RESEARCH REPORT

# North American Energy Storage Copper Content Analysis

Prepared for Copper Development Association

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**Alex Eller**
Senior Research Analyst

**Ian McClenny**
Research Analyst

**Dexter Gauntlett**
Principal Research Analyst

# Section 1
# EXECUTIVE SUMMARY

## 1.1 Introduction

This study has been commissioned by the Copper Development Association Inc. (CDA) to describe the market for stationary energy storage in North America and quantify the copper demand associated with this market. The CDA is the market development, engineering, and information services arm of the copper industry, chartered to enhance and expand markets for copper and its alloys in North America. This study will explore current trends and dynamics in the energy storage industry, along with an analysis of the use of copper in the market, specifically the report will cover:

- Energy Storage Market Overview
- Utility-Scale Energy Storage
- Distributed Energy Storage
- Energy Storage Technologies
- Market Trends and Dynamics
- Copper Demand Analysis & Methodology

Navigant Research publishes over 20 reports per year covering all aspects of the stationary energy storage industry worldwide. These reports include forecasts for market growth across all applicable technologies and segments of the market over the coming 10 years. Reports also cover emerging technologies, emerging uses of energy storage, policies, competitive landscapes, and overall market trends. To support this research, Navigant conducts ongoing secondary and primary research to gain insights on the market from technology vendors, project developers, regulators, and utilities. This study considers the three-main grid-tied energy storage market segments: utility-scale (in-front-of-the-meter), behind-the-meter commercial and industrial (C&I), and residential. Technologies covered in this report include both electrochemical and electromechanical storage systems.

Navigant's energy storage coverage and forecasts provide the foundation for the copper demand analysis included in this study. Estimates of copper demand in energy storage devices have been developed using a combination of secondary research (including previous studies on the topic) and primary research through interviews with industry players. These estimates are combined with Navigant's energy storage market forecasts to develop a 10-year forecast for copper demand in the North American market, segmented by technology and application.

## 1.2 Methodology

Navigant Research uses an applications-driven forecasting methodology to determine the deployments of energy storage in given markets based on the application or specific services those systems will provide. This methodology allows forecasts to be compiled for both the market penetration for each application considered within the energy storage market (i.e., the total addressable market) and what percentage will be delivered by energy storage. This is meant to reflect the competing technologies that will be addressing similar or identical markets to ESSs, such as demand response and natural gas peaker plants.

Forecasts for copper demand in the industry are based on the overall deployments of new energy storage projects. To develop estimates of the magnitude of copper demand associated with installed applications of energy storage, Navigant estimated representative configurations based on previous studies by KEMA, manufacturer interviews and industry experience.  Navigant also used copper intensity ranges from published research, interviews with storage developers and interviews with copper experts. Forecasts for copper intensity are included for individual utility-scale storage applications, as well as for commercial & industrial and residential projects.

