also worked as a Verification Associate at the Center for Resource Solutions as part of its Green-e Energy certification program.

DAVID MICHAEL

David has 15 years' experience as an analytical chemist working in research and development. He is currently a graduate student in the SPEA at Indiana University pursuing a dual masters' degree in chemistry and environmental science, with a focus on the science and economics of energy. Prior to working for ESN, David worked for Dr. John Graham, Dean of IU SPEA, and Professor Sanya Carley as a research associate examining the supply chain of lithium-ion batteries and the economic impacts of CAFE standards on the U.S. economy (*A Macroeconomic Study of Federal and State Automotive Regulation*, March 2017).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

REPORT BACKGROUND

The term "energy storage" is becoming more ingrained in the global vernacular. From first world nations to developing nations, the common energy consumer is discovering – and capitalizing on – the emerging value proposition of energy storage: the battery.

Historically, the vast electrical grid with its centralized power plants has provided excessive electricity to industry, communities, and homes, otherwise referred to as the built environment. The grid has been used to convey an ample supply of electrons to all the "nodes" of demand that tap into the grid and require electrical power for lighting lights, pressing metal, cooking, or cooling food.

The centralized power plant typically uses a fuel (e.g., coal, natural gas, etc.) for a variety of functions: to heat water, make steam, turn an electric turbine generator, generate electrons, and ship those electrons on copper cables to substations and the like, to eventually be used by individuals for powering devices like light bulbs and ovens.

The centralized power plant and grid strategy is to maintain a large "base load" of power and add in flexible power sources for peak use of the grid, such as a natural gas "peaker plant." Historically, the base load and peaker plant strategy works well, as the dynamics of energy supply and demand can be tolerated with massive infrastructures that absorb the nuances of power supply and demand conveyed by the grid.

With the advent and growth of renewable but intermittent energy sources (e.g., solar and wind), and the increased focus on energy efficiency and smart grid, the need for energy storage as a means of stabilizing 24-hour energy supply has come to the forefront of the energy conversation and strategy.

The ***Energy Storage Roadmap Report*** aims to provide comprehensive research, technical and trend data with expert opinion to answer the following questions:

- Will improvements in energy storage continue to drive performance and price per kWh down, and at what point will it reach parity with existing technology options?
- What market adjustments are required to allow energy storage systems, which can be both a load and a generation resource, to contribute their full benefits to the grid?
- How should energy storage projects be financed (e.g., rate base, independent power producers, etc.)?
- What role will public utility commissions (PUCs) need to play in developing policies or approving projects?
- How can utility providers create new revenue streams and business models using energy storage systems?

In order to comprehensively and uniquely answer questions like these, ESN has performed extensive research; reviewed professional research materials, market forecasts, and other data; interviewed experts; and established essential criteria for scenario planning of the economic implementation of energy storage to the built environment.

PRIMER: A TECHNOLOGY ROADMAP

The purpose of this section is to educate the reader on technology, terms, and performance criteria of various energy storage systems. A comparison matrix has been developed and can be reviewed in Table 1. A glossary of terms has been provided in Appendix A.

It is important to note that the battery industry has a vast and historical reputation for ambiguous or misleading product performance claims. Confusion is often created by early scientific discoveries that have not been fully matured into products, yet the claims are made public. The publicity of battery "inventions" or "discoveries" often motivate established battery producers to respond in their marketing materials or public claims and address improvements in safety, power, energy, cycle life, and the like. This public confusion in the battery industry causes experienced financial analysts, scientists, customers, and engineers to be wary of published materials and "breakthrough" battery claims.

Historically, the most recent battery technologies to hit the automotive market over the past three decades (e.g., VRLA, NiMH, Li-ion) have roughly been 10-year, $100 million high-risk ventures into an undetermined market. It is helpful to evaluate all "headlines of future batteries" from this perspective and interpret the "breakthrough technology" future, its timing, and investment in the context of battery investment history.

BATTERY TYPES

A battery is a cell or connected group of cells that converts chemical energy into electrical energy by reversible chemical reactions and that may be recharged by passing a current through it in the direction opposite to that of its discharge – also called a storage cell. There are a variety of chemistry types that have varying levels of energy density, power density, costs, and cycle life all applying to a variety of applications in the energy marketplace. In this section, an overview of each of the major chemistries follows.

LEAD ACID

The most prolific battery type in history, referred to as lead acid (PbA), was invented in 1859 by French physicist Gaston Planté and is also the oldest type of rechargeable battery. Despite having a relatively poor energy density (50 watt-hours per kilogram, or 50 Wh/kg), PbA does have an ability to supply high surge currents and have a relatively large power-to-weight ratio. These features, along with their low cost, makes PbA the battery of choice for "starting, lighting, ignition" (SLI) batteries for automotive vehicles.

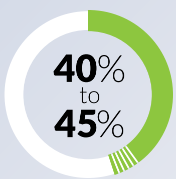
Inexpensive compared to newer technologies, PbA batteries are widely used when weight and volume are not important or essential requirements. Large-format lead acid designs are commonly used for storage in backup power supplies (i.e., UPS) in cell phone towers, data centers, hospitals, and stand-alone power systems.

Since PbA batteries have literally started the internal combustion engine (ICE) on every car since the 1912 Cadillac (first implemented and attributed to inventor Charles F. Kettering), there exists over 100 years of statistical data on the performance of PbA from the automotive industry. Paramount in its discovery, two-year warranty claims for PbA SLI batteries were the highest in hot-weather regions, indicating higher temperatures (i.e., above 100°F/38°C) have detrimental effects on PbA battery life (e.g., voltage drop and capacity fade).

When General Motors (GM) began its electric car development efforts in the early 1990s, it quickly realized that a better PbA technology must be developed, and in parallel with significant investment in other advanced battery types (e.g., nickel metal hydride, lithium ion). Gel-cells and absorbent glass-matte (AGM) batteries were successfully developed by GM and originally referred to as valve-regulated lead acid (VRLA) batteries. First introduced to the global automotive sector on GM's EV1 electric car program, Delco Remy's VRLA batteries delivered a 30 percent increase in energy density and a doubling of cycle life over previous "maintenance-free" flooded battery types (also invented by Delco Remy and attributed to William B. Wylam).

PBA BATTERY SALES

Today, it is estimated that PbA battery sales account for 40-45 percent of batteries sold worldwide (excluding China and Russia), and have a manufacturing market value of about $15 billion (today the majority of all-electric scooters and bicycles in China are powered by PbA technology).



of Batteries Sold

$15B

Market Value

NICKEL METAL HYDRIDE

Invented in 1967 and often abbreviated as NiMH (less often as "NMH") batteries, NiMH began at the Battelle-Geneva Research Center. Daimler-Benz and Volkswagen AG sponsored a NiMH development over a 20-year period. The early NiMH batteries' specific energy reached 50 Wh/kg (180 kJ/kg), power density up to 1,000 W/kg, and a life of 500 charge cycles (at 100 percent depth of discharge). Patent applications were filed in European countries (Switzerland), the United States, and Japan. The patents transferred to Daimler-Benz.

Interest grew in the 1970s with the commercialization of the NiMH batteries for satellite applications. The first consumer-grade NiMH cells became commercially available in 1989. In the early 1990s, GM purchased a controlling stake in the Ovonic Battery Company, which had improved the (Ti–Ni) alloy structure of the battery cell and received a patent for its innovations.

Mainly due to the wildly successful Toyota Prius hybrid electric vehicle (HEV) platform, more than two million hybrid cars worldwide were manufactured with NiMH batteries by 2008.[1]

NiMH batteries have superior power and energy densities over PbA battery types (see Table 1). The first NiMH battery packs were introduced to GM's EV1 owners in approximately 1996 for purchase or upgrade to their PbA original battery packs. NiMH had capabilities of doubling the range of its PbA counterpart (i.e., from 100 miles per charge to 200 miles per charge). GM's initial NiMH battery packs had an internal cost over three times the retail price of the EV1 vehicle. However, with production scaling and commodity stabilization of Nickel, the NiMH advanced battery solution could be brought in line with an expanding market in electric vehicles (EVs). Unfortunately, as documented in the award-winning film "Who Killed the Electric Car," the electric vehicle market was crushed by the OEMs who publicly blamed expensive and limited advanced batteries for lack of customer adoption.[2] History has proven that Toyota was very successful in its scaling of NiMH batteries for its Prius program(s), and additional HEV platforms.

With its moderate energy density, power density and cycle life capabilities, the NiMH battery has been fundamentally replaced with lithium ion in most automotive applications where range (deep cycling) and (10-year) warranty are internal drivers to OEMs (e.g., plug-in electric vehicles, PHEVs, or EVs).

Table 1: Battery Chemistry Comparisons

Lithium Battery Type	LCO	LMO (spinel)	LCA	NCM	LFP	LTO
Nominal Voltage	3.6	3.7-3.8	3.65	3.7	3.2	2.7
Operating Temperature (C)	0-55	0-55	-20-55	0-55	0-55	-40-55
Charge/ Discharge (C-rate cont.)	1C (limit)	5C	2C	5C	10C	30C
Specific Energy (Wh/kg)	170-190	140-180	200	130-150	90-130	70
Cycle Life Energy (100% Depth-of-Discharge)	500	1000-2000	3500	2000+	3000+	15000+
Applications	Cell phone, laptops, cameras	Cell phone, laptops, cameras	Automotive - EV/ PHEV	Automotive - EV/ PHEV	Power tools, HEV, PHEV, Grid	Power tools, HEV, Grid
Safety	poor	good	poor	good	excellent	excellent
Environmental	poor	good	poor	good	good	good
Comments	"18650" cylindrical design used in laptops, Tesla Roadster	In Chevy Volt and Nissan Leaf, replacement design for LCO	Johnson Controls, Saft design, Panasonic Tesla Model S (NCA)	Emerging, gaining market share in auto applications	Iron phosphate additive improves thermal runaway temp but decreases energy	High power performance, broad temperature range, low energy density (equal to NiMH), high cycle life

LITHIUM ION

Sometimes referred to as Li-ion battery or Lithium Polymer, Lithium Ion (Li-ion) is a somewhat generic term for a family of *rechargeable*, or secondary,[a] battery types in which ions of lithium (the lightest metallic element in the periodic table) move from the negative electrode to the positive electrode during discharge and move back when charging. The Li-ion battery is often referred to as the "rocking chair" battery as lithium ions "rock" back and forth from electrode to electrode upon discharge and charging of the cell.

Li-ion batteries use an intercalated (i.e., inserted between or among existing elements or layers) lithium compound that is applied to a substrate or an electrode material such as a copper or aluminum thin film sheet. Between the two electrodes is a polymer-based separator, which acts as an insulator between the two oppositely charged electrodes. The separator also acts as a conveyance mechanism or portal for the ion to "rock" back and forth from electrode to electrode (the polymer separator is actually porous and has micro-openings for ions to jump through to the opposite electrode). The addition of liquid electrolytes into the cell forms a fluid path for ionic movement through the separator. The two electrodes (with terminals), the separator, the electrolyte, and the external packaging (e.g., cylindrical or prismatic) are the constituent components of a rechargeable lithium-ion battery cell.

Historically, it is believed that M. Stanley Whittingham first initiated lithium battery development while working for Exxon in the 1970s. Sony and Asahi Kasei produced the first commercial lithium-ion batteries in 1991 for the consumer electronics industry. GM had developed partnerships in Li-ion technology, and eventually a joint venture with Valence Corporation, and started developing Li-ion batteries in 1991 for the electric vehicle industry.

Li-ion batteries are currently one of the most popular types of rechargeable batteries for portable electronics, stationary power, and automotive applications with a high energy density, high power density, negligible memory effect, and low self-discharge.

a Non-rechargeable, or primary, batteries will not be addressed in this report.

There are many popular Li-ion family derivatives available today on the open market including (see Table 1):

- Lithium Cobalt Oxide (LCO)
- Lithium Iron Phosphate (LFP)
- Lithium Manganese Oxide (LMO)
- Lithium Nickel Manganese Cobalt Oxide (NMC)
- Lithium Nickel Cobalt Aluminum Oxide (LCA)
- Lithium Titanate (LTO)

Promising Li-ion family derivatives not available but under development include:

- Lithium Sulfur (LiS)
- Lithium-Air (Li-Air)

As noted previously, the automotive industry has been at the forefront of energy storage technologies for over a century (i.e., 1912 Cadillac with electric starter and battery). With the advent of Li-ion technology, and the increased electrification of the automobile from 400 Watts in 1912 to over 100 kW today, the automotive industry collectively has invested over $10 billion in the safety, performance, durability, and warranty targets of Li-ion technology. The utility provider or building developer would be very judicious in leveraging the lessons learned through the tremendous investment of the automotive industry on the complex subject of Li-ion energy storage solutions.

In regard to promising Li-ion family derivatives, Li-S batteries have the potential to be significantly less expensive to create than conventional Li-ion batteries, mostly due to the low cost of sulfur. However, present Li-S batteries suffer from various instabilities, resulting in significant drops of efficiency and increased self-discharge. In addition, current Li-S battery electrodes can swell up to 80 percent, making it difficult to design battery enclosure materials. Nevertheless, Li-S batteries are one of the most promising technologies for the future.

Similarly, Li-Air has enormous potential to have energy densities approaching gasoline (12,200 Wh/kg), which would provide a Tesla Model S a range of 20,000 miles per full charge. The Li-Air battery cell is designed to use metallic lithium on its negative electrode and reacts with atmospheric oxygen on its positive electrode. In theory, only half of the battery materials are required to store the same amount of energy in the air medium, and can reduce the weight of the battery by 50 percent.

Due to the appealing science of Li-Air battery technology, IBM announced substantial investment in 2009 and many claims of technological progress are coming out of Cambridge University (addressing Li-Air poor cycle life issues).[3] As with all new electrochemistry and battery products, Li-Air has a substantial development journey ahead before achieving the life cycle costs of conventional Li-ion batteries and being produced for the marketplace.

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ULTRACAPACITORS

Formerly referred to as an electric double-layer capacitor (EDLC), the ultracapacitor (or "supercapacitor") is a high-capacity electrochemical capacitor with a performance value much higher than standard capacitors that emulates the cyclical nature of rechargeable batteries. Ultracapacitors typically store 100 times more energy per unit (volume or mass) than electrolytic capacitors, and can accept and deliver charge much faster than batteries. Ultracapacitors can provide a revolutionary amount of charge and discharge cycles over rechargeable batteries. However, their energy densities are extremely small when compared to batteries, and can be more than 10 times larger than conventional batteries for a given capacity or energy density.

Ultracapacitors are used in applications requiring many very fast discharges or rapid charge/discharge cycles, and in colder temperatures. If long energy durations are required (e.g., consumer electronics, golf carts, passenger vehicles, etc.) then ultracapacitors would be an improper fit for the application. However, if short-term energy storage or burst-mode power delivery is required (as in the cases of regenerative braking on cars, buses, trains, cranes and elevators) then "ultracaps" or "supercaps" might be an economic fit as they can provide short bursts, or short charge/discharge cycles, over a long period of time and cycles.

Historically, ultracapacitors have always been an attractive and promising technology for many electrical applications. However, when lithium-ion battery technology began producing high-power battery options with impressive cycle life such as lithium titanate (LTO), the value proposition of ultracapacitors diminished significantly due to its poor energy density and cost per kWh.

ZINC-AIR

Described as metal-air batteries powered by oxidizing zinc with oxygen from the air, these batteries have high energy densities and range from very small button cells for hearing aids to batteries for the electrical grid.

Zinc-air batteries operate similarly to fuel cells where the zinc is the fuel and the reaction rate can be controlled by varying the airflow. Once the electrolyte paste oxidizes (zinc) it can be replaced with fresh paste. Zinc-air has been used as a non-rechargeable, primary battery but a recent company has converted it into a rechargeable secondary battery.

Spun out from research at Arizona State University,[4] a Zinc-air battery company called Fluidic is providing Zinc-air "mini-grid solutions" to more than 400,000 residents in 100 remote villages and communities in rural Madagascar. The company also recently signed a memorandum of understanding to deploy similar solutions in Indonesia.

Fluidic has raised more than $150 million in funding from venture capitalists and government sources, and now has the financial backing of Caterpillar Inc. (CAT).

Fluidic claims to own more than 100 patents and claims to have more than 75,000 batteries in use around the world delivering electricity to 2.7 million people, with a stated goal of serving 100 million by 2025.[5]

SODIUM SULFUR

Invented by Ford Motor Company in the early 1960s, a sodium sulfur battery is referred to as a "molten-salt battery" constructed from liquid sodium (Na) and sulfur (S). It produces fairly high energy density (better than PbA efficiency in charge/discharge at 89–92 percent), good cycle life, and is fabricated from inexpensive materials. However, the operating temperature of sodium sulfur batteries is 300°-350°C and is highly corrosive in nature, which makes the battery more suitable for stationary energy storage applications. Sodium sulfur batteries have been used in the auto industry for more than a decade, primarily in Europe (e.g., "Th!nk" EV car program).

Typical sodium sulfur batteries have a solid electrolyte membrane between the anode and cathode, and are usually made in a cylindrical configuration. A steel casing that protects the cell from internal corrosion also encloses the entire cell. This outside casing serves as the positive electrode, while the liquid sodium serves as the negative electrode. The container is sealed with an airtight lid. In commercial applications, the cells are arranged in blocks for better heat conservation and are encased in a vacuum-insulated box.

Pure sodium presents a significant fire hazard because it spontaneously burns in contact with air and moisture, thus the system must be protected from water and oxidizing atmospheres.

*On June 6, 1994, the Chicago Tribune infamously reported, **"Ford Unplugs Electric Vans After 2 Fires"** (due to improper design and use of sodium sulfur batteries):*

DEARBORN, Mich. — Ford Motor Co. said it asked users of its Ecostar electric utility vans to park their vehicles outdoors and stop using them after an Ecostar being tested by the California Air Resources Board caught fire.

It was the second Ecostar to catch fire in the last month. The first incident occurred May 2, when an Ecostar leased by the Electric Power Research Institute in Palo Alto, Calif., burst into flames while recharging.[6]

FLOW BATTERY

A flow battery, or redox flow battery (after reduction–oxidation), is a type of rechargeable battery by two chemical liquid components contained within the system and separated by a membrane. Ion exchange (providing flow of electric current) occurs through the membrane while both liquids circulate in their own respective space. Cell voltage is chemically determined and ranges from 1.0 to 2.2 volts (per cell, and cells can be placed in infinite strings).

While a flow battery has technical advantages such as potentially separable liquid tanks and near unlimited longevity over most conventional recharging (i.e., just add more chemicals), current product offerings inherently have less power-producing capability than all other energy storage products and are 5-10 times larger than a Li-ion battery of similar energy densities (Wh/l).

POWER DENSITY AND ENERGY DENSITY

POWER DENSITY

The battery engineer considers many parameters in properly selecting the best energy storage solution for a given application. Power density (W/kg or W/l) is a parameter often represented in a Ragone chart, named after David V. Ragone (see Figure 1). A Ragone chart (pronounced "ruh-GO-nee") is a logarithmic chart used for performance comparison of various energy-storing devices. The values of specific energy (Wh/kg) are plotted versus specific power (W/kg). Both axes are logarithmic, which allows comparing performance of extremely high and extremely low power devices.

The Ragone chart was first used to compare performance of batteries, but is suitable to compare any energy-storing device. Conceptually, the vertical axis describes how much energy is available, while the horizontal axis shows how quickly that energy can be delivered, otherwise known as power, per unit of mass.

Power density is critical to assess for the specific application of the battery. If the application requires large and rapid bursts of power (e.g., HEVs, power tools, grid frequency regulation) then the power output of the battery (or ultracapacitor) is critical to the proper sizing, performance, durability, thermal management, and warranty period for the battery or battery system. Note: the "friendlier" the battery is toward providing high power, the less heat it generates and the longer it lasts (observe electrochemical performance on the right side of the Ragone chart below).

Figure 1: Sample Ragone Chart

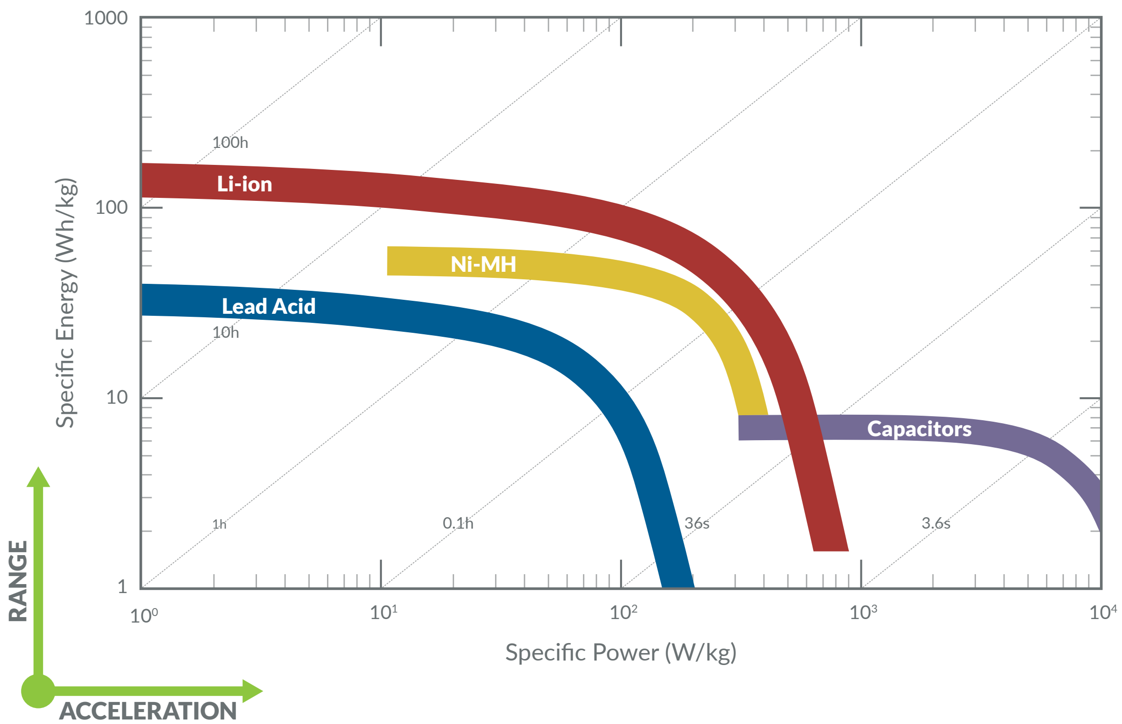
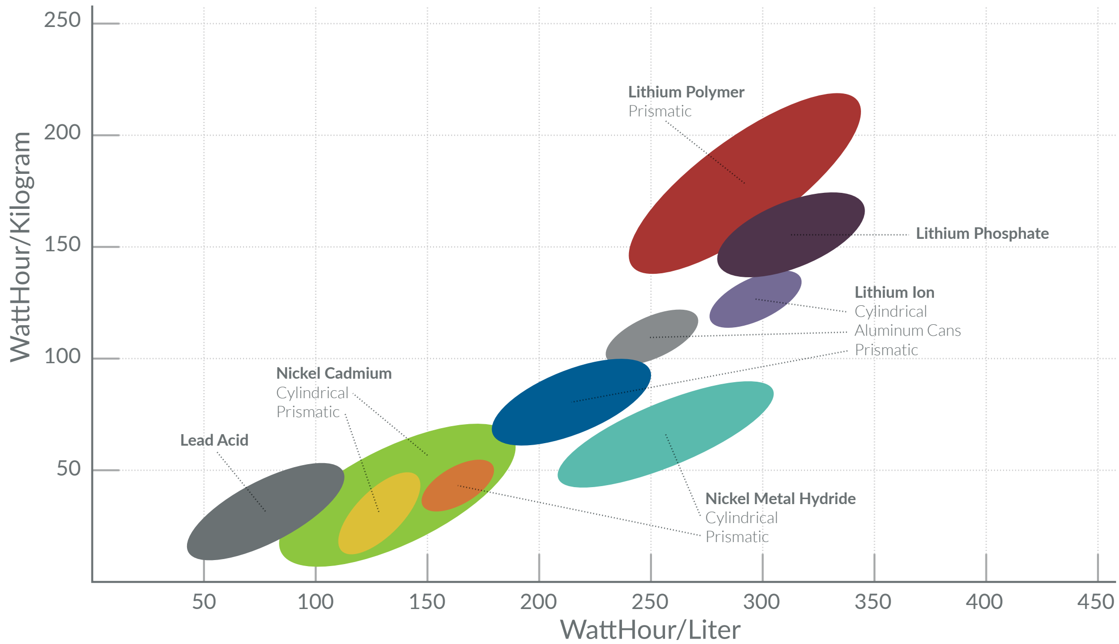


Figure 2: Battery Performance by Weight and Volume



ENERGY DENSITY

Usually in tension, or in a performance trade-off with power density, energy density is also critical to assess and size for the specific application of the battery. If the application allows or requires large, slow energy output or throughput (e.g., EVs, laptop computers, storing solar energy for use at night) or requires a maximum vehicle driving range (e.g., Tesla goal of 300 miles), then the energy density of the battery is paramount to the proper battery selection. Note: the higher the energy density of the battery, the smaller and lighter the battery will be, and usually directly relates to the system cost of the application if size and volume are critical to the value proposition (observe electrochemical performance on the upward direction in Figure 2).

CYCLE LIFE

A single charge cycle is the process of charging a rechargeable battery and discharging it. Often specified or referred to as "Depth-of-Discharge" (DOD), a full cycle can be determined by the user or the application (i.e., software). The number of cycles the battery can repeat at a certain performance level is referred to as "cycle life" but it can be affected by several parameters.

PARAMETERS

The cycle life of a battery can be affected by the following:

- ***Depth-of-Discharge (DOD):*** As noted earlier, the DOD of the battery can range from 100 percent (deep discharge) to 0.1 percent (trickle discharge). Inherently, the deeper the discharge of the battery the greater the impact on its cycle life. For example, a PbA SLI application battery is capable of approximately 200 cycles at 100 percent DOD. However, in an SLI application where the DOD is only 5-10 percent, the PbA cycle life can last over 200,000 cycles. This relationship between DOD and cycle life is common to most electrochemical energy storage technologies.

- ***Temperature:*** Briefly mentioned previously, typically temperatures above 100°F/38°C accelerate "aging" or reduce cycle life of the battery (unless the battery is a "hot" chemistry, such as sodium sulfur or rechargeable lithium metal). Most energy storage products available today are developed to operate most efficiently at 77°F to 104°F (25°C to 40°C).

  Cold temperatures at the freezing point (32°F/0°C) or below can limit charge and discharge capability of the battery. Lithium-based and Nickel-based batteries are virtually impotent at freezing temperatures (with the exception of LTO which, remarkably, can discharge 80 percent of its capacity at -35°F/-37°C). PbA can provide cranking power (SLI) at freezing temperatures and below.

  Obviously, external thermal management systems can ensure performance and cycle life of the battery system. Economic or "system" trade-offs must be made to evaluate the cost of the thermal management system to ensure battery life per the annual ambient temperature in the application. For example, LTO chemistry is capable of charging and discharging at freezing temperatures, but it is more expensive on a cost per kWh basis than other Li-ion chemistries (due to its lower energy density). Depending on the system and warranty requirements, LTO could be an overall less expensive solution since it requires less thermal management and temperature control.

- ***Time:*** Sometimes referred to as "self-discharge," it is essential to analyze the time or calendar life performance of batteries to determine maintenance, replacement, and warranty targets of the energy storage solution. A calendar life test evaluates cell degradation as a result of the passage of time with minimal cycling of the battery. This testing is not a pure "shelf-life" test, as the cells under test must be periodically subjected to reference discharges to determine the changes (if any) in their performance characteristics.

- ***Charge Rate (C):*** Charge and discharge rates of a battery are commonly referred to as C-rates. The charge rate of a 1 kWh capacity battery is commonly rated at 1C, meaning that a fully charged battery discharged at a rate of 1 kilowatt (C = 1 kW) can provide 1 kilowatt of constant power for one hour. The same battery discharged at a rate of C/2 can provide 500 watts for two hours, and finally, at a 2C discharge rate the battery delivers 2 kilowatts continuously for 30 minutes.

  It is important to realize that higher C-rates can increase internal thermodynamic reactions to the battery cell electrodes, seals, and packaging and can shorten the cycle life of the cell. Typically, the energy storage *application* defines the requirements or drives the need for battery C-rates. For example, most laptop computing batteries are discharged at a C/5, and as low as C/20, under mild ambient temperatures. Conversely, EV batteries can be subjected to 5C to 10C discharge rates under harsh accelerations or rapid recharge (i.e., Level III charging), and under harsh ambient temperatures.

Individual electrochemistries and the internal battery cell structure design dictate the charge/discharge rate capabilities of the battery cell. In addition, individual cells can be ganged together in a parallel string to better accommodate and distribute high charge/discharge rates in a battery pack system.

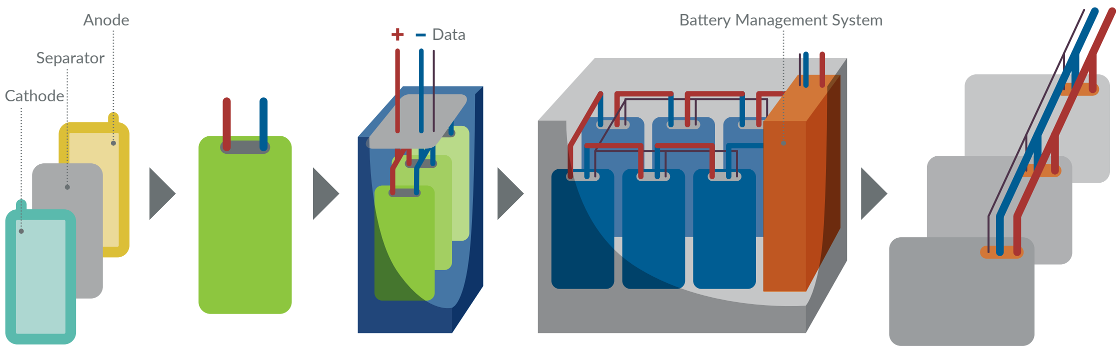
BALANCE-OF-SYSTEM

BATTERY MANAGEMENT SYSTEM (BMS)

The Battery Management System (BMS) is often referred to as the "brain" of the battery (unit, string, module, or pack). The BMS is designed to provide cell (voltage) balance, control, and consistent performance over the lifecycle of the battery. The BMS is a circuit board with an integrated microprocessor that monitors, records, and actually sends signals for charging and discharging individual lithium battery cells (or cell strings) to maintain voltage balance and system performance. (See Figure 3).

Lithium battery cell voltages are divergent in nature (to one another) and require an external control device (i.e., BMS) to maintain synchronized cell voltages as cells are "topped off" at full charge. All lithium batteries utilized today in energy storage systems, and when placed in a voltage series string, require a BMS to maintain safety, cell balance, performance, and warranty.

Figure 3: Balance-of-System



Mono-Cell
- Basic cell chemistry
- Basic cell voltage
- Voltage: 2VDC to 4 VDC
- Capacity: 2-3 Amp-hours (Ah)

Cell
- Stack of mono-cells
- Connected in parallel
- Voltage: 2VDC to 4 VDC
- Capacity: 10 Ah to 40 Ah

Module
- Stack of cells
- Connected in series and/or parallel
- Voltage: 4 VDC to 60 VDC (typical)
- Capacity: 0.5 kWh to 5 kWh (typical)

Battery Pack
- Stack of modules
- Connected in series and/or parallel
- Voltage: 100 VDC to 700 VDC (typical)
- Capacity: 10 kWh to 500 kWh (typical)

Battery System
- Stack of battery packs
- Connected in series and/or parallel
- Voltage: 100 VDC to 700 VDC (typical)
- Capacity: 500 kWh to 50 MWh (typical)

The BMS has "bleed resistors" on the circuit board which are used to divert charging energy of individual battery cells once the individual cells have reached their maximum charge voltage. For example, if the battery cell or the string cutoff charging voltage is 4.0 volts (i.e., maximum charge voltage per cell), and once the 4.0 VDC value has been reached via charging on an individual battery cell, the BMS diverts charging energy from that cell to the bleed resistor(s). The bleed resistor(s) converts the charge energy into heat and dissipates into the ambient air. These heat-generating bleed resistors must be considered in the overall thermal management of the lithium battery system.

BUSSING/CONNECTIONS

Critical to the efficient and reliable operation of an integrated battery system are the dozens, hundreds, and sometimes thousands (e.g., Tesla) of connections between cells and electrical bussing between cell modules (see Figure 3). Every buss bar weld, connection, or electrical joint is a potential failure point and can introduce electrical resistance into the energy storage system. Where resistance is evident or measurable, heat is generated causing secondary thermal management conditions that must be monitored and controlled for proper energy storage system use and operations.

Bussing and connections are critical engineering areas where volumes of research have been applied toward discovering low-cost, reliable, and low-resistance attachments or welds. As noted previously, the automotive industry has applied more investment and research into this area than any other industrial sector.

THERMAL MANAGEMENT

Emphasized throughout this report, the thermal maintenance of the individual battery cells is critical to the safety, performance, and warranty of the energy storage system. The industry has developed two fundamental thermal management solution paths:

- ***Active:*** Typically a liquid cooling system where a coolant, such as ethylene glycol, is circulated around and through heat generating areas to transfer heat from inside the battery system to outside and through a cooling loop, such as a radiator - often referred to as "convection." Similarly, thermal management can be accomplished through a forced-air system provided by a blower fan and ducting, but forced air is less effective in extracting larger amounts of heat from the cells or keeping cells warm in colder ambient temperatures.

- ***Passive:*** Due to the impressive 95 percent charge/discharge (under moderate C-rates) efficiency of most Li-ion technology, many energy storage solutions do not make provisions for active cooling systems and allow the minimal heat gains of the lithium cell to dissipate passively. Depending on the application, whether the energy storage system is moving or stationary, passive air channels can be designed into the enclosure allowing airflow, and even conduction of thermal conditions, to circulate past the individual battery cells for passive thermal management.

PACKAGING/ENCLOSURES

As noted in Figure 3, battery cells (Ah) are often placed and integrated into modules (Wh) then into battery packs (kWh). Multiple battery packs can comprise a battery system (e.g., MWh). Electrical design, mechanical design, material selection, thermal management, bussing, and connections are all critical to the external cell packaging, module packaging, pack enclosures, and the battery system.

In automotive battery packs, the packaging, wiring, connections, enclosures, etc. can approach 50 percent of the bill of material cost (the other 50 percent being the cells). Due to the harsh operating conditions and liability ramifications of the automotive industry, products, packaging, and enclosures are highly engineered and validated to automotive requirements for battery pack designs. Again, most automotive battery packs are considered powertrain products incorporating a 10-year, 100,000-mile warranty (with only a 20 percent capacity fade at end of year 10).

Conversely, stationary battery packs in moderate ambient air environments have less engineering and validation requirements. This allows for less expensive materials, bussing, thermal management, etc. At the right volumes over time, and depending on voltage requirements, the reduced application requirements in stationary power applications should move the ratio of battery pack bill of material costs to approximately 30 percent or less (the other 70 percent being the cells). Conversely, consideration must be given to the higher voltages of stationary grid-tied energy storage, which may require more specialized and thus expensive bussing, wiring, and connections.

INVERTERS

Inverters are electronic devices or circuitry that "inverts" direct current (DC) to alternating current (AC). The input voltage, output voltage, and the voltage frequency depend on the design of the specific device or circuitry, but the inverter does not produce any power as the power is provided by the DC source.

A power inverter in higher voltage batteries (above 48 VDC) is typically comprised of electronic circuitry using the "switching" capability of silicon (used in power transistors and diodes).

Examples of inverting include the following:

- 12 VDC: smaller consumer and commercial inverters that typically run from an SLI 12 VDC PbA battery or automotive electrical outlet
- 24, 36 and 48 VDC: common standards for home energy systems
- 200 to 400 VDC: common for photovoltaic solar panels
- 300 to 450 VDC: common for electric vehicle battery packs and vehicle-to-grid systems
- 700 to 800 VDC: common for large electric buses and mass transit systems
- 100,000+ VDC: common for high-voltage direct current power transmission system

BRICKS & MORTAR/HVAC

A safe and reliable control of the energy storage system is crucial for an economically viable operation. For large stationary energy storage systems, a supervisory control and data acquisition (SCADA) system is required. A SCADA coordinates the data from the multiple BMS's, the power conversion systems (e.g., inverters, inverter controllers) and external requests (e.g., electrical grid). As noted previously, the BMS monitors all relevant and individual battery cell measurements and ensures safe operation of the battery. If any of these limits is exceeded due to failure of any SCADA component, the BMS can switch off its inherent batteries by opening electrical contactors.

Additionally, there are auxiliary power loads caused by heating, ventilation and air conditioning (HVAC) and the SCADA. For simplification, the power need related to the HVAC can be assumed to be a percentage of thermal losses caused by the batteries (and dependent on the coefficient of performance, or COP, of the AC).

It is important to quantify system losses, often called "parasitic losses," of the battery thermal loads to the HVAC to the SCADA in order to properly calculate the true value proposition and overall system efficiency value for Return on Investment (ROI), Internal Rate of Return (IRR), etc. calculations.

On top of the SCADA, an energy management system (EMS) can be placed which optimizes the power dispatch and incorporates losses, aging of the cells or modules, thermal loads, and more. Designing and building a large energy storage system (MWh+) is a planning-intensive process where standardization of safety, battery technologies, building requirements, definitions of Key Performance Indicators (KPIs), and communication signals for SCADA are required. If best practices can be leveraged from the automotive industry, then significant gains can be made in the built environment at a fraction of the cost for internal development of large energy storage systems.

SAFETY

Due to poor systems engineering or poor handling in the public eye, Li-ion batteries have a negative public perception. However, like all energy storage mediums, including liquid fuels like gasoline, under certain conditions Li-ion batteries can pose a safety hazard. Since Li-ion batteries are sealed batteries, usually under pressure, and have the highest energy densities available in the battery market, improper handling (i.e., shorting) and/or thermal management can cause what the industry has termed a "thermal runaway" event.

In 1999, an infamous lithium battery fire occurred at the Los Angeles International (LAX) airport, upon two aircraft cargo pallets at the Northwest Airlines cargo facility at LAX.[7] The pallets had been taken off Northwest Airlines Flight 0026, an inbound passenger-carrying flight, from Osaka, Japan. The event consisted of two pallets, one containing 100,000 primary (non-rechargeable) Sanyo lithium cells, the other containing 20,000 more cells, some primary and some rechargeable or secondary cells. The cells were physically abused many times by forklift truck operators as they moved the pallets around an outdoor cargo area of the airport. Abuse occurred over a several-hour period resulting in a fire that could not initially be put out with the portable firefighting equipment and was finally extinguished when a large fire truck doused the pallets with large volumes of water, thus suffocating the flaming cells. The exact cause of the fire may never be known. Once the packaging integrity of the cells was destroyed, the cells could have been crushed, short-circuited, overcharged or experience a forced discharge.

The U.S. National Transportation Safety Board's (NTSB's) investigation of this incident resulted in the issuance of formal safety recommendations, which initiated regulations on the entire lithium battery industry, including soon-to-be adopted regulations for the United Nations.

The First Law of Thermodynamics, also known as Law of Conservation of Energy, states that energy cannot be created or destroyed in an isolated system. Therefore, battery cells or energy storage devices do not "create" fires or even energy transfers.

Proper handling and engineering of individual batteries and battery pack systems is required for safe use and operation over the 20-year expectancy of Li-ion products. The more recent Boeing 787 Dreamliner incident (2013)[8] is an additional example of an improperly engineered Li-ion battery system where proper and tested thermal management design (per automotive standards and requirements) was not implemented prior to flight.

As Li-ion-based and other electrochemistry energy storage systems are potentially evaluated and placed on the electrical grid and in the home, safety issues and robust systems engineering are highly relevant. Again, borrowing best practices from the automotive industry, which has dealt extensively with the thermal runaway issue of large battery systems for over three decades, can provide expertise and insight to the safety, handling, operation, and response to thermal incidents in energy storage systems for the built environment. Furthermore, standards bodies like Society of Automotive Engineers (SAE) and Underwriters Laboratories (UL) have developed a range of safety standards and certifications for mobile stationary energy storage systems that should be leveraged to reduce the risk of deploying energy storage on the grid.

APPLICATIONS

The applications for stationary storage can be broken down into five general categories: 1) Bulk Energy 2) Ancillary Services 3) Transmission & Distribution 4) Consumer Benefits 5) Renewables Integration. Within each category, batteries can be used as:

- A short-term tool: operating over millisecond-to-second timescale (frequency regulation, or power quality)
- A medium-term tool: operation from a minute to about 1 hour (reliability)
- A long-term tool: operating on the scale of several hours (energy storage, time-shifting)

On page 21 is a list of defined potential applications for battery storage. The economics for each application is specific to the system design, size, and market structure, though markets are beginning to emerge for several use case scenarios (see ***Primer: Economics of Energy Storage*** section).

Key Applications for Battery Storage

Electric Bill Management: Electric bill management reduces the energy drawn from the grid during periods of high demand charges. As electricity markets increasingly move towards a stratified rate structure, the ability to reduce demand from the grid during peak hours is going to become more profitable.