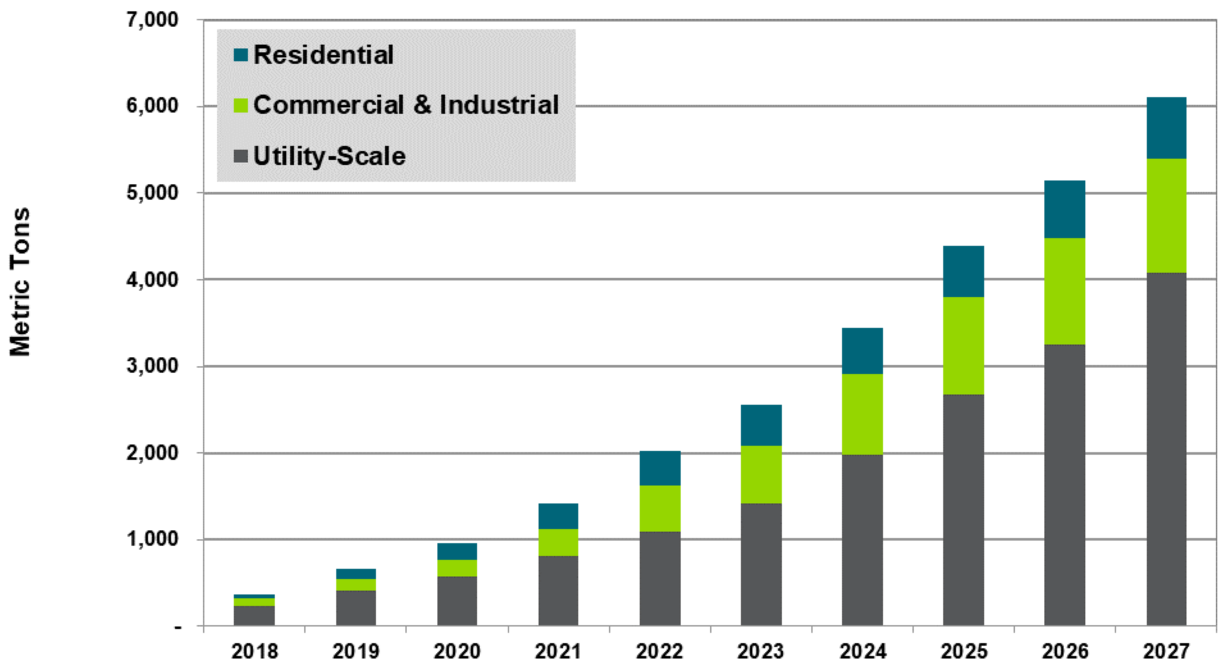
## 1.3 Summary of Results

Navigant Research predicts that the Asia Pacific region will be the leading region for energy storage, and consequently the most copper intensive region through 2027. While it is currently smaller than the North American market, some of the most developed electricity markets exist in the Asia Pacific region. Energy storage deployments to date, both for utility-scale and distributed applications, have been in select markets, namely Australia, Japan, South Korea, and China. The world's largest battery OEMs reside in this region, which further influences battery deployment.

Additionally, new markets are beginning to emerge in the Asia Pacific region with different dynamics and potential for storage both for utility-scale and distributed storage. For example, India aims to decrease its dependence on imported resources and become a global leader in the solar PV industry. India's rapid population growth, particularly in urban areas, is also driving the need for increased investment in T&D infrastructure across the country. Several other Asia Pacific countries have the potential to leapfrog more developed storage markets. Countries such as Vietnam and Indonesia are faced with rapidly growing electricity demand and the need for new infrastructure. These countries have also recently enacted aggressive new renewable energy development targets.

The North American market, primarily comprised the United States and Canada, is projected to be the second largest market through 2027. Federal support across both countries has created favorable landscapes for storage across the region. This consequently led new manufacturers and developers to enter the market with North America as their primary focus in the short term. Europe is also predicted to be a leading market because of its progressive policies supporting renewables and emissions reductions. Many European utilities have worked for years to integrate renewable generation in their energy mix which has called for increased energy storage deployments.

***Chart 5.1 Annual Copper Demand from Energy Storage Installations by Segment, North America: 2017-2026***




*(Source: Navigant Research)*

# Section 2
# INTRODUCTION

## 2.1 Market Overview

The grid-tied energy storage market is broadly categorized in three segments: utility-scale, behind-the-meter commercial and industrial (C&I), and behind-the-meter residential. These market segments each have unique dynamics in terms of the technologies being used, the services provided by energy storage, and the vendors and project developers. However, the market segments also have many similarities, with certain companies actively involved in multiple or all four of the segments. For this study the market is separated into two distinct segments, utility-scale and distributed. These two main market segments have similar technologies being used, similar companies involved, and similar project development processes. The following sections provide details on the uses of energy storage within each market segment, and the technologies most commonly deployed.

## 2.2 Utility-Scale Energy Storage

For the purposes of this report, "utility-scale" refers to systems that are located on the utility side of a customer's electricity meter and are either controlled by grid operators directly or are actively participating in energy and/or ancillary service markets. To capture the variety of services provided by energy storage systems (ESSs) on the grid and the differences in nomenclature from one market to another, services are grouped into application segments that serve similar functions and have similar technological requirements.

Table 2-1 outlines the five application segments for utility-scale energy storage forecast in this report. The following sections provide greater detail on what is included in these segments.

***Table 2-1. ESGAS Application Details***

| Application | Capacity Requirement | Classification | Discharge Cycles Per Year | Applicable Technologies |
|---|---|---|---|---|
| Generation Capacity | 2-6 hours | Bulk Storage | 200-600 | Advanced Batteries, CAES, Pumped Storage |
| T&D Asset Optimization | 2-4 hours | Bulk Storage | 201-600 | Advanced Batteries, CAES |
| Frequency Regulation | 1-15 mins | Ancillary/Power Services | 1,000-20,000 | Advanced Batteries, Flywheels, Ultracapacitors |
| Volt/VAR Support | 1-15 mins | Ancillary/Power Services | 1,000-20,000 | Li-ion, Advanced Lead-Acid, Flywheels, Ultracapacitors |
| Renewables Ramping/Smoothing | 1-15 mins | Ancillary/Power Services | 500-10,000 | Advanced Batteries, Flywheels, Ultracapacitors |

*(Source: Navigant Research)*

### 2.2.1 Generation Capacity

Energy storage to support generation capacity needs is considered a bulk storage application to meet both legal and technical requirements for energy reserve capacity on the grid. This application includes services typically provided by conventional thermal generators such as spinning reserves, non-spinning reserves, and load following. These services help operators meet hour-to-hour variations in electricity supply and demand, and may only be required a handful of times per year, which makes storage a good technological fit as the systems can perform other beneficial functions while still maintaining enough stored energy to meet capacity requirements.

Included in this application segment are ESSs that will be used to replace peaking generation plants, which are often only required during peak demand periods—generally less than a dozen days per year, depending on the region and grid conditions. Additionally, projects deployed to meet resource adequacy and local capacity requirements for serving peak demand in each area of the grid are also included.

The application segment also includes the shifting of renewable energy from when it is produced to times of high demand. This is an attractive application in areas with high levels of wind power curtailment at night and solar curtailment at mid-day, allowing energy to be shifted from off-peak to peak demand periods during the early evening. Utilities and grid operators utilize various business models to procure this service from energy storage, including power purchase agreements (PPAs), capacity contracts, and demand response (DR) programs. Longer duration technologies such as some flow batteries, certain lithium ion (Li-ion) chemistries, compressed air energy storage (CAES), and pumped hydro are the most applicable for this application.

### 2.2.2 T&D Asset Optimization

The T&D asset optimization application deals with ensuring that electricity lines, substations, and other equipment have enough bandwidth to handle peak demand. ESSs deployed to serve this application are often installed as an alternative to investing in new infrastructure such as feeder lines and substations. Many of the systems deployed for this application will be owned by utilities, as those companies are able to include storage in their rate base as a necessary investment to ensure grid reliability and asset optimization.

### 2.2.3 Frequency Regulation

Frequency regulation balances the fluctuations between electricity generation and electrical load, manages the variability in the grid's frequency, and maintains the frequency of the current on transmission lines within safe ranges by pulsing large bursts of power on and off the grid. To date, this has been one of the most popular applications for new ESSs, with significant storage capacity providing these services in the USA, the United Kingdom (UK), South Korea, and Germany. The benefit of energy storage over conventional generators to carry out this function is its ability to be fast-responding and accurate.

### 2.2.4 Volt/Var Support

This application manages reactive power to maintain the power system's voltage at acceptable ranges given the operating conditions it is likely to face. This is one of the shortest duration applications included in this report, often requiring much less than 5 minutes of discharge duration. ESSs will face competition for this service from new distributed power electronics capable of injecting reactive power to raise or lower voltages on distribution circuits.

### 2.2.5 Renewables Ramping/Smoothing

The renewables ramping/smoothing application includes services directly tied to renewable generation. The variable output from both wind and solar plants provides challenges to grid operators, as changing conditions can lead to dramatic swings in the amount of energy and voltage being fed onto the grid. Smoothing helps ensure stable output from a renewable plant if clouds pass overhead or wind speed changes; it protects grid infrastructure from damage due to fluctuations in voltage or energy output. Ramping refers to the controlled, measured reduction or increase in the output from a renewable plant while other generation sources can be brought on or offline to match demand.

## 2.3 Distributed Energy Storage

Distributed energy storage refers to systems installed behind-the-meter (BTM) for both C&I and residential customers, collectively referred to as distributed energy storage systems (DESSs). The overarching goal for all these customers is to reduce electricity costs by using storage to optimize consumption based on rate structures/pricing and the availability of on-site generation. However, DESSs are increasingly being used as a tool to manage grid stability and improve the efficiency of existing grid infrastructure by controlling electricity consumption and generation directly for customers. Table 2-2 below outlines the primary drivers, services, and benefits provided by DESSs.