Renewable Capacity Firming: Renewable capacity firming helps to smooth output from renewable sources to maintain consistent output over time. The inherent intermittency of renewables is often balanced with conventional generation that was not designed for this function. Batteries can reduce this particular demand and free up conventional sources for their intended purpose while lowering costs at the same time.

Electric Energy Time Shift: This application permits greater flexibility when power is used. For instance, during a period of high supply and low demand, energy can be stored and then released when demand is high or supply is low. Electric energy time shift reduces peaks and troughs in the supply curve, promoting greater stability.

Microgrid Capability: An energy storage system can be used to enhance the stability, reliability, and quality of a microgrid system and permits the integration of diverse energy sources. For instance, if a microgrid system is supplied by renewables, then a voltage source is needed to synchronize the system. Automation, diesel generation, or some form of battery storage system usually performs this synchronization.

Onsite Renewable Generation Shifting: This application allows end-use customers with onsite renewable energy sources to charge and store energy as it is produced so it can be used onsite as needed. Shifting also allows multiple sources of energy to be synchronized, increasing flexibility.

Frequency Regulation: The battery acts as both a source and sink for electricity from moment-to-moment to help maintain the frequency within the required range. Frequency regulation requires millisecond-to-second response to the grid. Batteries can be programmed to respond instantaneously to changes automatically.

Renewables Energy Time Shift: Renewable energy use can be optimized by allowing storage of that energy when it is being produced regardless of the current demand. This energy can then be used during periods of high demand or when renewables have reduced generating capacity.

Key Applications for Battery Storage
Electric Bill Management with Renewables: This application for energy storage permits the storage of energy during low-rate periods to be used during high-rate periods. Storage combined with renewables can work in conjunction with each other to improve the economics of both renewables and battery storage.
Resiliency: Resiliency enhances the ability to supply demanded power in the event of disruption. Storage systems can permit an orderly shutdown of the system or may act as a backup to maintain function until power is restored.
Voltage Support: Large power loads can move the voltage out of the specified range locally. Storage can dampen these effects with minimal draw of power from the battery.
Onsite Power: The battery can provide power locally as needed. These systems can be used in conjunction with, or in replacement of, conventional generators. For instance, institutions such as hospitals, server farms, and some manufacturing activities must have robust and uninterruptable energy supplies. Even in the event of a dedicated generator, backup power is usually installed as a fail-safe.
Grid-Connected Commercial (Reliability & Quality): Battery storage can maintain consistent power output in the event of a disruption of a commercial enterprise. The system may provide the needed power during the disruption or permit an orderly system shutdown or smooth transition to a backup generation unit. The storage system can also smooth out any unwanted variability such as spikes or drops in voltage or frequency.
Grid-Connected Residential (Reliability): Battery storage can maintain consistent power output in the event of a disruption for residential customers. The system may provide the needed power during the disruption or permit an orderly system shutdown or smooth transition to a backup generation unit. The storage system can also smooth out any unwanted variability such as spikes or drops in voltage or frequency.
Electric Supply Capacity: Having electric supply capacity can decrease the need to buy generating capacity on the wholesale market or build new generation capacity. Uncertainty in market demand for electricity - for instance, in new housing developments where demand may grow quickly if the development is successful or fail to materialize if the development falls through - is a source of risk for electricity suppliers. Storage may be effective in providing flexibility to energy suppliers.

Key Applications for Battery Storage

Ramping: Storage permits either ramping up or ramping down of the loading level of a generation unit in a manner that is consistent over time. Sudden changes in the ramping rate may significantly, or negatively, impact the efficiency of an electric generating unit. A storage source may act as a shock absorber to facilitate systematic and therefore more efficient use of the generator.

Electric Supply Reserved Capacity – Spinning: Spinning reserves are units that are synchronized with, but not releasing energy to, the grid. Their intended purpose is to be able to respond rapidly to "contingency" or loss of a significant source of generation. Storage can reduce the need for these units by supplementing them or replacing them altogether. Storage can further reduce the economic loss associated with spinning units by storing the energy they create while offline.

Load Following (Tertiary Balancing): Output changes in response to demand changes in a specific area. These units usually are intended to respond within minutes or hours. A battery's ability to respond quickly to demand changes makes them well suited to supplement traditional systems for load following.

Transporting Services: Batteries may provide a link between the grid and electric vehicles. For instance, as the market for electric vehicles grows, it will become increasingly feasible to utilize large numbers of electric vehicles to provide frequency regulation and voltage support to the grid, known as vehicle-to-grid or V2G. Tesla's current business model includes redefining electric vehicles eventually to act as mobile batteries for the grid, storing energy at night when costs are low and selling electricity to the grid during periods of high demand.

Stationary Transmission/Distribution Upgrade Deferral: Battery storage decreases or defers the need to replace or upgrade stationary T&D systems. Underground circuits and ground faults are expensive to replace and storage can decrease the load requirements, which reduces the heat and associated degradation of the units and auxiliary equipment, such as insulation.

Electric Supply Reserve Capacity – Non-Spinning: Non-spinning reserves are brought online only after spinning reserves have been brought online. These units are not synchronized (frequency) with the grid and are offline until they are required. Non-spinning reserves are often the most expensive generators and are only called for when demand exceeds normal capacity and spinning reserve capacities. Storage can defer the high costs of construction and utilization of non-spinning reserves.

Key Applications for Battery Storage

Transmission Congestion Relief: Storage discharges during periods of peak demand can reduce transmission capacity requirements and congestion-related costs. Congestion may also negatively impact frequency and voltage stability. Storage units can offer increased stability by responding as a source or sink for energy as needed, reducing the expense associated with energy dumping.

Transmission Support: This application is used in conjunction with transmission to compensate for variability, such as unstable voltage and resonance issues. Storage increases the load-carrying capacity of the transmission system, which may benefit the system owner and the utility. Transmitting energy can be costly to utilities that need additional capacity but do not own the transmission system. They usually pay an access charge as well as other fees, such as operation and maintenance costs to the system owner.

Distribution Upgrade due to Wind: Upgrading distribution systems for wind energy can decrease strain on the distribution system and reduce the need for associated upgrades required due to increased variability from electricity generated by wind.

Transmission Upgrades due to Solar: Transmission upgrades can decrease strain on the transmission system and reduce the need for associated upgrades required due to increased variability from electricity generated by solar.

Transmission Upgrades due to Wind: Transmission upgrades can decrease strain on the transmission system and reduce the need for associated upgrades required due to increased variability from electricity generated by wind.

THE VALUE AND ISSUES ASSOCIATED WITH APPLICATION STACKING

While the market for each of these applications alone is currently small, there is the potential for compounding value from multiple applications from the same battery system. In general, stacked services/applications are essential to make battery storage systems economical. However, there are several challenges to application stacking.

A first challenge is that the regulatory environment is still evolving to accommodate the dual nature of batteries; namely, that they can provide services to the grid system and act as a power/energy generator at the same time. The regulatory environment is currently not adequately flexible to allow all of a battery system's potential applications to be used in the same installation.

A second challenge is the system's design and use being conducive to some services but not others. For instance, a system that is designed for short-duration frequency regulation, a power application may not provide renewable energy integration to an energy application.

PRIMARY CHALLENGES OF APPLICATION STACKING:

1	2	3
Regulatory Environment	System Design	Application Costs

Third, the costs associated with applications will vary based upon the application requirements. For instance, equipment for a high-voltage application is significantly more expensive than costs incurred for low voltage applications. A chain of increased cost – from the battery management system to grid installation equipment and system controls software – can complicate the economics of stacking with high-voltage applications. Along with the increased equipment cost, an increased balance-of-system complexity increases by stacking multiple applications. These complex dynamics must be factored in as utilities and other end-use customers consider generating additional revenue streams from application stacking.

PRIMER: ECONOMICS OF ENERGY STORAGE

The goal of this primer is to educate the reader on the economics and market conditions impacting the price of stationary energy storage. The section reviews key criteria that make up the full cost of energy storage, including pricing targets and forecasts; identifies which applications are currently economical; and addresses current efforts to compare energy storage pricing to alternative technologies.

DRIVERS OF BATTERY PRICES

The battery industry is global, with a supply chain spanning several continents. For Li-ion batteries, roughly 85 percent of manufacturing capacity is concentrated in China, Japan, and South Korea. The European Union and the United States cover most of the rest of production.[9] The lead acid battery market is even more diffuse, with production again centered in Asia Pacific, North America, and Europe.[10]

There are several factors at play that are impacting the costs of batteries:

- ***Raw materials:*** A fundamental component of the cost of different battery chemistries will rely on a wide variety of raw materials, and each with their own supply chain. A drop in the price of raw materials should lead directly to the cost of batteries falling. Conversely, a supply shortage could trigger sharp price increases (e.g., nickel). Thus, sourcing raw materials from an unstable region could lead to a higher risk of disruption and price shocks.

- ***Technological innovation:*** Through extensive research and development, technological innovation can result in battery designs that are much more efficient and powerful, which lowers the cost of performing a certain function. However, as discussed in the ***Primer: A Technology Roadmap*** (see page 6), the battery industry has a history of overhyping the immediate market impact of technical innovations, and "breakthrough" electrochemistry or battery claims. Therefore, energy storage advances in technology require careful analysis to understand if and when such improvements can be realized in a real-world application (e.g., automotive battery packs).

- ***Production volume:*** Demand for battery technologies, and the volume of cell and module production to meet demand, is a key cost driver. For instance, lead acid batteries are used mostly in automobiles (SLI), and the industrialization of developing countries has continued to suppress prices for the technology.[11] Sustained demand for consumer electronics and increased demand for electric vehicles may be the dominant forces lowering the price of Li-ion batteries. The market for Li-ion batteries used in other applications (e.g., for grid purposes) also benefits since it shares the same underlying technology. Most recently, Tesla launched its Gigafactory in order to meet demand for its own line of electric vehicles.[12] Tesla's Gigafactory is one example of increased demand leading to suppliers moving toward very high production volume facilities and taking advantage of the resulting economies of scale. Similar lithium production facilities have been, or are being, developed by BYD and Daimler-Benz.

- ***Policy and regulation:*** Government policy and regulation shapes the market through taxes, subsidies, procurement mandates, government-funded research and development, international trade laws, and by shaping rules for market participation. The ***Primer: Policy and Regulatory Implications*** section (see page 43) in this report goes into further detail on how policy drives the market for energy storage more generally.

- ***Cost of competing technologies:*** The cost of conventional and competing technologies can influence the degree of market penetration that storage technologies can achieve. For grid-scale applications, energy storage will always be competing with other technologies and techniques that have traditionally accomplished the same functions. For instance, barring any regulatory mandates, batteries serving the function of transmission upgrade deferral will only be deployed if they are less expensive than the transmission upgrades themselves. Similarly, energy storage technologies capable of dispatching energy to the grid will compete with conventional power plants. However, energy storage technologies may have advantages that can bridge the price gap, such as being more responsive or able to dispatch more quickly.

- ***Balance-of-system (BOS) costs:*** BOS costs, including non-battery hardware components (e.g., inverters) and soft costs (e.g., interconnection), are a substantial component of the overall cost of a battery energy storage system. As batteries reach higher levels of commercialization and module costs fall, attention will likely turn to reducing BOS costs to bring costs down further. This has been seen in rooftop solar; after the biggest gains in module costs were realized, attention turned to reducing BOS costs. Such actions have been the dominant drivers of cost declines over the past few years.[13, 14]

BATTERY SYSTEM COST BREAKDOWN

Installed battery systems for stationary storage are designed for a specific purpose and the costs can vary widely according to each use case. The costs of a battery storage system are a function of a wide-ranging list of factors, including: chemistry, battery management system, system size, power electronics and balance-of-system, grid interconnection requirements, installation cost, battery life, operations and maintenance, whether the battery is for power or energy, discharge timescale (milliseconds to hours), grid condition and demands on the storage system, local operation conditions (such as climate), etc. Within each layer is a range of associated costs. The economics of a battery system and associated revenue streams is directly affected by the local market conditions in which the system will operate, available alternatives, government policies, expected market growth rates, market size, rate structures, etc. The highly variable nature of each system and the conditions in which they operate produced a wide variability in the economics of battery storage.

The costs associated with an installed battery system can be broken down into five categories:

- Cells
- Packs (including battery management system)
- Balance-of-system
- Installation
- Operation and Maintenance

MARKET MATURITY OF ENERGY STORAGE COST COMPONENTS

The below synopsis and analysis of energy storage cost components is based on data compiled from approximately 20 different industry and government agency reports. See the *ESN Insights* section (see page 54) for the author's perspectives on this data and future market forecasts.

BATTERY CELLS

The markets associated with energy storage cost components are at varying degrees of maturity. Japan's "first-mover" status in the consumer electronics industry in the 1980s means the supply chain for Li-ion batteries themselves is relatively mature thanks to Asia's nodal manufacturing practices and close ties with raw and processed material suppliers and manufacturers. Battery cell manufacturing in gigafactories in Asia and the United States associated with electric vehicle manufacturing is extending the role of batteries from consumer electronics into applications with high energy and power demands. These gigafactories are quickly achieving cost reductions due to economies of scale and standardization.

BATTERY PACKS

Li-ion battery pack prices for transportation applications have declined by 65 percent since 2010 with costs decreasing from $1,000 to $350/kWh in 2015.[15] It should be noted that in the automotive market, battery pack pricing and estimates often include cells (only) but other reports include modules, and BMS, but rarely include enclosure costs and other balance-of-system components. In general, overall high-voltage battery pack prices are expected to continue decreasing at a rate between 8 and 15 percent per year depending on electric vehicle growth rate and policy implementation assumptions.[16]

Li-ion battery pack prices for transportation applications have declined by 65 percent since 2010 with costs decreasing from $1,000 to $350/kWh in 2015. In general, overall high-voltage battery pack prices are expected to continue decreasing at a rate between 8 and 15 percent per year depending on electric vehicle growth rate and policy implementation assumptions.

BALANCE-OF-SYSTEM (BOS)

The market becomes less developed, however, as the cost component chain moves from packs to BOS and installation, particularly for stationary storage. The growth of the solar industry is putting pressure on inverter prices, and this is expected to extend somewhat into the stationary storage market; but two-way inverters for battery systems are inherently more complex, and therefore more expensive than solar inverters. The wide diversity of stationary storage systems in terms of size and interconnection requirements means that standardization in the BOS market will be slower to materialize. A lack of uniformity in the industry and adoption of safety standards and certifications could mean increased cost in the medium term.

Installation in progress for the Clay Terrace Plug-In Ecosystem, a first-of-its-kind advanced plug-in electric vehicle charging system with solar and battery storage integration. The system, now fully operational in Carmel, Ind., includes Level 2 and quick charge charging stations connected to a 10-kilowatt roof-mounted solar panel.

ESN's partners include Duke Energy, ITOCHU Corporation, Simon Property Group, and Toshiba Corporation.

INSTALLATION

Battery systems are often unique and the skilled workforce needed to install them is relatively small. In many cases, the only personnel qualified to install and troubleshoot these systems will be those who work for the manufacturer, and in the absence of significant competition this will keep prices relatively high for these services in the near- to medium term. Furthermore, increased safety standards such as those included in the most recent National Fire Code may require more specialized technicians to oversee installations.

OPERATION AND MAINTENANCE (O&M)

A similar trend is expected in the operation and maintenance (O&M) market. A lack of widely available qualified technicians will place a premium on O&M and monitoring services. Utilities are expected to initially internalize these costs to support pilot- and small-scale deployments. However, these high costs should provide an incentive for third-party specialists who will bring more competition to the market and reduce prices in the medium- to long term. Battery manufacturers are likely to respond by providing competitive service contracts with their systems. Established BOS companies could bid for these contracts and drive prices down further through standardization; however, without the levels of investment in the supply chain seen in the electric vehicle industry, O&M costs are unlikely to decrease at a rate comparable to battery cells or packs.

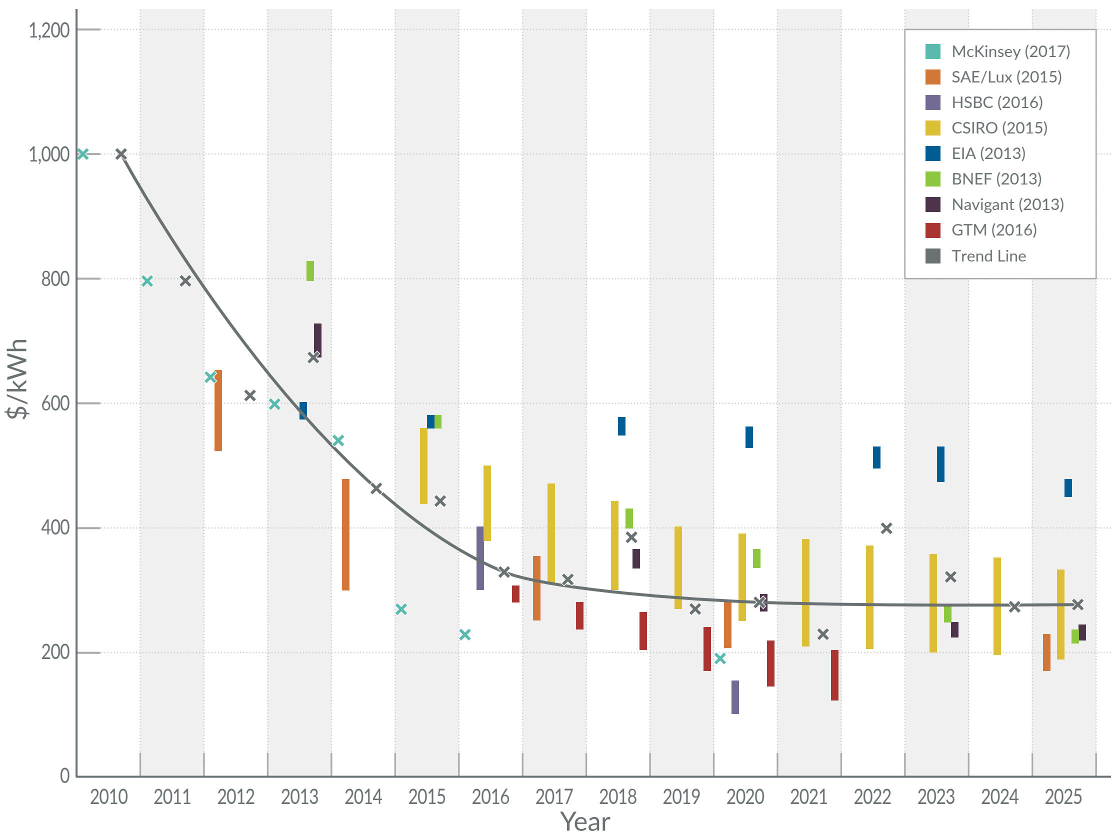
BATTERY PRICING ANALYSIS AND FORECASTS

SUMMARY OF RESEARCH

Understanding current and future pricing of energy storage systems is a complex task. While there are many reputable government, market analysts, manufacturers, and end users publishing data on battery and energy storage system pricing, the underlying assumptions and specific components included in such price forecasts vary widely. ESN reviewed more than a dozen research reports and market studies addressing current and future battery pricing. After a comprehensive review, we narrowed our focus to eight reports that we felt were coming from reputable sources and were not too dated. The majority of the reports focus on price forecasts for battery packs in the automotive industry, for which the market is most mature. It should be noted that the accumulation of this data represents several tens of thousands of dollars in value to access and review the reports and markets studies that draw from a wide range of automotive OEMs, Tier One battery suppliers, battery industry consultants, and government entities.

Each research and consulting firm's results have been plotted and represented in Figure 4.

Figure 4: Battery Pack Price Forecasts by Industry Market Study, 2010-2025



Assumptions and Disclaimers:

1. Trend line calculated by average of all reported prices forecasted for each year of data included.

As one can immediately observe from the data plots, the deviation among the reports' battery pack pricing projections demonstrates great variance among the researchers and market analysts. In fact, ***the data is so varied that it calls into question any valid guidance to the future of battery pack pricing in the automotive industry***. Frankly, this deviation in industry research, and in regard to the battery industry, is nothing new. There are two key factors that we believe lead to this variation.

First, researchers do not clearly define what specific cell chemistries or components are included in their "battery pack" pricing. In many cases, and as noted previously, report pricing represents only the cost of cells, battery management systems and modules, and possibly battery pack enclosures and housing, while not addressing or comprehending other important components like active thermal management, wiring and cabling connections, buss-bars, cost of assembly, etc.

Second, market researchers often derive their price forecasts by seeking direct figures from OEMs. This sensitive market dynamic Q&A with an OEM can lead to artificially low price quotes as a result of OEMs seeking to communicate to the market (primarily the investment community) that battery pack prices are actually coming down to justify their higher volume sales projections for EVs and PHEVs.