***Table 2-2 Behind-the-Meter Energy Storage Drivers, Services, and Benefits***

| Market Drivers | Customer Services | Description/Benefit |
|---|---|---|
| Rising electricity rates, increasing electric vehicle (EV) use, increasing building energy management system (BEMS) use | Demand charge reduction | Respond automatically to building load spikes—reduced electricity expenses |
| | Time-of-use (TOU) energy bill management | Manage charging and discharging based on retail electricity rates—reduced electricity expenses |
| Increasing solar PV installations | Onsite generation self-consumption | Maximize consumption of onsite generation, primarily solar PV—reduced electricity expenses |
| Need for resiliency/power quality | Backup power/improved power quality | Protect sensitive equipment from power quality fluctuations/outages—ensure operability during grid outage |
| **Market Drivers** | **Grid/Utility Services** | **Description/Benefit** |
| Grid stability concerns and capacity needs | Ancillary services | Provide frequency regulation, voltage support, electric supply reserve capacity, etc.—improved efficiency of centralized generation, smoother integration of variable generation |

| | | |
|---|---|---|
| | Demand response (DR)/ Peak load reduction | Limit need to purchase wholesale power at peak prices/run expensive peaker plants |
| New utility infrastructure needs | Transmission and distribution investment deferral | Limit investments in new infrastructure through reduced peak demand |

*(Source: Navigant Research)*

C&I buildings represent the largest segment of the market for BTM energy storage. As with all segments of the ESS market, C&I storage requires a few favorable conditions to enable a solid business case for installed systems. The primary driver of C&I storage to date has been the increasing demand charges levied by electric utilities based on the maximum electricity demand of a customer within a specific period—typically over the short interval of 1 month. Such charges can account for a significant portion of a C&I customer's bill.

As the primary function of energy storage for C&I customers is energy cost management, utility rate structures are expected to determine the economics in a given market. The higher and more volatile the electricity prices and demand charges for C&I customers, the better the business case for commercial energy storage. Moreover, the growing popularity of time-of-use (TOU) rate structures for C&I customers can allow building owners to utilize an ESS to limit the amount of higher priced on-peak electricity that they purchase, and reduce overall expenses

The growing interest in C&I energy storage is also driven by the increasing deployments of building-level distributed energy systems including solar PV, EV charging, and building energy management systems (BEMSs) to improve energy efficiency. All three technologies are driving a greater awareness of electricity usage for building owners, which is a precursor to understanding the value provided by a C&I ESS. The installation of EV charging equipment often leads to significant increases in electricity expenses driven by peak demand charges, which an ESS can effectively reduce. This has resulted in several offerings from BTM storage providers specifically to help building owners reduce expenses associated with adding EV charging systems.

The residential energy storage industry is driven by many of the same factors as the C&I sector. Notably, the growing levels of solar PV deployment, evolving utility rate structures, and the desire for resilience/backup power along with decreasing systems costs are generating interest in home storage solutions. Residential ESSs are viewed by many as a highly disruptive technology that have the potential to drive a major restructuring of energy markets.

Critical factors enabling this market are the programs supporting residential solar PV that compensate system owners for excess generation. However, many utilities are opposed to these programs, including net metering and feed-in tariffs that are seen as unhealthy for the grid and power industry as whole. The elimination of these programs will prove to be a key driver in the market, as the vast majority of residential ESS customers are expected to have existing or new solar PV systems.

Collaborations between utilities and residential ESS providers have been one of the key factors in the industry's growth to date. Residential storage offers numerous benefits for utilities and grid operators, perhaps most notably the ability to reduce congestion on the network and limit the need for peak capacity resources. By distributing ESSs in homes throughout the grid, overall stability can be improved despite the growing number of distributed PV systems. Many utilities see RESSs as a new avenue to improve their services and relationships with customers at a time when new technologies are presenting a real risk of load defection.

## 2.4 Technologies

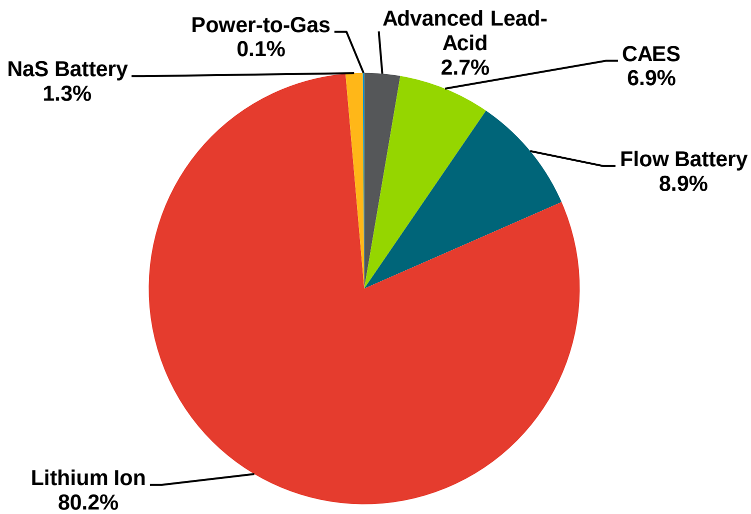
The energy storage market includes a diverse range of technologies for different applications including both electrochemical and electromechanical systems. The specific technologies utilized on the grid varies by market segment. The distributed storage market has limited technological diversity, with battery systems accounting for the clear majority of installed capacity. Navigant Research forecasts the deployment of three battery technologies in the distributed storage market segment: advanced lead-acid, flow batteries, and lithium ion batteries.

There is much more technological diversity in the utility-scale storage market. Navigant Research forecasts the deployment of 10 technologies for the utility-scale market:

- Advanced Lead-Acid
- CAES
- Flow Battery
- Flywheel
- Lithium Ion
- Molten Salt/Sodium Batteries
- Pumped Hydro
- Ultracapacitor
- Other Advanced Batteries

Many of the technologies listed above are designed specifically to provide either short-duration power services, or longer duration bulk energy storage services. As the market has matured, technologies capable of providing both power and bulk storage services are becoming the most attractive due to their flexibility to maximize revenue generation through multiple services. Specifically, li-ion batteries have emerged as by far the most popular technology in this market. Chart 2.1 below illustrates the market share among these technologies for new projects that were announced in both 2016 and 2017, excluding pumped hydro storage.

***Chart 2-1. Total Power Capacity of New Projects by Technology, Excluding Pumped Hydro Storage, Projects Announced in 2016 and 2017: World Markets***




*(Source: Navigant Research)*

As shown in the chart above, li-ion batteries are now by far the most popular technology for new projects being built worldwide. There are three primary reasons why the technology is now the default choice for most projects.

- **Performance and energy density:** Li-ion batteries are among the best storage technologies in terms of round-trip efficiency. The technology is also the most energy dense, resulting a smaller physical footprint for large-scale systems. This characteristic is an important consideration for projects in urban areas and on islands where real estate and land is at a premium.
- **Price:** Prices for large-format li-ion batteries have decreased dramatically in the past several years. Navigant Research estimates that installed system prices for li-ion bulk storage systems decreased 48% from 2014 to 2017. Falling costs are driven by the rapid expansion of li-ion manufacturing capacity to serve both the stationary and electric vehicle markets with similar products.
- **Bankability and warranties:** Perhaps the most important factor in the success of li-ion batteries is the reputation and financial strength of the leading vendors. While many other ESS technologies are provided by smaller start-up companies, li-ion batteries are produced by some of the world's largest multi-national electronics manufacturers. These companies have the financial resources to both lower prices and provide reliable long-term warranties. As the market is still in relatively early stages, and requires significant upfront investments and risks, customers typically chose hardware from vendors that can stand behind their products throughout the life of a warranty.

Although li-ion batteries have taken a dominate lead in the utility-scale energy storage market, there remains significant competition among technologies depending on applications. Certain technologies are more suited and cost-competitive for longer-duration bulk energy storage, such as pumped hydro, compressed air, and flow batteries. Other technologies are optimal for short-duration high power applications requiring many cycles, including flywheels and ultracapacitors. The following sections provide background on the primary stationary energy storage technologies and their position in the industry.