Therefore, having an accurate and comprehensive pricing roadmap for energy storage could be more useful and strategic than having access to the majority of "expert" reports available today.

THE BATTERY PRICING FUTURE: AN ESN PERSPECTIVE

One of the reasons there is such a wide variety of data and debate in the future of energy storage pricing topic is due to the wide range of unique concepts and technologies involved in an automotive battery pack. Many of these technologies are often overlooked or improperly assessed.

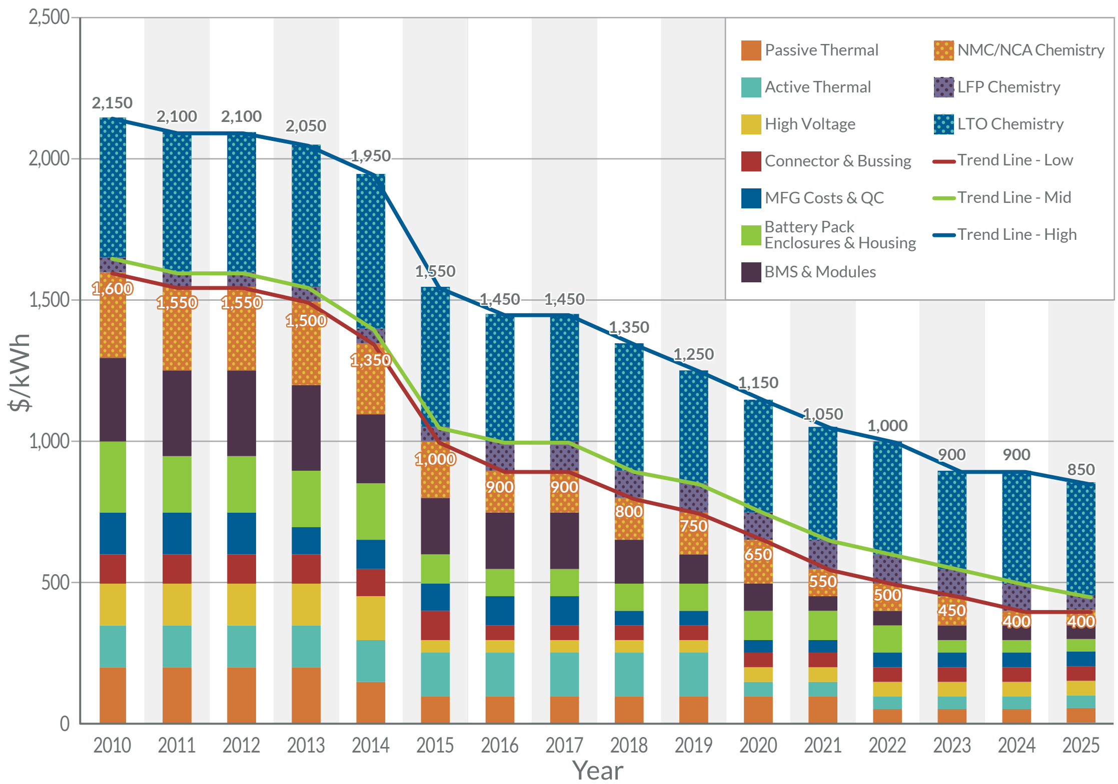
To reach the highest integrity in assessment, ESN has broken down the automotive battery pack into the following sub-components and topics:

- Battery cells (i.e., NMC, NCA, LFP, LTO)
- BMS and module assemblies (e.g., plastic parts and connections used in sub-assemblies)
- Passive thermal management (e.g., thermal conduction)
- Active thermal management (e.g., thermal convection via air/fans, liquid, etc.)
- High-voltage safety (e.g., automatic, and manual disconnect and switching devices)
- Wiring and cabling connections and buss-bars (between modules)
- Battery pack enclosures and structural housings (i.e., crashworthiness)
- Manufacturing (pack) assembly and end-of-line (EOL) quality testing

Research and consulting firms are typically not comprised of engineers or battery pack specialists, so they rely heavily on industry journals, interviews, and some inside industry consultants. In the reports, there appears to be little appreciation or close agreement on a consistent "bill of materials" or even the fundamental battery pack design concept, and what it includes and does not include. An "apples-to-apples" comparison approach is needed before attempting to assess the future costs of energy storage in the automotive industry.

As mentioned throughout this report, the automotive industry is the global leader in (high-voltage) energy storage solutions; therefore, a direct correlation to future energy storage pricing and stationary power applications or "grid-tied" solutions can be accurately assessed by drawing from the experience of the automotive industry. In reality, the durability and life cycle performance requirements for automotive battery packs are much higher than stationary energy storage applications, thereby over time driving battery pack costs higher in the automotive industry. The stationary battery industry would be wise to "borrow" the learnings, pricing structures, and supply chain reductions of the automotive industry and apply to stationary applications. Otherwise, common mistakes and costs are repeated (e.g., Boeing 787 Dreamliner incident; see page 20).

Figure 5: ESN Price Forecast for Full Battery Systems, 2010-2025



Assumptions and Disclaimers:

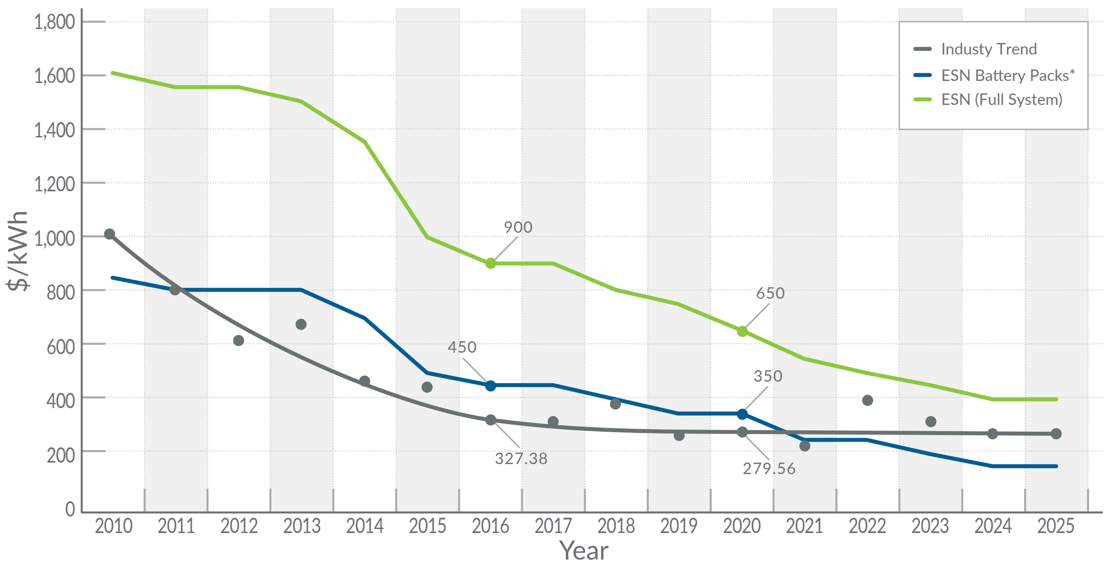
1. Individual component costs (i.e., thermal, BMS, connector and bussing, etc.) are not precise estimates, but reflect an approximate percentage of the total system cost.
2. Pricing of raw materials for NCM and NCA chemistries is fairly similar, so their pricing is combined in this report.

The reader can observe the plots on ESN's "Price Forecast for Full Battery Systems, 2010-2025," in Figure 5. Notice the previous years-to-date and the future projections. The previous years are highly accurate with unique industry expertise that ESN has been able to acquire through detailed battery system engineering and manufacturing expertise. The future projections were not merely developed for this report, but leverage learnings from the past 25 years of energy storage solution pricing in the automotive industry.

It should also be noted that the ESN price forecast includes variation for cell chemistry which can impact the batteries' energy vs. power profile, cycle life, and safety as well as the full balance-of-system components required to deliver an energy storage system for an automotive application. The forecast does not include an inverter, which is commonly included in a stationary energy storage system bill of materials but typically viewed as a separate system in automotive applications.

If you compare the ESN trend line to the average trend line from the eight industry reports, you will see that ESN shows a much higher cost for a true energy storage system than what is commonly being reported in most market studies. However, given that most market studies only consider a battery pack to include the lowest cost chemistries and a subset of the true balance-of-system components, ESN developed a second trend line that represents more of an "apples-to-apples" comparison. This second trend line that does not include full systems costs is much closer to the average trend line of the eight industry reports.

Figure 6: Comparison of Industry and ESN Battery Pack Price Forecasts, 2010-2025



Assumptions and Disclaimers:

1. The Industry trend line represents an approximation of pricing trends averaged across all previously mentioned market studies.

*2. "ESN Battery Packs" pricing includes approximate pricing (based on approximate percentage of total system cost) for cells (NMC/NCA chemistry), BMS and modules, battery pack enclosures and housing only.

3. "ESN Full System" trend line represents all system costs as represented in Figure 5.

EXPLAINING THE VARIANCE

There are many external factors driving the disparity between industry data and ESN's projections:

1. ***Inconsistent ingredients:*** Until recently, industry analysts did not distinguish between battery cells and the balance-of-system. Even today, it is difficult to tell if analysts are accurately evaluating the price of individual lithium-ion chemistries, battery management systems, thermal management systems, connections, structural housing and containment, and the cost of assembly and QC final checks. It is ESN's opinion that all these components are critical to understanding the reality of the full battery costs. Excluding them makes for an incomplete and unrealistic picture of what commercial or retail customers can expect to pay for these systems. And for the stationary storage market, ignoring these components is not a luxury to be afforded. ESN, as a result, has included all of the above components to ensure a complete view of system costs.

2. ***Public statements made by company leaders:*** The financial sector is quite in tune with the fact that the future success of the electric vehicle market is highly dependent on battery risk and cost. In order to create a vision for shareholders and future investors, OEM CEOs or company leaders often make orchestrated statements on future projections of costs per kilowatt-hour on both battery cells and battery packs. When these statements are made, the financial analysis ensues. Nevertheless, investment decisions are made by large institutions investing based on their assessment of the OEM costs per kWh of the future.

3. ***Illusion of battery pricing moving to $0/kWh:*** The automotive industry is infamous for driving profit out of its Tier One supply communities to the point of bankrupting companies (e.g., Delphi, Visteon, etc.). The U.S. Department of Energy (DOE) set industry target projections several years ago for automotive battery packs reaching $100/kWh. The reality of this target pricing could only result from commodity pricing of aluminum, cobalt, copper, lithium, manganese, and nickel reaching $1/ton of materials or less. It is simply not a sustainable future for battery suppliers not to make a profit on their R&D, supply chain, assembly, and battery delivery products.

Resources within ESN have been accurately predicting the future of advanced energy storage since 2005, with documented and positive results. As the world increases their demand for energy storage, more attention will be paid to the automotive industry which is driving global supply chains, production, assembly, warranty, and recycling efforts of lithium-ion chemistries. ESN has the unique experience and advanced systems approach to provide an ***Energy Storage Roadmap*** with the highest integrity and insight possible.

Leveraging the "lessons learned" from the automotive industry will accelerate stationary energy storage implementation in the built environment and decrease technology risk. Conversely, ignoring the "lessons learned" from the automotive industry will increase costs, delays, and risk in advanced energy storage solutions.

> Since its introduction to the market in the late 1990s, the lithium-ion camcorder battery has retailed between $75-$100 (maintaining profits for two decades).

IMPLICATIONS FOR STATIONARY STORAGE

The implications of ESN's price forecast analysis shed light on a significant and ongoing concern regarding the price of stationary energy storage systems. The utility industry and other customers of stationary energy storage systems are often puzzled by the seemingly dramatic difference in $/kWh of automotive and stationary energy storage systems. While there are limited comprehensive industry reports and forecasts for the price of stationary storage systems, ESN's review of available reports and real-world pricing of more than a dozen systems (including several procured by our industry partner, the Battery Innovation Center) suggests an average price for stationary energy storage systems in 2017 as follows:

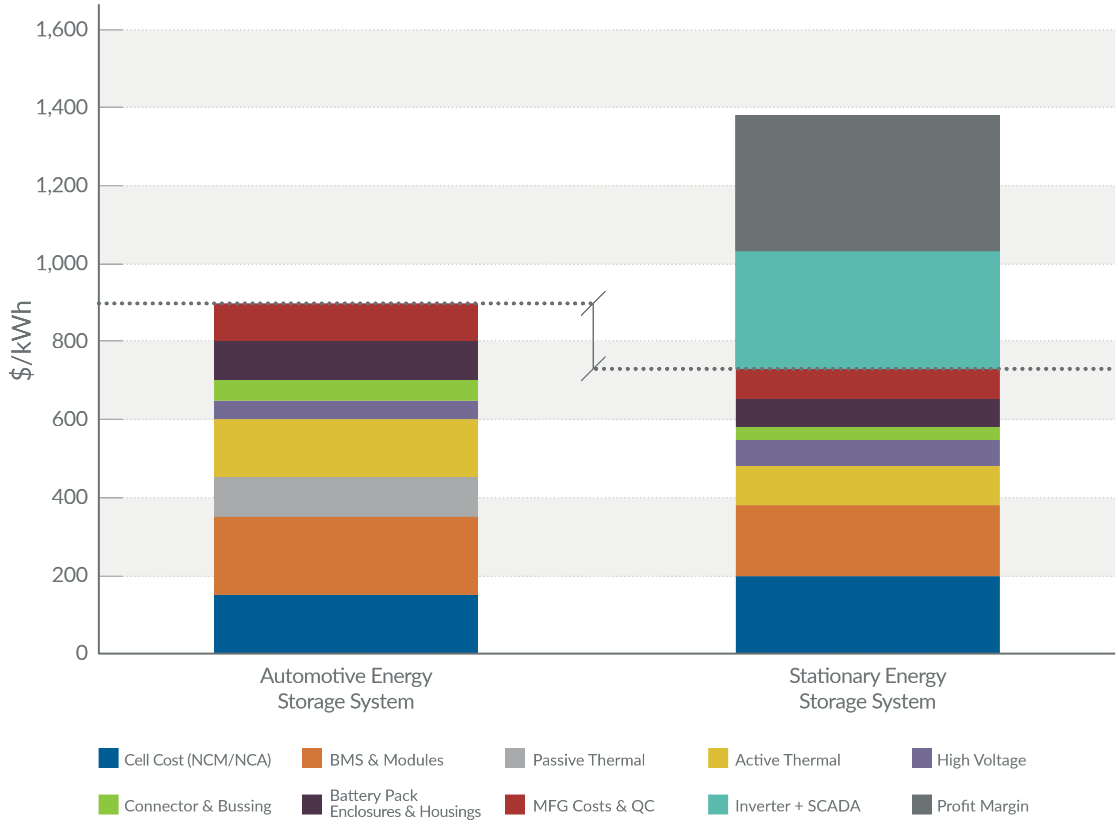
Table 2: Average Pricing for Stationary Energy Storage Systems – 2017

Stationary Storage System Type	Price ($) per kWh
Home Energy Storage Systems (5 - 20 kWh)	$1,200 - $1,700
Community Energy Storage Systems (100 – 500 kWh)	$1,100 - $1,400
Grid Storage Systems (500 kWh +)	$950 - $1,300

If one considers the average of the eight industry reports analyzed, one could conclude that the difference between an automotive battery system and grid storage system is approximately $870 per kWh ($1,200 grid - $330 automotive). However, ESN's price forecast, which considers the full system cost for an automotive energy storage system, reveals there is only an approximate price difference of $300 per kWh ($1,200 grid – $900 automotive). Additionally, there are costs typically included in the price of stationary storage systems but not automotive packs that further minimize the price difference. For example, the cost of an inverter is typically left out of automotive energy storage system costs, but regularly included for stationary applications. Also, the sale price of stationary storage systems includes roughly a 20 percent profit margin, but is often excluded from automotive battery systems since the profit is taken at the full vehicle level. Once these additional costs are added, the price difference between automotive and stationary energy storage systems nearly disappears.

In summary, the real difference between the full systems cost of energy storage in an automotive or stationary application is not as dramatic as one might think given the numbers often published in reports and news articles on the battery industry. Understanding this "analyst reporting" reality requires a deeper dive that fully accounts for the balance-of-system costs. However, given that automotive applications require stricter safety (e.g., crashworthiness), higher

Figure 7: Price Comparison of Stationary and Automotive Energy Storage Systems – 2017

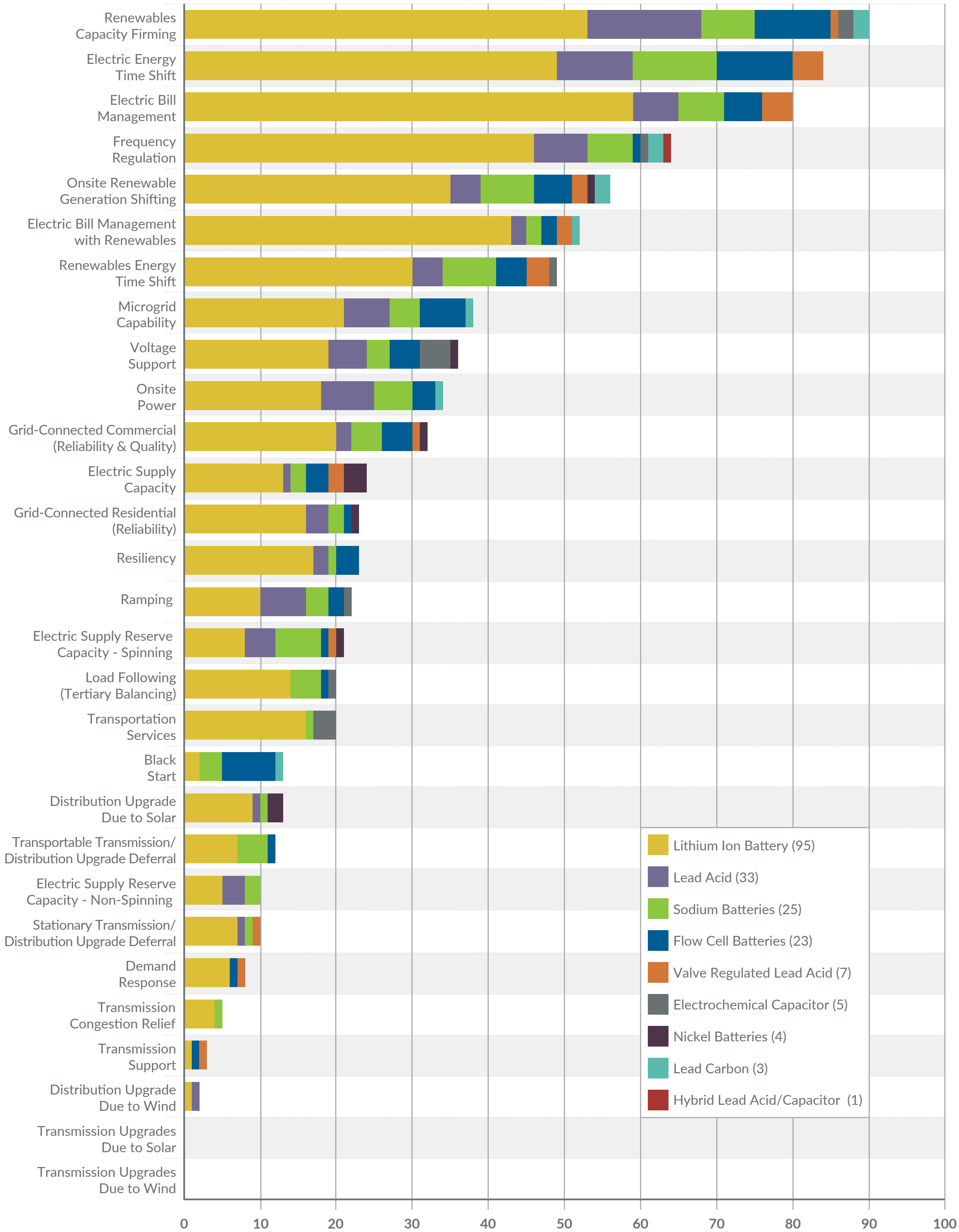


durability performance measures (e.g., 100,000-mile powertrain warranties), higher temperature variation, and tighter packaging requirements, it seems clear from an engineering and manufacturing standpoint that stationary energy storage systems should over time become less expensive than automotive energy storage systems on a price per kWh basis. Reaching this point will require the stationary storage system industry to develop greater standardization in design and packaging, more mature supply chains, and higher-volume demand from utilities and other customers.