### 2.4.1 Flow Batteries

Flow batteries are generally defined as single-celled batteries that transform the electron flow from activated electrolyte into electric current. They achieve charge and discharge by pumping a liquid anolyte (negative electrolyte) and catholyte (positive electrolyte) across a membrane. The anolyte provides electrons during discharge, while the catholyte receives electrons. The spent electrolyte can then be recharged from external electricity and used again. Flow batteries primarily come in three chemistries: zinc bromine, vanadium redox and iron chromium. Each of these chemistries have a different redox (reduction and oxidation) couple, whereby oxidation takes place on the negative side of the battery while reduction takes place on the positive side of the battery.

Flow batteries are advantageous in that they can store energy for long periods of time by simply adding more tanks of liquid electrolyte. This makes them favorable for low-cost, long-duration applications that require shifting of multiple hours' worth of energy from one time of day to another. They are also generally safer than Li-ion batteries, as thermal management is not required. They also have little to no depletion of active materials over time, giving them greater lifecycle expectancies than other battery types. This benefit is magnified by the fact that many flow batteries use inexpensive and readily available materials, vanadium being the primary exception.

While there are many advantages to using flow batteries, a few characteristics may deem them unsuitable for certain applications. For example, increasing the area of the electrodes and replacing the ion exchange membrane is expensive, which makes it challenging for flow batteries to compete with Li-ion batteries for short-duration applications such as frequency regulation. Maintenance and reliability issues with pumps can also exist, leading to lost revenue and reduced reliability due to system downtimes. Low efficiencies, where present, can significantly affect revenue for applications like arbitrage that rely on high margins between the price of energy being discharged and the cost of energy for charging.

Leading flow battery vendors include: Sumitomo Electric, UniEnergy Technologies, Primus Power, Vionx Energy, redT, and Redflow.

### 2.4.2 Advanced Lead-Acid Batteries

The traditional lead-acid battery has been a mainstay of industrial society as a starter battery, an emergency bridging power, and a remote power conditioning asset. However, it is best used within a narrow depth of discharge (DoD) and for applications that require infrequent use, which makes it unsuitable for emerging grid applications that require frequent cycling. While advanced lead-acid batteries use the same lead dioxide cathode and sulfuric acid electrolyte, they distinguish themselves by utilizing carbon doping of the anode. This carbon doping turns the battery into an ultracapacitor, creating more efficient and longer lasting batteries with a greater DoD. It was expected that advanced lead-acid batteries would be roughly competitive with Li-ion batteries in terms of performance capabilities and price points. However, they have not had quite as much success in the market as they are less efficient and pose a higher risk for overheating during charging than Li-ion batteries. Most advanced lead-acid batteries are also unsuitable for fast charging applications, which is a primary reason for the success of Li-ion batteries in the battery electric vehicle market where the ability to charge quickly is vital

One of the leading contenders in this space is the UltraBattery, which is currently being marketed in Australia by Ecoult, in the rest of Asia Pacific by Furukawa, and in North America by East Penn Manufacturing. The technology is a hybrid long-life advanced lead-acid energy storage device. It combines the fast charging rates and longevity of an ultracapacitor technology with the energy storage potential of an advanced lead-acid battery technology in a hybrid device with a single common electrolyte. The system has proven in laboratory tests to have excellent cycle life (greater than 5,000 cycles at relatively high DoD) and power performance specifications. Thus, the UltraBattery is a contender in the frequency regulation market, as well as other power-intensive applications like extended reserve power and battery smoothing for solar PV.

#### 2.4.3 Lithium Ion

Li-ion batteries utilize the flow of lithium ions between the cathode and anode of the battery to charge and discharge. The cathode is typically made from one of three materials: a layered oxide; a polyanion such as lithium iron phosphate (LFP); or a spinel such as lithium manganese oxide (LMO). The anode is most often graphite and is separated from the cathode by a liquid or solid electrolyte. Li-ion batteries have excelled as the primary chemistry of choice in consumer electronics for the last decade, but are now finding their place on the grid. Newer cathode chemistries and new manufacturing processes are allowing for large-format battery cells designed for larger systems on the power grid. Popular subchemistries include LFP, LMO, lithium cobalt oxide (LCO), lithium nickel cobalt aluminum (NCA), lithium nickel manganese cobalt (NMC), and lithium titanate oxide (LTO).

In general, Li-ion batteries have excellent energy and power densities, round-trip efficiency, and lifecycle expectations, making them particularly well-suited for power-intensive grid applications. Li-ion batteries have emerged as the leading technology for utility-scale energy storage applications because of their flexibility and availability through mass production, causing them to be further down the experience curve than other new technologies. Several leading vendors including Tesla, Panasonic, LG Chem, Samsung

SDI, Kokam, Leclanche, and BYD have rapidly expanded manufacturing capabilities in recent years, contributing to the falling costs for the technology.

Li-ion batteries do have some shortcomings in that they require complex thermal management and safety systems since they contain a flammable electrolyte. For example, New York City's 2014 Fire Code limits Li-ion battery systems to 1000 pounds in weight, and requires each system to be kept in a non-combustible cabinet. There is also a limited supply of lithium globally, causing the energy industry to become skeptical of its ability to keep up with demand. This is a growing concern, especially given Tesla and other company's plans to mass produce greater quantities of Li-ion batteries.

Additionally, vendors are investing heavily in ongoing R&D for Li-ion cells, primarily involving the use of new materials aimed at boosting performance, reducing cost, and minimizing risks. An example of such R&D efforts is the development of new anodes like silicon, sulfur, titanium dioxide gel, and pure lithium. Other efforts have focused on improving the ionic conductivity of solid-state electrolytes, which can potentially prevent thermal runaway. These next-generation chemistries have the potential to reduce the material costs and safety concerns associated with Li-ion batteries, which will likely increase their market share in the battery storage industry.

#### 2.4.4 Compressed Air

CAES systems are similar to pumped hydro power plants in that they are particularly well-suited to longer duration, energy-intensive grid services such as spinning reserves. However, instead of pumping water from a lower to higher elevation point, a CAES system traditionally compresses ambient air, stores it underground under high pressure conditions, and heats and expands the pressurized air through a generator-tied turbine when it is time to produce electricity. CAES technology typically utilizes natural gas as fuel, although it uses about two-thirds less fuel than conventional gas turbines. To date, there are only two large-scale CAES plants in operation around the world—in Alabama in the United States and in Germany—highlighting the difficulty of cost-effectively siting and developing these complex systems.

CAES systems are advantageous for the purposes of large-scale storage deployments as they typically range from 50 to 300 MW and can be brought to full load in about 10 minutes. They provide flexible cycling options, operating on hourly, daily, or weekly frequency to provide grid balance. Thus, CAES enables utilities to optimize baseload units by minimizing load swings, which maximizes efficiency and extends unit life. Next-generation CAES systems that are more efficient and above ground are increasing the technology's value proposition as a utility-scale storage solution, as these are not limited by geological conditions. However, companies developing these next-generation technologies have struggled to bring the technology to commercial scale while maintaining competitive costs and efficiencies.

Hydrostor of Toronto is developing another approach in which it stores the compressed air in accumulators (balloons) 50 to 500 meters below the surface of a body of water. Hydrostor claims round-trip efficiencies of 70% without the need for additional fossil fuel heat. This performance profile makes modular CAES technologies such as Hydrostor's suitable for bulk storage applications but less desirable for power-driven applications. The company is currently developing several pilot and demonstration projects around the world.

#### 2.4.5 Flywheels

A flywheel is a mass rotating on an axis that stores energy mechanically in the form of kinetic energy. An electrical input accelerates the rotor with a built-in motor. When power is interrupted or needs to be supplied, inertia keeps the flywheel moving, and the built-in motor functions as a generator, converting kinetic energy into electricity.

Flywheels offer several important advantages. They are approximately 85% efficient and have extremely rapid response times. They can provide a significant power surge, despite duration traditionally being low (typically between a few seconds and a few minutes). For example, the world's largest flywheel has an effective capacity of 160 MW and a discharge time of around 30 seconds. Temporal Power, which announced its first grid-connected flywheel facility in Canada in mid-2014, claims that its 100 kW/50 kWh steel flywheel achieves duration of 30 minutes. The facility provides regulation services to Ontario's IESO. In late 2015, Amber Kinetics announced a four-hour flywheel system, which is a game changer in the flywheel technology's value proposition as a utility-scale storage solution, particularly for enabling higher levels of renewable energy penetration into the grid. The company signed a multiyear contract with PG&E for 20 MW of storage capacity in early 2016.