ECONOMICAL APPLICATIONS OF ENERGY STORAGE

As presented in the ***Primer: A Technology Roadmap*** (see page 6) there are a wide range of applications which energy storage systems can serve. Figure 8 illustrates the number of energy storage system projects installed and their respective battery chemistries that are serving various applications. There are a number of markets in which stationary energy storage is proving to be more economical than others and not surprisingly more projects have been commissioned that serve these markets. The next several pages will provide a summary of the most prominent applications for which economic returns are being realized.

Figure 8: Installed Energy Storage Applications by Chemistry



Source: U.S. Department of Energy Global Energy Storage Database, 2017. (https://www.energystorageexchange.org/)

RENEWABLES CAPACITY FIRMING

Renewables such as wind and solar are intermittent in nature and pose a challenge to a grid that is designed for generation from coal, natural gas, and nuclear power – all of which are more consistent sources of generation. As renewables connected to the grid grow, the value of a storage system that can smooth the power/energy profile will grow as well. The value of these storage systems will need to be compared with the cost of fast-ramping generation sources, such as natural gas, which is also currently being used to compensate for the intermittency of renewables. Renewable capacity firming is the most stated potential application for battery systems (90) according to the U.S. Department of Energy Global Energy Storage database, accounting for about 11 percent of all declared potential applications for batteries.

DEMAND CHARGE MANAGEMENT

In general, long-term energy storage is the most expensive application of a battery. The economics of long-term storage is most likely to be feasible only when the cost of energy is high, such as high peak demand charges. Various studies currently place the break-even price point for demand charge management at between $.09 and $.15/kWh[25] As the costs of battery systems decline, the break-even price point should decline as well – possibly as low as $.04-.05/kWh by 2020.[26] Electric bill management accounts for 10 percent of all declared potential applications for installed battery systems in the U.S., according to the U.S. Department of Energy Global Energy Storage database.

FREQUENCY REGULATION

Frequency regulation is a short-term (millisecond-to-second) combination of energy absorption and emission by the storage system to help maintain optimum operating frequency range on the grid. These applications do not necessarily require high-energy-density, large-capacity battery systems; therefore, they are more likely to provide value without the relatively high capital investment that is required for long-term discharge systems that are needed for demand charge management and time shifting systems. Services such as frequency regulation play to batteries' strengths as a technology that can both receive and produce energy and operate on shorter timescales than conventional technologies. Frequency regulation accounts for 8 percent of all declared potential application for installed battery systems in the U.S., according to the U.S. Department of Energy Global Energy Storage database.

TRANSMISSION AND DISTRIBUTION UPGRADE DEFERRAL

The grid system needs to be designed to manage energy demands throughout the year. Even in a relatively stable profile, there will be times when energy demand can peak above what is normally required. Knowing this, utilities must be prepared for peak loads that may only be expected to happen over a very short time frame – sometimes only a few peak hours throughout the entire year. Installing equipment to account for this fact is very expensive and the equipment is often permanent – a sunk cost.

Energy storage is likely to have real value in this case because it can be installed in place of expensive transmission and distribution (T&D) equipment to handle the expected, but rare, peak loads. This may serve the needs of the utility for a couple of years. However, as the local market grows, the demands may exceed the ability of the storage system to meet those needs. At this point, the storage system can be called on to meet other needs such as frequency regulation, capacity firming, etc. It should also be noted that it is possible the storage system was performing these functions since it was installed, so it may have value as a stacked resource beyond simply providing T&D equipment investment deferral.

Furthermore, the system can be moved to another location and again permit the deferral of T&D investment elsewhere. In this way, the storage system's value can be extended over a longer time frame and for multiple applications.

Transmission and distribution upgrade deferral can also be used to reduce the risks associated with uncertainty in demand growth. For instance, a new housing development may quickly become a source of growing electricity demand, but the development itself is a source of uncertainty. A utility may avoid investing in permanent infrastructure and use storage to meet peak demand until the development becomes more ascertainable.

ELECTRIC CAPACITY SPINNING RESERVES

Spinning reserves are systems that are already frequency synchronized but not releasing energy to the grid. Usually they are spare capacity in a unit that is currently generating electricity. Storage is seeing a small but growing market as an element in spinning reserves. One example is the GE-Southern California Edison (SCE) partnership to create a battery/gas turbine hybrid system to mitigate the gas supply shortages associated with the Aliso Canyon gas leak.[27] There are currently at least 22 battery systems with the potential to act as spinning reserves throughout the U.S., including several in California, Texas, Alaska, New York and the Midwest.

While the market for each of these applications alone is currently small, there is the potential for added value from multiple applications from the same battery system. See "The Values and Issues Associated with Application Stacking" in the Applications section.

These economical applications are demonstrated by real-world installations across the United States, illustrated in Figure 10 (see page 48).

MEASURING THE VALUE OF STORAGE COMPARED TO ALTERNATIVES

To attract private investment in the budding storage industry, investors must have confidence that storage technologies will bring greater value (adjusted for risk) than that of comparable investments. Thus, measuring the value of storage is key to being able to compare it to that of other technologies. This continues to be a great challenge and priority for the storage industry.

The ***levelized cost of electricity*** (LCOE) (sometimes referred to as "levelized cost of energy") is a metric developed as a means to compare the competitiveness of different power generation technologies. The LCOE gives a $/kWh value representing the cost of building, financing, fueling, operating, and maintaining a plant over its useful life, inclusive of certain operating assumptions (e.g., capacity factor). The advantages of LCOE are its familiarity in the power industry and its ability to offer a method of easily comparing technologies. However, LCOE depends heavily on the assumptions it embodies – particularly the cost of different fuels and estimates of government policies. The LCOE is also less useful at the local level, where other factors may be more important in making decisions regarding which technology is best to meet a given need.[28]

LCOE has been an important metric in the tracking of costs for wind and solar relative to other generation technologies and estimating when they may reach price parity. Lazard – a leading finance and asset management firm – develops an annual "Levelized Cost of Energy Analysis," which may be the most complete analysis of LCOE across technologies, inclusive of sensitivities across all major inputs.[29]

Due to the role LCOE has played in informing the wind and solar industries, analysts created a similar measure to serve the same purpose for storage technologies. The ***levelized cost of storage*** (LCOS) was developed as an analog to LCOE to attempt to characterize the value of storage compared to generation technologies. Storage cannot use LCOE directly since it is not a traditional generation

Table 3: Levelized Cost of Storage Ranges by Chemistry

Lazard LCOS (Nov 2015)	Chemistry	Low range ($/MWh)	High range ($/MWh)
Microgrid	Flow battery	429	1046
	Lead	433	946
	Lithium	369	562
	Zinc	319	416
Island	Flow battery	593	1231
	Lead	700	1533
	Lithium	581	870
	Zinc	523	677
Commercial & Industrial	Flow battery	349	1083
	Lead	529	1511
	Lithium	351	838
	Zinc	310	452
Commercial Appliance	Flow battery	947	1504
	Lead	928	2291
	Lithium	784	1363
	Zinc	661	833

LAZARD Levelized Cost of Storage Current LCOS – Single Application Utilization without subsidies

Lazard LCOS (Nov 2015)	Chemistry	Low range ($/MWh)	High range ($/MWh)
Residential	Flow battery	721	1657
	Lead	1101	2238
	Lithium	1034	1596
Comparison to conventional alternatives	Diesel Reciprocating Engine	212	281

Source: Lazard Levelized Cost of Storage – Current LCOS, Single Application Utilization without Subsidies (2015).

asset; even when serving an application for the provision of energy, its costs depend on the price of charging. LCOS attempts to measure the average net revenue per unit of energy a storage system must bring in over its lifetime to recover its capital and O&M costs.[30] Table 3 (see page 40) demonstrates the LCOS range by chemistry across several different applications.

However, even the LCOS is far from a perfect means of comparing storage and generation technologies. The measure is arbitrary in that its value depends on the actual application it serves and the context in which it's deployed. It is also incomplete, as it does not capture all of the avenues through which storage can generate revenue.[31] The LCOS may not take other important features into account, including a storage technology's advantage in flexibility, dispatch time, or added value to the grid in terms of reliability or reduced emissions. At this time, there is no single method of comparing storage with generation assets, making it difficult to know when a technology reaches cost parity.

Revenue streams depend on context (e.g., application, generation portfolio of the grid, market structure), so one measure (e.g., LCOS) likely cannot exist to characterize storage in general. Thus, focus should be placed on the specific value storage can bring to a particular situation.

Lazard is also the primary source for LCOS estimates. Lazard's analysis covers a combination of a wide range of energy storage technologies and ten "use cases." Yet while the analysis provides insightful information, Lazard recognizes and states upfront that it does not analyze several important aspects, including:

- Storage systems serving and drawing revenue from multiple applications;
- The value of storage in a particular market context;
- A clear comparison to conventional generation technologies, among other factors.[32]

In measuring the true value of storage, one must consider a range of factors. The cost curve is a very important component of a storage technology's financial viability and must be understood. On the revenue side, a representation of a storage technology's revenue streams – derived from the value storage can bring to the grid by serving one or more applications – is also needed. Revenue streams depend on context (e.g., application, generation portfolio of the grid, market structure), so one measure (e.g., LCOS) likely cannot exist to characterize storage in general.[33] Thus, focus should be placed on the specific value storage can bring to a particular situation.

However, while LCOS and Lazard's study may not tell the whole story, they do provide helpful cost-based information and represent the best ***generalized*** measure of value available at this time. As long as market analysts understand that there are value aspects that LCOS does not cover, they can still glean useful information about the value of different storage technologies in different applications. They can also make educated guesses about how they compare to relevant conventional technologies and discuss the value of storage with a common unit of measure. Thus, it is still a useful exercise to become familiar with the latest LCOS estimates.

The Battery Innovation Center (BIC), formed and launched in 2013 by ESN, is a $20 million R&D and prototype manufacturing facility focused on advancing the energy storage market. It is also home to Underwriters Laboratories' (UL) Battery & Energy Storage Technology (BEST) Test Center.

PRIMER: POLICY AND REGULATORY IMPLICATIONS

Public policy is an essential factor influencing the successful development and commercialization of new energy technologies. The right policies can trigger innovation, improve access to the power market, enhance the technical potential for integration with the grid, and stimulate key early-stage funding. An absence of policies – or the existence of policies that discriminate against new industry entrants and don't recognize the multiple value streams of new technologies – can slow market penetration or otherwise lead to barriers to adoption.

THE AMERICAN RECOVERY AND REINVESTMENT ACT (ARRA)

$4.5B invested in grid modernization projects

including

$600M for smart grid and energy storage demonstration projects

Source: Office of Electric Delivery and Energy Reliability.[39]

In general, policies support new energy technologies through three avenues:

- ***Research and Development (R&D):*** Government-funded R&D is often necessary to spur innovation in the power industry. Despite having high potential rewards, new energy technologies tend to carry high risks and require enormous start-up funding, both of which fail to attract participation from private investors. The Department of Energy's national laboratories, universities, and industry receiving government funding all carry out R&D critical to the early stages of development for new technologies.

- ***Commercial Pilots and Demonstration:*** Similar to R&D, private investors may not be willing to fund and develop pilot projects for new energy technologies due to their high risks. Pilot projects are necessary to bridge the gap between concept and market by testing laboratory designs in real-world conditions. Pilot projects can demonstrate new technologies in the field and prove their technical and economic feasibility, or they may affirm that further testing and design modifications are necessary before the technologies can achieve commercialization.

- ***Commercialization Support:*** Once new technologies are proven, they are often still more expensive than existing technologies and must be supported for a temporary period. The costs associated with new technologies fall with industry experience and economies of scale. Commercialization support can take the form of tax credits, mandates and goals, and other financing strategies to attract private sector investment. Such subsidies can be scaled down over time as the industry for the new technology develops and blends with the larger power market.

> *An absence of policies – or the existence of policies that discriminate against new industry entrants and don't recognize the multiple value streams of new technologies – can slow market penetration or otherwise lead to barriers to adoption.*

Additionally, commercialization support may also take the form of changing or clarifying market rules, particularly for technologies that do not fit traditional models for the power industry.

FEDERAL POLICY

KEY FEDERAL BODIES:

- ***The Federal Energy Regulatory Commission (FERC)*** is an independent federal agency responsible for regulating the interstate transmission of natural gas, oil, and electricity. FERC also has regulatory power over the wholesale electricity market; it does not have jurisdiction at the retail level, however.[34] FERC plays a role in the commercialization of energy storage by revising market rules to level the playing field and enable new technologies to participate in wholesale power markets. FERC has been fairly active in the energy storage space over the last decade; initially, it issued orders preventing discrimination against storage technologies, and more recently considered a rule that would create a market participation model for energy storage resources that accounts for their unique characteristics.[35,36,37]

- ***The Department of Energy (DOE)*** is a federal agency overseeing several energy, environmental, and nuclear programs. DOE affects energy storage through research and development at its national laboratories, and by funding advanced research projects and grid modernization, clean energy, and energy efficiency programs.[38] DOE oversaw the implementation of funding for energy projects from the American Recovery and Reinvestment Act (ARRA) of 2009. Through ARRA, DOE invested about $4.5 billion in grid modernization projects, including $600 million dedicated to smart grid and energy storage demonstration projects.[39] ARRA also granted the initial budget of DOE's Advanced Research Projects Agency – Energy (ARPA-E), which funds high-potential, high-impact energy technologies that are not sufficiently developed to attract private sector investment.[40]

- ***The North American Electric Reliability Corporation (NERC)*** is a nonprofit international organization that focuses on maintaining the reliability and security of the North American power grid. NERC accomplishes this by designing and enforcing reliability standards and monitoring the grid. While NERC's reliability standards indirectly affect the use of energy storage as a grid asset, NERC does not focus specifically on the advancement of these technologies, nor does it promote a public-facing position.[41]

Over the years, certain orders, programs, and standards from FERC, DOE, and NERC have changed the landscape regarding the capacity of, and market rules for, energy storage to participate in the grid. These bodies are also the entities most likely to change federal, interstate, and wholesale market rules moving forward.

PROMINENT FEDERAL ACTIONS:

- ***FERC Order 890 in 2007*** required increased transparency and coordination in the planning and use of the transmission system, with a goal of addressing undue discrimination (i.e., against the use of energy storage).[42,43]

- The ***DOE Smart Grid Demonstration Program (SGDP)***, first authorized by the Energy Independence and Security Act of 2007, was created as a means to demonstrate the feasibility of new smart grid-related technologies. Through this program, DOE offers to fund up to 50 percent of the costs of selected projects. Energy storage projects used for grid-scale applications are specifically identified as being eligible for SGDP grants.[44,b]

- ***FERC Order 719*** in 2008 required Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) to allow demand response (DR) resources to participate in ancillary service and joint energy-ancillary service markets. Such resources must make clear their limits on the duration, frequency, and amount of the service they are offering. This order therefore allows energy storage systems to participate directly in such markets.[45,46]

- ***FERC Order 1000*** in 2011 is a landmark rule that reformed FERC's requirements for electric transmission planning and cost allocation for public utility transmission providers. Under this order, grid operators must plan transmission on a regional level and allow for competition by independent power producers (IPPs) in building power lines. Since energy storage can often provide a cost-effective alternative to building or upgrading transmission lines, this order provides another avenue for storage participation in the power market.[47,48,49]

- ***FERC Order 755*** in 2011 requires that technologies providing frequency regulation services to the grid receive compensation based on the value of the service. ISOs and RTOs traditionally look to a variety of resources to provide frequency regulation, but these resources differ on their flexibility and accuracy. This order promotes energy storage technologies, since they have the potential to provide much higher quality frequency regulation services and now must be compensated for their added value.[50,51]

- In 2016, the ***White House*** announced executive actions and private sector commitments expected to result in more than 1.3 GW of energy storage procurement or deployment and $1 billion in energy storage investments within the next five years. Such actions range from building new storage capacity on military bases to utilities announcing programs to install smart water heaters.[52]

- FERC issued a policy statement in 2017 through ***Docket No. PL17-2-000*** providing guidance for energy storage resources

b The Smart Grid Investment Grant (SGIG) program operates in a similar manner, and also includes funding for energy storage projects.

looking to recover costs through cost- and market-based revenues. The statement discusses that energy storage technologies are technically capable of providing multiple services, and it clarifies issues that should be addressed should a storage system seek to recover costs through multiple revenue streams.[53]

- The ***DOE Energy Storage Technology Advancement Partnership (ESTAP)*** is a cooperative between DOE and interested states that provides funding for and promotes information sharing regarding energy storage technologies. ESTAP manages the State Energy Storage Network, gathers information about state energy storage activities, works with stakeholders to develop new storage projects, and provides technical assistance through energy storage webinars.[54]

ACTIONS UNDER CONSIDERATION:

- Under ***FERC NOPR 16-23-000*** issued in November of 2016, FERC is proposing to remove several barriers to energy storage participation in ISO/RTO capacity, energy, and ancillary service markets. The first portion of the proposal looks to implement market rules that accommodate the unique "physical and operational characteristics" of energy storage technologies. The second portion defines a "distributed energy resource aggregator" as an entity that can participate in any markets in which it is capable of serving based on its characteristics.[55,56] A distributed energy resource aggregator may consist of solar PV, battery storage, and a hot water heater, for example.[57]

INDEPENDENT SYSTEM OPERATORS (ISO) AND REGIONAL TRANSMISSION ORGANIZATIONS (RTO)

ISOs and RTOs have been set up around the country and play a few key roles, including managing unbiased access to the transmission system for all resources; managing the reliable, efficient commitment and dispatch of those resources with respecting to the flow limits of the transmission system; and directing the overall reliability of the system. They commit and dispatch generation and other resources based on the offers provided by the asset owners. They also set the terms by which assets must participate in each particular market. These rules are tariff-based and regulated by FERC. RTOs are voluntary organizations. Choosing to opt in generally reduces a utility's cost and provides them opportunities to sell excess capacity or energy. Seven ISO/RTOs serve various regions across the United States, while the Southeast and much of the Southwest (except California) operate independent of an ISO/RTO. The seven ISO/RTOs are as follows:

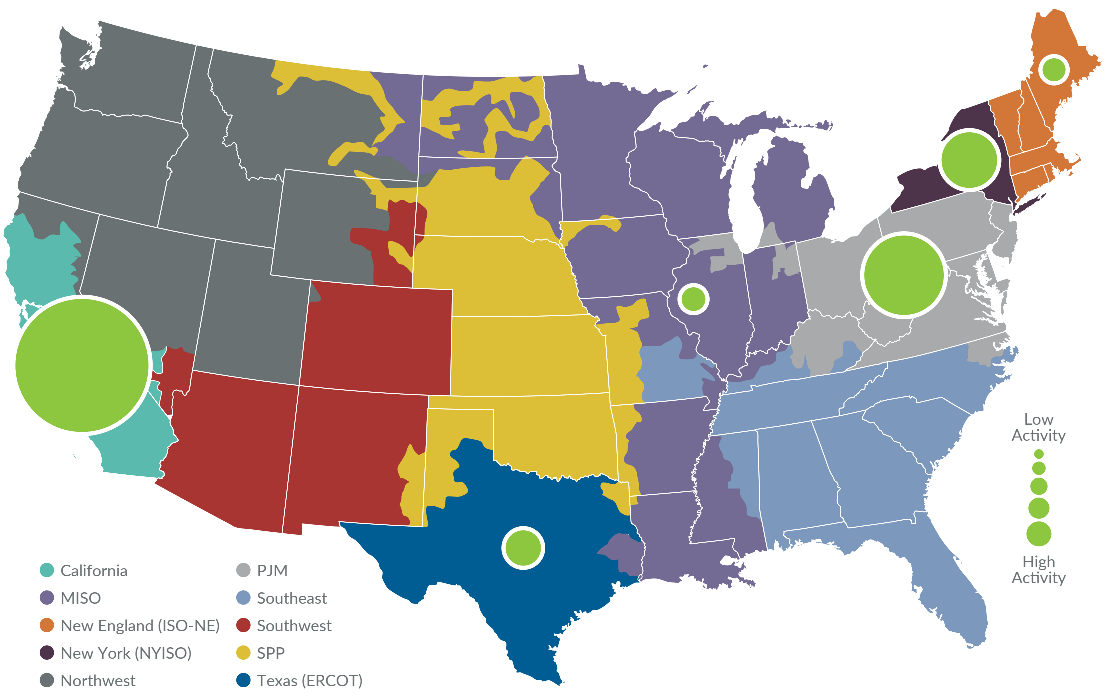
- ***California Independent System Operator (CAISO)*** occupies most of California and parts of Nevada. CAISO has been very active in the energy storage space, working with the California Public Utility Commission and the California Energy Commission on a detailed roadmap to advance the use of storage technologies.[58] CAISO's roles in the roadmap include clarifying rules and evaluating new opportunities in rate treatment, interconnection, and market participation of energy storage. CAISO is also working through a multi-phase Energy Storage and Distributed Energy Resources (ESDER) initiative, which has recently led to new tariff structures and FERC filings.[59] California's relatively high penetration of renewable resources and its stringent renewable energy and greenhouse gas targets contribute to CAISO making energy storage a priority.

- ***PJM Interconnection*** covers a group of Mid-Atlantic states from the east coast stretching to Chicago. PJM has been very active in attracting energy storage projects through its implementation of FERC Order 755, which serves to recognize the value energy storage brings to frequency regulation. PJM has over 300 MW of energy storage technologies, in addition to a long history of operating pumped hydro storage facilities. The RTO is also exploring where energy storage can play a role in transmission upgrade deferral.[60]

- ***New York ISO (NYISO)*** covers the entire state of New York. NYISO was the first ISO to create new market rules for energy storage technologies to provide frequency regulation services in 2009. NYISO also provided research to inform the state's Reforming the Energy Vision (REV) strategy (which involves shaping the power sector to better accommodate distributed energy resources) and is assisting with implementation.[61]

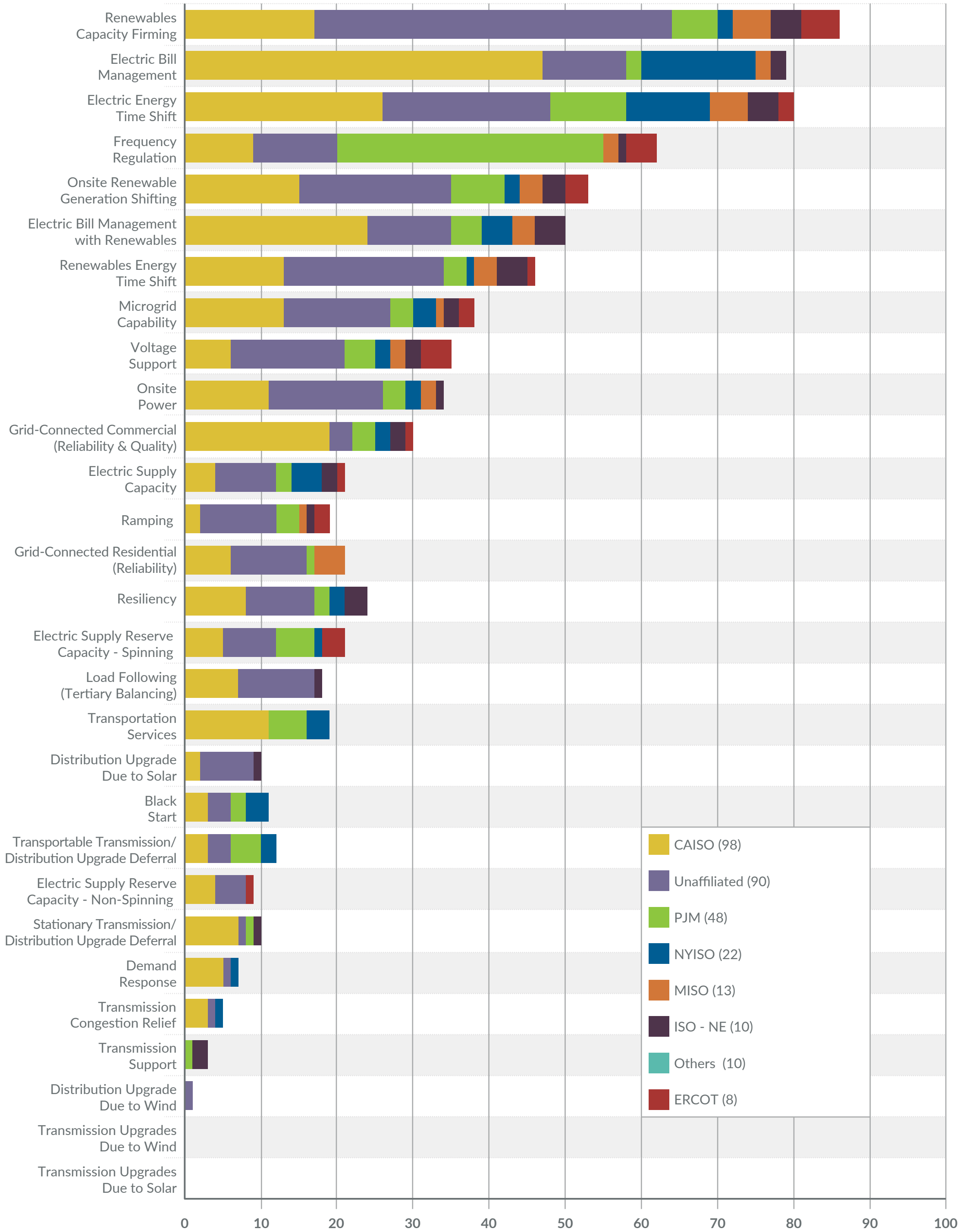
- ***ISO New England (ISO-NE)*** covers the whole of New England. ISO-NE altered its market structure to include a new dispatch signal allowing energy storage technologies to participate in frequency regulation services.[62] It has since taken

Figure 9: U.S. Energy Storage Activity by ISO/RTO



Source: Federal Energy Regulatory Commission: Electric Power Markets – National Overview (February 29, 2016). https://www.ferc.gov/market-oversight/mkt-electric/overview.asp

Figure 10: Installed Energy Storage Applications by ISO/RTO



Source: U.S. Department of Energy Global Energy Storage Database, 2017. (https://www.energystorageexchange.org/)

actions to further enable and clarify options for participation in other markets.[63,64] The first grid-scale battery system was deployed in 2015, and ISO-NE now has an additional 77 MW of battery storage in the interconnection queue.[65]

- ***Midcontinent ISO (MISO)*** occupies a range of southern and Midwestern states from Louisiana to Minnesota and into Canada. MISO is still in the early stages of developing market alterations that would further enable energy storage participation and compensation, but it is actively working with stakeholders.[66] Indianapolis Power & Light Company (IPL) introduced the first battery storage system in MISO's territory in 2016. Following a recent filing by IPL, FERC issued an order providing further guidance to MISO to accommodate energy storage technologies in whichever markets they are technically capable of serving.[67]

- ***Southwest Power Pool (SPP)*** covers a range of Midwestern states from the northern tip of Texas to the Dakotas. SPP has arguably taken the fewest actions with regard to energy storage, although it has begun discussions with stakeholders.[68,69]

- ***Electric Reliability Council of Texas (ERCOT)*** occupies most of Texas and consists of its own interconnection (separate from the Western and Eastern Interconnections that make up the rest of the United States). Since the Texas Interconnection does not cross state lines, ERCOT is not subject to FERC jurisdiction. ERCOT has hosted some pilot projects, which allows them to test new technologies and use the information to enable future legislation related to these technologies.[70,71]

> *States are often critical in the demonstration and commercialization phases of policy support for energy technologies, and it is clear that some states have taken much more aggressive action than others in the energy storage industry.*

STATE POLICY

At the state level, ***public utility commissions (PUCs)*** play a prominent role in influencing the access to, and funding for, energy storage technologies. In regulated electricity markets, PUCs set utility tariff structures to ensure that they (1) are able to recover their costs plus a reasonable return on investment, and (2) do not abuse their monopoly power and take advantage of ratepayers. PUCs also influence state electricity markets by setting rules and standards that utilities must follow.

The ***state legislatures*** also have considerable influence over energy markets. State lawmakers may step in to set ambitious procurement mandates, require their PUCs to pursue certain agendas, or even actively change market rules in lieu of PUCs. State lawmakers seeking to promote renewable energy have adopted renewable portfolio standards or goals, instituted net energy metering policies, and established carbon dioxide emissions trading regimes. Other lawmakers have sought to slow the growth of renewable energy and protect legacy power plants by repealing policies, adopting sunset provisions or caps, and even proposing to tax renewable energy.[72] While some states have put forth significant bills related to energy storage, legislative action on this issue is still relatively new.

States are often critical in the demonstration and commercialization phases of policy support for energy technologies, and it is clear that some states have taken much more aggressive action than others in the energy storage industry. By looking at PUC and legislative actions, significant differences become evident among states in their support of (or indifference to) energy storage.

PROMINENT STATE ACTIONS:

- The ***California Public Utility Commission (CPUC)*** enacted the ***Self Generation Incentive Program (SGIP)*** in 2009, allowing customers of qualified behind-the-meter distributed energy systems to receive rebates on their purchases on a $/W basis. The program currently funds *advanced* energy storage systems, but CPUC reopened the incentive to energy storage projects in May 2017.[73]

- The ***Public Utility Commission of Texas*** ordered ***Project Number 39917*** in 2012, which determined that energy used to charge an energy storage facility should be treated as a wholesale transaction rather than be priced as end-use consumption. This price difference affects the economic efficiency and viability of storage projects and influences decisions regarding their location on the grid.[74]

- The ***California Public Utility Commission*** adopted an ***Energy Storage Procurement Framework*** in 2013 (as directed by ***Assembly Bill 2514***) and set an energy storage target of 1.325 GW for the state's three major utilities by 2020. The utilities must submit periodic procurement plans to be approved by the CPUC. The CPUC is also engaging in continued work to refine and improve the program.[75]

- The ***Public Utility Commission of Texas*** ordered ***Project Number 40150*** in 2013, which granted the Electric Reliability Council of Texas (ERCOT) the authority to conduct pilot projects, exempt from ERCOT rules. These pilot projects allow ERCOT to test new technologies (e.g., energy storage), the results of which can influence future ERCOT rules and procedures.[76]

- The ***Hawaii Public Utilities Commission*** was directed in 2014 by ***House Bill 1943*** to value the use of advanced grid modernization technology in an effort to improve the grid's reliability and efficiency. The commission must base decisions on several principles, including increasing the ease with which distributed generation resources can connect with the grid and determining fair compensation for different grid services.[77]

- The ***State of Utah*** released an updated ***10-Year Strategic Energy Plan*** in 2014 which recommends an evaluation of the state's role in energy storage strategies with a focus on compressed air energy storage.[78]

- In ***Oregon, House Bill 2193*** (signed in 2015) set a mandate for Oregon's two largest utilities to procure at least 5 MWh of energy storage by January 1, 2020, with a cap of 1 percent of each company's peak load.[79,80]

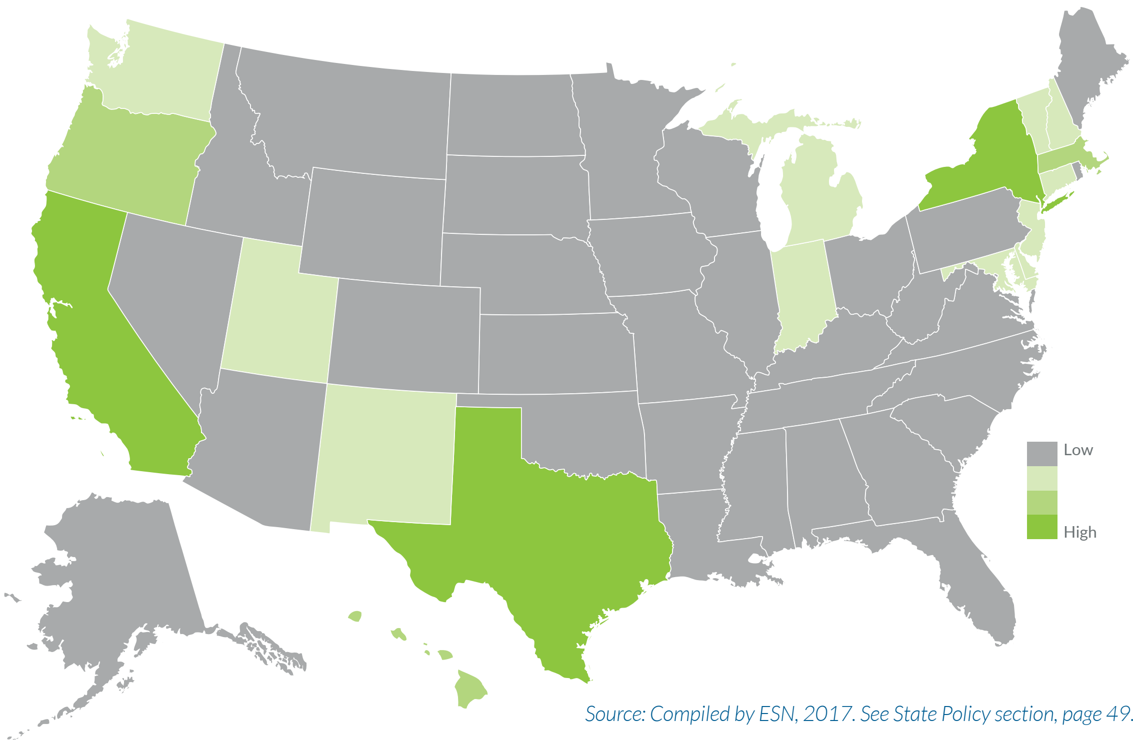
- The ***Vermont Department of Public Service*** (in a joint effort with the federal government) awarded a grant to Green Mountain Power to build a solar and battery storage project designed as a microgrid (commissioned in 2015). The project is intended to demonstrate the technology and improve the resiliency of the area.[81]

- The ***State of New Mexico*** released an ***Energy Policy & Implementation Plan*** in 2015 which lists several recommendations to expand the development and deployment of energy storage technologies in the state. New Mexico is also home to two existing battery storage demonstration projects.[82]

- The ***New York Public Service Commission*** ordered a fundamental change in its ratemaking model as part of the state's ***Reforming the Energy Vision*** strategy. The 2016 reform established new ways for utilities to earn a profit – for example, with earnings tied to actions that reduce capital spending and achieve performance goals. This opens additional funding opportunities for energy storage systems; for instance, a utility may install storage technologies to delay distribution system upgrades.[83,84]

- In ***Massachusetts, House Bill 4568*** (signed in 2016) directed the commonwealth's ***Department of Energy Resources*** to determine whether a procurement goal for energy storage would be "prudent," and if so, to establish a target for 2020.[85,86]

Figure 11: Energy Storage Activity by State



Source: Compiled by ESN, 2017. See State Policy section, page 49.

- The ***Delaware Sustainable Energy Utility*** – a nonprofit created by the state in 2007 to further its sustainable energy goals – approved a plan in 2016 to offer solar and battery storage pilot projects to four emergency response facilities and school districts.[87,88]

- In Indiana, ***Indianapolis Power & Light Company (IPL)*** filed a complaint in 2016 (***FERC Docket EL17-8-000***) to challenge several aspects of a MISO tariff. FERC ruled in 2017 in favor of IPL's argument, providing further guidance to MISO to allow energy storage systems access to all markets in which they are technically capable of participating.[89] In addition, Indiana invested state and public funds into the ***Battery Innovation Center*** (launched in 2013), a collaborative research center in southern Indiana designed to manufacture, test, and validate battery prototypes to spur them toward commercialization.[90]

- In ***New Jersey***, the ***Board of Public Utilities*** created the ***Renewable Electric Storage Program***, which was granted a $3 million budget for fiscal year 2017. The program provides financial assistance for energy storage systems that are coupled with non-residential renewable energy projects behind the meter.[91]

SAFETY AND TECHNICAL STANDARDS

Energy storage technologies – and batteries in particular – may be subject to existing or new safety and fire codes. Some of these codes are developing in parallel to the increased deployment of batteries along various points of the grid and behind the meter. Further, inevitable safety incidents or storage-related fires resulting from the early, formative years of the industry will spur the continued evolution of such codes and standards over time.

Codes and standards signal maturity for a particular system or industry. They can also reduce costs, since companies do not have to reinvent operational and safety procedures with each new system. Additionally, standards can reduce the number of system failures or health and safety incidents, thereby increasing consumer and investor confidence. Alternatively, standards may also add to costs as manufacturers are subject to additional testing and validation requirements to achieve certain listings.

RELEVANT ORGANIZATIONS:

- ***Underwriters Laboratories (UL)*** develops codes and standards for buildings and equipment and offers certification services and technical assistance. UL provides specific codes and services for battery and energy storage technology in order to help its clients design safe systems and achieve compliance.[92,93] For example, UL recently released UL 9540 in November 2016 – its Standard for Energy Storage Systems and Equipment.[94]

- ***SAE International*** similarly develops standards for the mobility engineering industry. This includes a set of standards for batteries in electric vehicles.[95]

- ***The Institute of Electrical and Electronics Engineers (IEEE)*** has a Standards Association (IEEE-SA) that develops standards and recommended practices for electrical systems and electronics, including large stationary batteries.[96]

- The ***American National Standards Institute (ANSI)*** works to increase U.S. competitiveness, consumer health and safety, and environmental protection through the development of standards across all industries.

- ***The International Code Council (ICC)*** publishes and updates the ***International Fire Code (IFC)***, which sets minimum regulations for fire prevention and protection systems.[97] The IFC is expected to add requirements for energy storage systems in its 2018 edition of the code.[98]

- ***The National Fire Protection Association (NFPA)*** is an international nonprofit focused on reducing damage and injury from fire through its codes and standards, research, technical assistance, and advocacy. NFPA is currently developing a Standard for the Installation of Stationary Energy Storage Systems (NFPA 855).[99] NFPA also distributes information about best practices and industry workshops, such as the Workshop on Energy Storage Systems and the Built Environment.[100] In 2016, NFPA released the 2017 edition of the National Electric Code (NEC), in which a new article addresses the installation, disconnection, shutdown, and safety labeling of energy storage systems.[101]

ENERGY SYSTEMS NETWORK INSIGHTS

To provide a full picture of the energy storage industry and all the factors affecting its growth and performance in the future, ESN has outlined key questions facing the industry and has provided expertise and insight into these questions based on extensive review of the research material. This synopsis is intended to provide the readers with a summary of research findings and ESN's expert perspective in relation to each question.

1. Will improvements in energy storage continue to drive performance up and price/kWh down? At what point will it reach parity with existing technology options?

The research literature agrees that the price of energy storage will continue to fall fairly quickly over the next several years and decades. However, the studies disagree on the price at which energy storage will be cost competitive with other options, and when such cost parity will be reached. All the relevant reports reviewed are prefaced with some expression of great uncertainty in their forecasts. Moreover, these reports only partially or tangentially address the question of when energy storage might reach cost parity with competing conventional methods of achieving the same goals.

Energy storage takes many forms (e.g., batteries with different chemistries, flywheels, pumped hydro, etc.) and can serve many applications (e.g., voltage support, transmission deferral, black start, renewable firming, etc.). The economics of each system for each application are also very dependent on local conditions, including the structure of the electricity market, the utilities' rate structures and generation portfolios, and environmental and geographic factors. Different combinations of the above conditions, along with regulatory uncertainty and the lack of market experience for many storage technologies and applications, make energy storage pricing very challenging to accurately forecast.

In their efforts to estimate future prices of energy storage, most reports focus on very specific scenarios. For instance, a 2016 GTM Research report forecasts that 1-hour energy storage systems used for commercial demand charge management will be attractive investments (i.e., IRR over 5 percent) by 2021 in about one third of U.S. states under the base scenario, and nearly half of the states under a more optimistic scenario.[102] In the Australian market, a CSIRO report (2015) estimates the payback periods for new integrated solar PV and storage systems (IPSS) in NEM states as 4-5 years by 2035 under a standard tariff, and 7-11 years by 2035 under a time-of-use tariff.[103] As for direct pricing estimates, HSBC Global Research (2016) expects large-capacity Li-ion batteries (used in BEVs) to fall from about $300-400/kWh in 2016 to $100-150/kWh in 2020; other studies point to Tesla's stated goal of reducing Li-ion battery costs to $100/kWh by 2020, which its Gigafactory may be capable of achieving.[104,105,106] Other reports differ in how they talk about energy storage costs – for instance, by presenting recent trends, current prices, or forecasts of prices, penetration, or future market share.

The reports produce several insights related to future energy storage prices, however. CSIRO (2015) concludes that the economics of energy storage for consumer applications are significantly affected by the utilities' tariff structures.[107] The European Commission (2015) stresses that the financial viability of energy storage depends on regulatory initiatives to properly value storage's use in different markets and applications.[108] Greensmith Energy Management System (2016) notes that the electric vehicle market will primarily drive the cost curve of Li-ion batteries, the results of which utilities can take advantage.[109] Finally, Oppenheimer (2016) expects the energy storage market to reach an important inflection point by 2018, leading to significant growth – similar to the history of solar and wind deployment.[110] The authors also predict a boost in revenue from energy storage systems switching to serving multiple applications.

ESN INSIGHTS: BALANCE-OF-SYSTEM COSTS WILL DETERMINE THE PACE OF ENERGY STORAGE SYSTEM COST REDUCTION

It is our view that a reduction in the cost of stationary energy storage systems will depend less on a reduction in the price of battery cells and modules, but will be driven by balance-of-system (BOS) pricing. This view is supported by the fact that over the last 10 years, battery cell and module prices have dropped by nearly half from $600/kWh to $300/kWh; and yet, the price of grid-tied energy storage systems continue to hover between $1,200 - $2,000/kWh. Simply put, the industry has not yet matured to the point of pulling down the cost of the balance-of-system components (e.g., inverters, thermal management, high-voltage connections, packaging, etc.). While battery cell and module suppliers have moved to high-volume production with a mature supply chain of raw materials and subcomponents, the suppliers of power electronics and other BOS components have continued to employ a more "cottage industry" approach with low-volume, specialized production, often building systems based on orders with long lead times. Even well-established T&D companies like Eaton, Snyder Electric, Siemens, S&C, and others have not yet invested in the high-volume production capacity to dramatically reduce the price of inverters and other key BOS components.

It is our view that a reduction in the cost of stationary energy storage systems will depend less on a reduction in the price of battery cells and modules, but will be driven by balance-of-system (BOS) pricing.

This challenge is exacerbated by the fact that utilities are not accustomed to taking risks with alternative energy solutions and products. Until utility and other energy storage system customers send a strong demand signal with specific megawatt procurement expectations over a 5-10-year period, suppliers of BOS components will likely continue to take a "wait and see" approach. A positive industry insight is that the demand signal sent by the consumer electronics and later the automotive

ESN forecasts a stationary energy storage inflection point where many more "use cases" and applications will hit economic targets once stationary storage systems reach a (full system) price of $400/kWh to $500/kWh, which is projected to occur by 2025.

industry, which led to a dramatic drop in battery cell and module pricing, resulted in similar price drops in inverters and other BOS costs for automotive energy storage system "packs." Companies like Delphi, Bosch, Hitachi, and others have been able to substantially pull the cost out of inverters, DC-to-DC converters, and controllers and other BOS components for the automotive industry. Automotive supply companies did this by leading, embracing risk, using sound physics and economic assessments, R&D, and investing heavily in high-volume production capacity. These actions reduced packaging size and costs, and increased round-trip system efficiency based on clear performance requirements and somewhat clearer procurement commitments coming from automakers.

ESN believes that a vision of the future can be learned from the suppliers of automotive BOS components and that it is critical to leverage "lessons learned" and best practices to those supplying the grid energy storage system industry. In order to drive down the cost of energy storage systems, a concerted effort should be made to send a clear demand sign to the utility sector's BOS suppliers. Cross-industry partnerships need to be forged to draw from the learnings of automotive industry suppliers for creating the market adoption features of advanced energy storage systems.

Predicting the point at which stationary energy storage systems will reach price parity with other options such as generation, back-up power systems, and traditional T&D equipment upgrades is quite challenging and depends on several market and regulatory factors. However, ESN forecasts and analyses conclude that price parity for their specific "use cases" (including frequency regulation, demand charge management, and T&D upgrade deferral) can be reached at a price of approximately $900/kWh in many markets across the U.S. There are a few vendors offering stationary storage systems at the $900/kWh price point today, but ESN expects additional products to become available by the end of 2018.

Based on multiple discussions with utilities, backup power systems integrators, and other industry experts, ESN forecasts a stationary energy storage inflection point where many more "use cases" and applications will hit economic targets once stationary storage systems reach a (full system) price of $400/kWh to $500/kWh, which is projected to occur by 2025.

2. What market adjustments are required to allow energy storage systems – which can be a load and generation source – to contribute their full benefits to the grid?

Energy storage encompasses a range of technologies that are in many cases sufficiently developed to contribute benefits to, and compete with, more conventional systems on the grid. Yet unlike more traditional grid components, energy storage systems can act in two directions (i.e., as a sink or a source of energy) and serve a wide range of applications. As such, the rules for integrating storage systems and participating in electricity markets remain largely unclear and underdeveloped. Further, the lack of transparency in pricing of grid services leads to distortions that harm the financial viability of energy storage.[111]

Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) need to clarify how their current policies and rules for market participation apply to energy storage systems. From the perspective of a well-defined framework, ISO/RTOs and other stakeholders can then assess barriers to market participation and identify opportunities for energy storage to provide and be compensated for grid services. ISO/RTOs should then focus on updating existing or defining new rules to help integrate energy storage systems – especially those with the greatest near-term potential – and manage systems serving multiple applications.[112]

More generally, it is challenging to define a broad system of compensation covering every type and use for energy storage, which can be placed anywhere on the grid from generation to end-user. Different stakeholders are involved at different levels (e.g., IPPs, transmission system operators, distribution system operators, consumers), and some are regulated while others are not. Questions about who should own storage systems will also need to be answered. New business models may be needed to capitalize on the value that storage systems bring. For instance, in the near-term, storage provides more value in the provision of frequency and voltage regulation than energy. In some cases, the market challenge is simply integrating energy storage systems of different sizes and applications into different points onto the grid. Targeted upgrades to distribution and transmission systems to enable smart grid technologies can facilitate storage adoption.[113]

The lack of transparency in pricing of grid services leads to distortions that harm the financial viability of energy storage.

As noted by World Energy Resources, it is also important to change the discussion around the value energy storage brings to the grid.[114] As discussed in the ***Primer: Economics of Energy Storage*** chapter (see page 26), levelized cost of energy (LCOE) is a common metric to compare costs of different sources of power generation, but its more applicable analog – the levelized cost of storage (LCOS) – still falls short of accurately characterizing the value of storage.

The cost curve for energy storage is a very important component of its financial viability, but a representation of its revenue streams – derived from the value that storage brings to the grid – is just as critical.

An estimate of the LCOS of a particular storage technology is arbitrary since the value it provides depends on the application it serves. Further, the LCOS is incomplete as a cost measure since it does not capture the unique business models through which storage can generate revenue. The cost curve for energy storage is a very important component of its financial viability, but a representation of its revenue streams – derived from the value that storage brings to the grid – is just as critical. Since revenue streams depend so heavily on the context of the storage system (e.g., application, generation portfolio of the grid, market structure), one measure (such as LCOS) likely cannot exist to characterize storage in general. In comparing storage to other technologies, the focus should be placed on the specific value storage can bring in that particular situation.

ESN INSIGHTS: WHOLESALE MARKETS SHOULD RECOGNIZE AND COMPENSATE ENERGY STORAGE AS A MULTI-VALUE ASSET

Energy storage is fundamentally different than the purely generation-based resources to which it is often compared. In order for energy storage to fully participate in electricity markets, its value must be clearly specified in each application, and rules must be modified or created to explicitly value these applications. The pressure to develop these new markets will intensify with the increased penetration of intermittent energy sources (i.e., wind, solar) on the grid. As these markets are developed – and as smart grid technologies increase opportunities for storage and demand-side management (DSM) to participate – rules should be carefully crafted to allow full participation of energy storage in a manner that allows for the capture of multiple revenue streams tied to parallel value propositions. For example, from a technological standpoint, an energy storage system using Li-ion batteries with a high C-rating (e.g., lithium titanate) can simultaneously follow a frequency regulation signal while also discharging the balance of its energy into the grid. Under such a scenario, the energy storage system should be compensated in both the grid services market for frequency regulation and the energy market. However, current rules do not allow for such stacking of value streams in a way that is properly compensated.

To more fully understand how energy storage systems can serve as a multi-value asset to the grid, deeper dialogue and engagement is required among FERC, State PUCs, ISO/RTOs, utilities, and experts in battery technology to better understand the diversity of potential use cases associated with energy storage systems. Pilot projects that can technically validate the multiple value streams of energy storage should be pursued with close oversight from regulators and ISO/RTOs and shared across states and regions nationally. Once there is a deeper understanding of the technology, then ISO/RTOs will be more open to re-evaluating market rules and making adjustments that support further integration of energy storage.

3. How should energy storage projects be financed?

The "valley of death" between R&D and commercial deployment via debt financing is a major issue stalling growth in the energy storage industry. Many current projects are self-funded, indicating a lack of financing.[115] The Renewable Energy Association (REA) suggests that government financing and coordinated support among national storage initiatives would signal a commitment to the industry and draw more private investment.[116]

Government support will need to give way to standard private sector financing opportunities, however. Many storage technologies and applications are relatively new and unproven; not enough data exists to show investors that they will obtain a sufficient return from financing these projects.[117] When market rules are more clearly specified, and as underwriters increase their familiarity with energy storage technologies and how they fit into electricity markets, financing opportunities should increase sharply.[118]

A report from Sandia National Laboratories (2016) describes the U.S. DOE's strategy in two parts. First, DOE is to expand and coordinate on key efforts in which the agency already plays a role, including data collection and analysis, safety and standards, demonstration projects, and the provision of financing support. Second, DOE is to turn to private investors to (1) clarify the technology, business, and credit risks in the industry; (2) develop methodology to monetize these risks; and (3) assist lenders through insurance and contracts. DOE would accomplish this via the following:

- Performance ratings that are technology- and application-specific;
- Performance guarantees to operationalize ratings, reduce risk, and pave the way for insurance;
- Energy service performance contracts for behind-the-meter projects that allow customers to finance the project through a service rather than an ownership model.[119]

The future of battery storage financing is still unclear, but current and potential options include the following:[120]

- ***Operating Leases:*** Operating leases allow customers to use energy storage without having to furnish the large capital expenditure up front; these would mostly be used behind-the-meter for demand charge reduction.
- ***Master Limited Partnerships (MLPs):*** MLPs allow for tax-exempt financing through quarterly payments to investors; if the

> *The Renewable Energy Association (REA) suggests that government financing and coordinated support among national storage initiatives would signal a commitment to the industry and draw more private investment.*

Master Limited Partnerships Parity Act is passed, MLPs may be expanded to include energy storage systems.

- ***Real Estate Investment Trusts (REITs):*** It is too early to tell whether energy storage systems might qualify for a REIT, but their chances should improve if the systems are installed with or as part of a building.

- ***YieldCos:*** YieldCos are attractive to storage developers, but they often require highly stable revenue streams; developers may have more luck seeking YieldCos with storage as part of a larger renewable energy system.

- ***Bonds:*** Bonds are possible down the road, but the energy storage industry will first need to achieve a certain level of market maturity, operational history, and risk reduction.

ESN INSIGHTS: FINANCING ENERGY STORAGE WILL VARY WIDELY BY MARKET AND APPLICATION

The multi-value nature of energy storage makes it hard to categorize for purposes of financing. It is not similar to wind or solar which simply provide generation capacity on the grid. Of further complexity is the fact that an energy storage asset could be providing value in multiple markets over the course of the same day or week: for example, frequency regulation in the RTO market, peak shaving for a utility local distribution network, demand charge management for an apartment building developer, and resiliency/back-up power for tenants in the apartment. Traditional sources of financing for capital investments prefer predictability and simplicity, which can drive developers of energy storage projects toward a single application use case that can significantly undervalue the energy storage assets.

To reach the full potential of energy storage market integration, a range of existing financing options must be leveraged and some new approaches developed. Some of the existing financing options to consider include:

- Rate-Based Cost Recovery
- Power Purchase Agreements (PPA)
- Operating Leases
- Master Limited Partnerships
- YieldCos
- Real Estate Investment Trusts
- Performance-Based Energy Services Contracts
- Bank Financing or Bonds

Regardless of the method that is used, financing energy storage as a standalone asset today requires a "baseload" use case (e.g., frequency regulation, firming renewables, demand management, etc.) that is driving the business case. Any additional use cases, even if they can provide a revenue stream, are often viewed as a secondary upside for the project. Over time, as more use cases are validated with performance data, it will become easier to finance energy storage as a multi-value asset. In many cases, financing an energy storage system as a standalone asset will not be as attractive as including energy storage as a component of broader project financing. For example, a developer of a commercial building includes an energy storage system to reduce demand charges, to participate in a utility DR program, and to provide back-up power in tandem with an onsite diesel gen-set, and finances the asset as part of the overall building construction.

In the near term, the most direct method to get an energy storage project financed is to connect the project to a utility rate base. This may include a utility purchasing an energy storage system as an asset it will own in their local distribution network, or a utility providing a long term PPA- type guarantee to a developer who will own the asset but provide services to the utility. Another variation that is likely to work in the near term is an energy storage project that is tied in part to a utility rate base with some portion of the project financed based on expected wholesale market revenue. Over time as ISO/RTOs make adjustments to their market rules to better allow energy storage to participate in multiple markets in parallel, and more data on technology performance in multiple markets is validated, then financing energy storage projects as standalone assets outside of a utility rate base will be possible. This is most likely to happen in CAISO and PJM markets first based on their current openness to energy storage.

Finally, the behind-the-meter energy storage market, which includes smaller systems located in residential or commercial buildings, may offer another financing option that has taken off in the solar industry. Third-party solar financing companies (e.g., SolarCity, Vivint Solar, Sunrun, etc.) have already begun marketing their third-party financing model to energy storage systems. A third-party financer is better positioned to deal with the technical, regulatory, and tax challenges of integrating energy storage at a residential or commercial level. They are also able to raise more equity or risk capital in the market to draw down larger sums of project financing. In the near term, market penetration of this model is limited to states with highly variable energy rates or additional tax incentives. As saturation of residential and small commercial solar increases, state regulators could begin requiring storage in order to smooth renewables, which will further increase the value of storage.

In summary, there is no "one size fits all" solution to financing energy storage. Much like the multiple use cases that energy storage systems can support, multiple financing tools and approaches will be required. The most likely solution in the near term is financing tied to a utility rate base, which could become the norm for many energy storage applications, particularly those benefiting the local distribution system. Energy storage projects that are tied to performance of the wholesale market will remain challenging unless multiple market revenue streams can be accessed. And third-party financing of behind-the-meter storage is an attractive model to support broad adoption, but will depend heavily on time-of-use energy price variability and future regulations on rooftop solar.

Investors at large may keep a distance from the energy storage industry until they have a better grasp on the risks involved. The industry can support itself by self-funding more pilots to demonstrate revenue reliability and taking advantage of conventional financing by attaching storage to more familiar projects (e.g., solar). Developers should also establish and promote clear, standardized technology applications of energy storage products to build investor understanding of, and reduce perceived risks within, the industry.

4. What role will PUCs need to play in developing policies or approving projects?

PUCs can play a role in four key areas: planning, procurement, ratemaking, and interconnection. In terms of planning, PUCs should clarify needs in the distribution system (especially with greater penetration of distributed energy resources) and the specifications of resources that can meet these needs. This will involve greater discussion with the utilities under PUC supervision. As part of this process, PUCs should accept energy storage systems as potential options to defer or displace distribution system upgrades. Further upstream, PUCs should encourage ISO/RTOs to include storage technologies as market participants for both energy- and power-based applications, and call for flexibility in the market rules that allow for energy storage systems to participate in multiple markets simultaneously. Finally, since storage can play many different roles, PUCs should make decisions on integrated storage based on the context of benefits over averaged cost estimates of one application.[121,122,123,124,125]

PUCs' opportunities for procurement include direct mandates and altering rules around Resource Adequacy (RA). PUCs can require the utilities they regulate to procure a certain capacity of energy storage; for instance, the CPUC has a mandatory target of 1.3 GW by 2020 among California's three largest utilities.[126,127] RA ensures that utilities have the needed capacity and dispatchability to maintain safe and consistent service. PUCs have rules that determine which resources count toward RA. To remove barriers to storage participation, PUCs should adjust rules to permit energy storage systems to act as multi-valued assets as part of RA plans.[128,129]

There are several avenues for change at the rate-making level. First, PUCs should determine how to compensate behind-the-meter energy storage systems, particularly when net energy metering is at play. Next, PUCs can encourage the adoption of storage systems by changing the structure of their base rates to more accurately match the costs of meeting demand (e.g., by switching to time-of-use rates). PUCs can also look to ongoing cases in other areas (e.g., smart grid, load shifting, electric vehicle charging) to examine where storage can add value. Finally, PUCs should both develop a comprehensive and sophisticated methodology for valuing storage and require that storage be considered by utilities as an alternative to other proposed technologies or upgrades for both generation and T&D.[130,131,132,133,134]

PUCs should also improve interconnection processes. For instance, PUCs can clearly spell out the requirements for connecting energy storage projects to both transmission and distribution systems. They can also look for opportunities to simplify and streamline the processes for projects meeting predetermined criteria. Finally, PUCs can clarify the costs involved in interconnection to give project developers the information they need to make decisions.[135]

ESN INSIGHTS: TRANSMISSION & DISTRIBUTION USE CASES ARE THE FASTEST WAY TO SECURE PUCS' SUPPORT FOR ENERGY STORAGE

In general, PUCs have been slow to take directed actions that spur investment in energy storage technologies, with the significant exception of California, which adopted an ambitious energy storage mandate of 1.3 GW by 2020. Oregon followed that action with a more modest mandate for its two utilities to procure 5 MWh or 1 percent of peak capacity by 2020. The California PUC's action has created its own unique market and is by far the strongest demand signal for energy storage in the U.S. However, the unique energy market conditions and state policy history in California makes their action of a broad energy storage mandate an unlikely precedent to be followed in most states. Furthermore, with the change in federal policies moving away from the Clean Power Plan and pushing for increased domestic coal and gas production, it is even less likely now that individual states will pursue a mandate approach to support energy storage deployment.

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It is our view that the most likely action by PUCs to support deployment of energy storage is through the approval of cost recovery for utilities so they may include energy storage systems as part of their updating and further build-out of their T&D systems. The number of transmission-related projects in the U.S. doubled in both 2014 and 2015 compared to the number of projects added in 2013. Another $30 billion in T&D construction investment is slated for the 2016-2017 period. This dramatic increase in T&D spending is occurring throughout the country driven by aging infrastructure in need of modernization as well as a need to connect new generation assets (i.e., gas and renewables) and smart grid systems. Many PUCs have been granting significant rate increases to utilities specifically for grid modernization projects. Investments are also being made in expanded regional high-voltage transmission corridors.

Energy storage can offer a wide range of value propositions to the T&D system at both the local distribution and high-voltage transmission levels. Furthermore, the cost of energy storage is more easily justified in the context of specific T&D applications, like deferring the build-out of an expensive substation by managing peak load, improving power quality and reliability on an unstable line, or offering distributed demand side management. The benefits of such specific T&D use cases are clear and more easily quantifiable to PUCs than the more abstract benefits of energy storage as a way to increase renewables or reduce CO_2 emissions. For this reason, we expect a number of PUCs to begin granting cost recovery for energy storage as a T&D asset, both in terms of specific projects as well as broader use in utilities' T&D long-term grid modernization plans. Such action can create a robust and stable market for energy storage systems across the country. It is likely that energy storage systems as a T&D asset will favor systems in the 50 kWh - to 5 MWh scale vs. home energy storage systems (5-10 kWh) or large high-voltage grid storage systems (10 MW+). Furthermore, a growing T&D market for energy storage will offer the clear demand signal to suppliers needed to spur investments in high-volume production and to reduce the cost of balance-of-system components.

5. How can utility providers create new revenue streams and business models using energy storage systems?

Utilities face several challenges as they seek to operate the power grid safely, reliably, and at low cost. For instance, utilities rely on the most expensive sources of power to meet periods of peak capacity. Further, they must manage increased difficulties in maintaining power quality, resilience, and robust T&D networks as more renewable, intermittent, and distributed energy is deployed on the grid. To meet their goals, utilities can take advantage of the benefits that energy storage technologies have to offer, either directly through purchase and cost recovery, or indirectly through creating new revenue streams for third parties and end users to adopt storage.

Utilities can explicitly define goals and specify how storage can serve as competition to other means of achieving these goals. For example, to manage demand charges, utilities can switch to time-of-use electricity pricing; this alone incentivizes ratepayers to consider storage as a way to shift the times when they purchase power to avoid peak charges. Utilities can also open markets for reliability, in which storage can bid for providing voltage support and frequency regulation; they can also open markets for resiliency, in which the black start capability of a storage system can bring in revenue. Utilities can create other revenue streams by focusing on storage as an option for capacity and other ancillary service markets, and by creating markets for non-wire upgrades (e.g., T&D upgrade deferral). In explicitly defining these markets, utilities may find that storage holds advantages over more conventional options, such as by preventing the curtailment of renewable energy during peak production by storing the excess and discharging it later, thereby raising the technologies' revenue potential.[136,137,138,139,140]

There are two key aspects utilities must consider when working to create these value streams. First, they should account for the fact that a particular combination of an energy storage system's type, location on the grid, and context with regard to the power generation portfolio collectively determines its value.[141] Second, they should allow for the grouping or stacking of storage applications for a given system. An energy storage system deployed for a single application may

> *To meet their goals, utilities can take advantage of the benefits that energy storage technologies have to offer, either directly through purchase and cost recovery, or indirectly through creating new revenue streams for third parties and end users to adopt storage.*

only be active for a fraction of its useful life. During the time when it is otherwise idle, a system may be able to serve other functions without compromising its ability to carry out its primary use. Stacking applications allows for flexibility in use and an avenue for extra revenue that could tip the system into being economically favorable.[142,143,144]

Utilities should also look to the development of "smart markets" as a business model. In some ways, smart markets – which involve technologies and strategies allowing for end-user demand to respond to price changes – enable energy storage systems to provide their highest value. For instance, if a homeowner's storage system can respond to signals and prices from the grid or its operators, it can pull and dispense energy as needed to maximize grid reliability and efficiency. By definition, these markets would deploy distributed storage systems when it is most valuable for them to do so, thus bringing in the greatest achievable revenue streams.[145,146,147]

ESN INSIGHTS: STACKING APPLICATIONS AND MARKETS WILL GENERATE GREATEST VALUE AND REVENUE

Energy storage is a uniquely flexible grid technology in its ability to serve a variety of use cases. This grouping or stacking of applications allows for energy storage systems to provide multiple value streams to the grid that should result in revenue streams that reflect such diverse value. However, there are regulatory, market, and technological challenges that need to be overcome to achieve a multi-value/multi-revenue stream market environment for energy storage systems. Regulators including PUCs and ISO/RTOs have to adjust current or create new regulations and market rules to allow flexibility in how value or revenue is applied to energy storage assets. PUCs will need to offer utilities cost recovery that is tied to multiple value propositions that may include a combination of T&D, generation, and energy efficiency benefits. Similarly, ISO/RTOs will need to adjust market rules to ensure energy storage assets can participate in and move between energy, grid services, and capacity markets simultaneously. To support the development of a more flexible marketplace, improvements in energy storage system technology integration are needed. Better software, communications, and controls capabilities for energy storage systems that allow for improved remote operations, monitoring, and reporting are also needed. Standardized performance verification and validation that can ensure regulators, utilities, and end-use customers that the multi-value benefits of energy storage are in fact being realized is also an important step that has yet to be taken.

Utility companies are key to building this multi-value/multi-revenue stream market environment. They are on the front lines interacting with the key stakeholders including regulators, technology vendors, and customers. Furthermore, utilities have the specialized understanding and supporting data to validate the range of use cases that energy storage can support and how those use cases add value to the grid. From 2008 to 2015, utility companies were largely viewing energy storage as an emerging technology and used federal grants or special allocations by PUCs to conduct pilot projects demonstrating the benefits of energy storage. However, in 2017 and beyond we can expect a sea of change with utilities across the country seeking regulatory approvals with

Regulators including PUCs and ISO/RTOs have to adjust current or create new regulations and market rules to allow flexibility in how value or revenue is applied to energy storage assets.

PUCs and ISO/RTOs for broader deployment of energy storage. The pace at which this happens will vary by state, region, and utility, but it will be broad enough to establish a robust marketplace by 2025.

The emergence of a more flexible market for energy storage will not only benefit utility companies which can generate new revenue or save money by deploying energy storage; third-party developers, and even consumers, will be able to benefit as well. Third-party financing companies, which have taken off in the residential and commercial solar market, will be able to extend their model to energy storage systems by linking them to utility programs or even accessing wholesale markets. For example, CAISO has allowed for bundling of smaller-scale residential distributed energy storage systems to be bid into the wholesale market by third-party aggregators. Individual consumer or commercial customers may use energy storage systems to access utility DR programs or reduce their bills by optimizing time-of-use rates or avoiding peak demand charges.

APPENDIX

GLOSSARY OF TERMS

Active Thermal Management	Typically a liquid cooling system where a coolant, such as ethylene glycol, is circulated around and through heat generating areas to transfer heat from inside the battery system to outside and through a cooling loop, such as a radiator, often referred to as "convection."
American National Standards Institute (ANSI)	The American National Standards Institute (ANSI) works to increase U.S. competitiveness, consumer health and safety, and environmental protection through the development of standards across all industries.
Application Stacking	Application stacking refers to the compounding of multiple use cases for energy storage to amplify their benefits and minimize costs, making them more economical. For example, using the same energy storage system to provide grid services but also act as a power/energy generator at the same time (currently, the regulatory environment is not flexible enough to allow all of a battery system's potential applications to be used in the same installation).
Balance-of-System (BOS)	Balance-of-System (BOS) refers to all the hardware components in a power installation other than the module and power electronics.
Battery Management System (BMS)	The Battery Management System (BMS) is often referred to as the "brain" of the battery. The BMS is designed to provide cell (voltage) balance, control and consistent performance over the lifecycle of the battery. The BMS is a circuit board with an integrated microprocessor that monitors, records, and actually sends signals for charging and discharging individual lithium battery cells (or cell strings) to maintain voltage balance and system performance.
Charge Rate (C-rate)	Charge and discharge rates of a battery are commonly referred to as C-rates. Higher C-rates can increase internal thermodynamic reactions to the battery cell electrodes, seals, and packaging and shorten the cycle life of the cell. Typically, the energy storage application defines the requirements or drives the need for battery C-rates. The C-rate is calculated by dividing the power output by the capacity of the battery (kW/kWh), so a 10 kWh battery that was discharging at a rate of 10 kW would have a 1 C rating.

Cycle Life	Cycle life is how many single charge cycles the battery can conduct before reaching the determined "end of life" status.
Demand Charge	The price charged for electricity for a specific point in time as a result of when customers use the highest electrical power - peak energy demand, or times when more customers are requiring electricity, vs. off-peak energy demand, when fewer customers need electricity (i.e., overnight).
Department of Energy (DOE)	The U. S. Department of Energy (DOE) is a federal agency overseeing several energy, environmental, and nuclear programs.
Depth of Discharge (DOD)	See Cycle Life
Electric Bill Management	Reduces the energy drawn from the grid during periods of high demand charges. As electricity markets increasingly move towards a stratified rate structure, the ability to reduce demand from the grid during peak hours is going to become more profitable.
Electric Bill Management with Renewables	Permits the storage of energy during low rate periods to be used during high rate periods. Storage combined with renewables can work in conjunction with each other to improve the economics of both renewables and battery storage.
Electric Energy Time Shift	Permits greater flexibility when power is used. For instance, during a period of high supply and low demand, energy can be stored and then released when demand is high or supply is low. Electric energy time shift reduces peaks and troughs in the supply curve, promoting greater stability.
Electric Supply Capacity	Can decrease the need to buy generating capacity on the wholesale market or build new generation capacity. Uncertainty in market demand for electricity, for instance, in new housing developments where demand may grow quickly if the development is successful or fail to materialize if the development falls through, is a source of risk for electricity suppliers. Storage may be effective in providing flexibility to energy suppliers.

Electric Supply Reserve Capacity - Non-Spinning	Non-spinning reserves are brought online only after spinning reserves have been brought online. These units are not synchronized (frequency) with the grid and are offline until they are required. Non-spinning reserves are often the most expensive generators and are only called for when demand exceeds normal capacity and spinning reserve capacities. Storage can defer the high costs of construction and utilization of non-spinning reserves.
Electric Supply Reserved Capacity - Spinning	Spinning reserves are units that are synchronized with, but do not release energy to, the grid. Their intended purpose is to be able to respond rapidly to "contingency" or loss of a significant source of generation. Storage can reduce the need for these units by supplementing them or replacing them altogether. Storage can further reduce the economic loss associated with spinning units by storing the energy they create while offline.
Energy Density	The amount of energy able to be stored per unit of mass, measured in Watt-hours per kilogram units of measurement.
Federal Energy Regulatory Commission (FERC)	The Federal Energy Regulatory Commission (FERC) is an independent federal agency responsible for regulating the interstate transmission of natural gas, oil, and electricity. FERC also has regulatory power over the wholesale electricity market; it does not have jurisdiction at the retail level, however.
Flow Battery	A flow battery, or redox flow battery (after reduction–oxidation), is a type of rechargeable battery by two chemical liquid components contained within the system and separated by a membrane. Ion exchange (providing flow of electric current) occurs through the membrane while both liquids circulate in their own respective space. Cell voltage is chemically determined and ranges from 1.0 to 2.2 volts (per cell, and cells can be placed in infinite strings).
Frequency Regulation	The battery acts as both a source and sink for electricity from moment-to-moment to help maintain the frequency within the required range. Frequency regulation requires millisecond-to-second response to the grid. Batteries can be programmed to respond instantaneously to changes automatically.

Grid-Connected Commercial	Battery storage can maintain consistent power output in the event of a disruption of a commercial enterprise. The system may provide the needed power during the disruption or permit an orderly system shut down or smooth transition to a backup generation unit. The storage system can also smooth out any unwanted variability, such as spikes or drops in voltage or frequency.
Grid-Connected Residential	Battery storage can maintain consistent power output in the event of a disruption for residential customers. The system may provide the needed power during the disruption or permit an orderly system shut down or smooth transition to a backup generation unit. The storage system can also smooth out any unwanted variability, such as spikes or drops in voltage or frequency.
Independent System Operator (ISO) and Regional Transmission Organizations (RTO)	ISO/RTOs are nonprofits that coordinate the balancing of supply and demand of electricity in a region. They essentially control their regions' respective transmission systems, choosing which generators to run and when to run them (based on price). They also have control over which assets can participate, including the particular market and tariff structure. Utilities can voluntarily opt into or out of participation in an ISO/RTO; choosing to opt in gives up some autonomy as a utility, but it provides greater assurance that the reliability standards will be met.
Institute of Electrical and Electronics Engineers (IEEE)	The Institute of Electrical and Electronics Engineers (IEEE) has a Standards Association (IEEE-SA) that develops standards and recommended practices for electrical systems and electronics, including large stationary batteries.
International Code Council (ICC)	The International Code Council (ICC) publishes and updates the International Fire Code (IFC), which sets minimum regulations for fire prevention and protection systems. The IFC is expected to add requirements for energy storage systems in its 2018 edition of the code.
Inverters	An electronic device or circuitry that "inverts" direct current (DC) to alternating current (AC) or vice versa.

Lead Acid (PbA)	The most prolific battery type in battery history, referred to as lead acid (PbA), was invented in 1859 by French physicist Gaston Planté and is also the oldest type of rechargeable battery. Despite having a relatively poor energy density (50 watt-hours per kilogram, or 50 Wh/kg), PbA does have an ability to supply high surge currents and have a relatively large power-to-weight ratio. These features, along with their low cost, makes PbA the battery of choice for "starting, lighting, ignition" (SLI) batteries for automotive vehicles.
Levelized Cost of Electricity (sometimes referred to as "**Levelized Cost of Energy**")	Levelized Cost of Electricity (sometimes referred to as "Levelized Cost of Energy") is a metric developed as a means to compare the competitiveness of different power technologies. The LCOE gives a $/kWh value representing the cost of building, financing, fueling, operating, and maintaining a plant over its useful life, inclusive of certain operating assumptions (e.g., capacity factor). The advantages of LCOE are its familiarity in the power industry and its ability to offer a method of easily comparing technologies. However, LCOE depends heavily on the assumptions it embodies—particularly the cost of different fuels and estimates of government policies. The LCOE is also less useful at the local level, where other factors may be more important in making decisions regarding which technology is best to meet a given need.
Levelized Cost of Storage (LCOS)	Levelized Cost of Storage (LCOS) attempts to measure the average net revenue per unit of energy a storage system must bring in over its lifetime to recover its capital and O&M costs. However, even the LCOS is far from a perfect means of comparing storage and generation technologies. The measure is arbitrary in that its value depends on the actual application it serves and the context in which it's deployed. It is also incomplete, as it does not capture all of the avenues through which storage can generate revenue. Finally, the LCOS may not take other important features into account, including a storage technology's advantage in flexibility, dispatch time, or added value to the grid in terms of reliability. At this time, there is no single method of comparing storage with generation assets, making it difficult to know when a technology reaches cost parity.

Lithium Ion (Li-ion)	Lithium ion (Li-ion) is a somewhat generic term for a family of rechargeable, or secondary, battery types in which ions of lithium (the lightest metallic element in the periodic table) move from the negative electrode to the positive electrode during discharge and back when charging. The Li-ion battery is often referred to as the "rocking chair" battery as lithium ions "rock" back and forth from electrode to electrode upon discharge and charging of the cell. Li-ion batteries are currently one of the most popular types of rechargeable batteries for portable electronics, stationary power, and automotive applications with a high-energy density, high power density, negligible memory effect and low self-discharge.
Load Following	Load Following is also referred to as Tertiary Balancing. Output changes in response to demand changes in a specific area. These units usually are intended to respond within minutes or hours. A battery's ability to respond quickly to demand changes makes them well suited to supplement traditional systems for load following.
Master Limited Partnerships (MLPs)	Master Limited Partnerships (MLPs) allow for tax-exempt financing through quarterly payments to investors; if the Master Limited Partnerships Parity Act is passed, MLPs may be expanded to include energy storage systems.
Microgrid Capability	Storage system used to enhance the stability, reliability, and quality of a microgrid system and permits the integration of diverse energy sources. For instance, if a microgrid system is supplied by renewables then a voltage source is needed to synchronize the system. Automation, diesel generation, or some form of battery storage system usually performs this synchronization.
National Fire Proection Association (NFPA)	The National Fire Protection Association (NFPA) is an international nonprofit focused on reducing damage and injury due to fire through its codes and standards, research, technical assistance, and advocacy.
Net Energy Metering (NEM)	A unique billing arrangement in which electricity customers with solar photovoltaic systems can get credit for their excess generated electricity for the full retail price of the electricity and then draw on that credit when they have insufficient generation (i.e., winter and night time).

Nickel Metal Hydride (NiMH)	Invented in 1967 and first commercially available in 1989, Nickel Metal Hydride (NiMH) batteries have superior power and energy densities over PbA battery types. Toyota Motor Corporation was very successful in scaling NiMH batteries for its Prius program(s), and additional HEV platforms. With its moderate energy density, power density, and cycle life capabilities, the NiMH battery has been fundamentally replaced with lithium ion in most automotive applications.
North American Electric Reliability Corporation (NERC)	The North American Electric Reliability Corporation (NERC) is a nonprofit international organization that focuses on maintaining the reliability and security of the North American power grid. NERC accomplishes this by designing and enforcing reliability standards and monitoring the grid.
Onsite Power	The battery can provide power locally as needed. These systems can be used in conjunction with or replace conventional generators. For instance, institutions such as hospitals, server farms, and some manufacturing activities must have robust and uninterruptable energy supplies. Even in the event of a dedicated generator, backup power is usually installed as a fail-safe.
Onsite Renewable Generation Shifting	Allows end-use customers with onsite renewable energy sources to charge and store energy as it is produced so it can be used onsite as needed. Shifting also allows multiple sources of energy to be synchronized, increasing flexibility.
Operating Leases	Operating leases allow customers to use energy storage without having to furnish the large capital expenditure up front; these would mostly be used behind-the-meter for demand charge reduction.
Passive Thermal Management	Depending on the application, whether the energy storage system is moving or stationary, passive air channels can be designed into the enclosure allowing airflow, and even conduction of thermal conditions, to circulate past the individual battery cells for passive thermal management.
Performance-Based Energy Services Contracts	A Performance-based Energy Services Contract is a contract in which energy customers are provided with a series of energy-saving measures (e.g., energy efficiency technologies, renewable energy) that guarantee enough energy cost savings to pay for the project over the life of the contract.

Power Density	The amount of power available per unit of mass, measured in Watts per kilogram unit of measurement.
Public Utility Commission (PUC)	In regulated electricity markets, the Public Utility Commission (PUC) sets utility tariff structures to ensure that they (1) are able to recover their costs plus a reasonable return on investment; and (2) do not abuse their monopoly power and take advantage of ratepayers. PUCs also influence state electricity markets by setting rules and standards that utilities must follow.
Ragone Chart	A Ragone chart (pronounced "ruh-GO-nee") is a logarithmic chart used for performance comparison of various energy-storing devices. The values of specific energy (Wh/kg) are plotted versus specific power (W/kg). Both axes are logarithmic, which allows comparing performance of extremely high and extremely low power devices.
Ramping	Storage permits either ramping up or ramping down the loading level of generation unit in a manner that is consistent over time. Sudden changes in the ramping rate may significantly, negatively, impact the efficiency of an electric generating unit. A storage source may act as a shock absorber to facilitate systematic and therefore more efficient use of the generator.
Renewable Capacity Firming	Smoothes output from renewable sources to maintain consistent output over time. The inherent intermittency of renewables is often balanced with conventional generation that was not designed for this function. Batteries can reduce this demand and free up conventional sources for their intended purpose while lowering costs at the same time.
Renewables Energy Time Shift	Permits optimal utilization of renewable energy by allowing storage of that energy when it is being produced regardless of the current demand. This energy can then be used during periods of high demand or when renewables have reduced generating capacity.
Resiliency	Enhances the ability to supply demanded power in the event of disruption. Storage systems can permit an orderly shutdown of the system or may act as a backup to maintain function until power is restored.
SAE International	SAE International develops standards for the mobility engineering industry. This includes a set of standards for batteries in electric vehicles.

Sodium Sulfur	Invented by Ford Motor Company in the early 1960s, a sodium sulfur battery is referred to as a "molten-salt battery" constructed from liquid sodium (Na) and sulfur (S). It produces fairly high energy density (better than PbA efficiency in charge/discharge at 89–92 percent), good cycle life, and is fabricated from inexpensive materials. However, the operating temperature of Sodium Sulfur batteries is 300°-350°C and is highly corrosive in nature, which makes the battery more suitable for stationary energy storage applications.
Spinning Reserves	See Electric Supply Reserved Capacity - Spinning
Stationary Transmission/ Distribution Upgrade Deferral	Battery storage decreases or defers the need to replace or upgrade stationary transmission and distribution (T&D) systems. Underground circuits and ground faults are expensive to replace and storage can decrease the load requirements, which reduces the heat and associated degradation of the units and auxiliary equipment such as insulation.
Supercapacitors	See Ultracapacitors
Supervisory Control and Data Aquisition (SCADA)	A Supervisory Control and Data Acquisition (SCADA) coordinates the data from the battery management system, the power conversion systems (e.g., inverters, inverter controllers) and external requests (e.g., electrical grid).
Tertiary Balancing	See Load Following
Transmission Congestion Relief	Storage discharges during periods of peak demand to reduce transmission capacity requirements and congestion-related costs. Congestion may also negatively impact frequency and voltage stability. Storage units can offer increased stability by responding as a source or sink for energy as needed, reducing the expense associated with energy dumping.
Transmission Support	Used in conjunction with transmission to compensate for variability such as unstable voltage and resonance issues. Storage increases the load carrying capacity of the transmission system, which may benefit the system owner and the utility. Transmitting energy can be costly to utilities that need additional capacity but do not own the transmission system. They usually pay an access charge as well as other fees such as operation and maintenance costs to the system owner.

Transporting Services	Batteries may provide a link between the grid and electric vehicles. For instance, as the market for electric vehicles grows it will become increasing feasible to utilize large numbers of electric vehicles to provide frequency regulation and voltage support to the grid, known as vehicle-to-grid or V2G.
Ultracapacitors	Formerly referred to as an electric double-layer capacitor (EDLC), the ultracapacitor (or "supercapacitor") is a high-capacity electrochemical capacitor with a performance value much higher than standard capacitors which emulates the cyclical nature of rechargeable batteries. Ultracapacitors typically store 100 times more energy per unit (volume or mass) than electrolytic capacitors, and can accept and deliver charge much faster than batteries. Ultracapacitors can provide a revolutionary amount of charge and discharge cycles over rechargeable batteries. However, their energy densities are extremely small when compared to batteries, and can be more than 10 times larger than conventional batteries for a given capacity or energy density.
Underwriters Laboratories (UL)	Underwriters Laboratories (UL) develops codes and standards for buildings and equipment and offers certification services and technical assistance. UL provides specific codes and services for battery and energy storage technology in order to help its clients design safe systems and achieve compliance.
Voltage Support	Large power loads can move the voltage out of the specified range locally. Storage can dampen these effects with minimal draw of power from the battery.
Zinc-Air	Described as metal-air batteries powered by oxidizing zinc with oxygen from the air, these batteries have high energy densities and range from very small button cells for hearing aids to batteries for the electrical grid. Zinc-air batteries operate similarly to fuel cells where the zinc is the fuel and the reaction rate can be controlled by varying the airflow. Once the electrolyte paste oxidizes (zinc) it can be replaced with fresh paste. Zinc-air has been used as a non-rechargeable, primary battery but a recent company has converted it into a rechargeable secondary battery.

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NOTES

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We leverage our network of global thought leaders to develop integrated energy solutions that:

- Reduce costs, emissions and waste;
- Influence policy; and
- Advance technological innovation

…to increase quality of life for today and tomorrow.

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ESN is building an energy ecosystem that integrates all aspects of the energy landscape: energy generation, distribution, the built environment, and transportation.

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