Flywheels also have nearly identical charge/discharge profiles, meaning they take the same time to fully charge as to fully discharge. They have a superior cycle life (up to the hundreds of thousands of cycles), and they typically require little maintenance over a 20-year period or longer. It comes as no surprise that the primary application for flywheels is to manage frequency regulation, which requires near instantaneous response time and a duration of discharge most often measured in seconds.

A downside to flywheels is the high upfront cost. While much attention has been paid to the cost of the composites (typically carbon fiber) that make up the actual flywheel, the real contributing factor is the cost of the structures around them. Flywheels reach high speeds, and in order to do so, they must be kept in a vacuum, which requires a fair amount of equipment. Moreover, to safely contain them, a large structure such as a subterranean concrete bunker must be built around them. These safety structures account for much more of the project cost than the materials in the spinning mass, and for flywheels to achieve a significant share of the ancillary services markets, the cost of these safety structures will need to be reduced.

### 2.4.6 Molten Salt/Sodium Batteries

Molten salt batteries include NaS and sodium-metal halide (NaMx) systems. Each of these utilizes a molten sodium anode and a solid beta-alumina electrolyte at high operating temperatures of about 300°C or more. However, both systems each use different electrolytes. Typical performance characteristics of NaS and NaMx batteries are relatively similar regarding high energy density, long cycle life, and moderate-to-high efficiency.

Molten salt batteries gained traction in the market early on but the battery storage market has shifted heavily toward Li-ion technologies. This is because its high price point—which is driven by expensive beta-alumina membranes—and performance characteristics make them better suited for long-duration applications. Li-ion batteries, on the other hand, are more cost-effective when it comes to short-duration applications such as frequency regulation and demand charge management.

However, the high temperature conditions under which the solid beta-alumina electrolyte operates are a safety concern. Beta-alumina is a highly corrosive compound that works well under these high temperature conditions and contributes to round-trip efficiency in the system. This high operating temperature has effects on internal resistance within the battery cells, generating heat during discharge, which can in turn additionally raise the temperature of the entire system. This makes molten salt batteries a fire hazard. For example, NaS batteries manufactured by NGK Insulators and installed at one of Mitsubishi Materials Corporation's plant in Tokyo, Japan caught fire in 2011 because of a breach in just one battery cell that leaked hot molten material. The incident was a cause of concern to other users of NGK's NaS batteries, who were asked to halt use of the batteries while the investigation was pending. NGK resumed production of their NaS batteries in 2012 once the investigation was complete, and introduced several new safety features including insulation and anti-fire boards between battery modules, as well as a fire detection monitoring system. The company offered to replace existing batteries free of charge.

### 2.4.7 Pumped Hydro Storage

Pumped storage has traditionally been the technology of choice for delivering ancillary services since it is the most mature and the largest capacity storage technology available, with over 161 GW of capacity in operation worldwide. Facilities pump water from one reservoir into another at a higher elevation, typically using lower priced off-peak or surplus renewable electricity. When energy is required, the water in the higher elevation reservoir is released and runs through hydraulic turbines that generate electricity. One key advantage of this system is gravitational energy stored in the upper reservoir can be stored for long periods of time with virtually no energy loss. There are two basic designs for the generation turbine: single speed pump turbine and variable speed pump turbine. Single speed pump turbines represent the standard turbine technology. Compared to variable speed pump turbines, equipment costs are approximately 30% lower, project schedules are shorter, and operations and maintenance (O&M) costs are lower. A variable speed pump turbine can be regulated to plus or minus 20% of capacity during a pumping cycle. In addition, it has superior load following response capabilities of as little as 6 seconds.

Pumped storage is an efficient way to augment baseload generation from conventional power plants. However, overall plant efficiency is limited by the efficiency of the pump and turbine unit used in the facilities. It also requires two proximal large reservoirs with sufficient water surface and pressure elevation between them. Suitable geologic formations are rare and tend to be found in remote off-grid locations, such as mountains, where construction is difficult, restricted, or cost-prohibitive. This results in complex and lengthy development processes for pumped storage projects as well as a high cost for labor. As many of the ideal sites have already been developed, it is expected that new pumped hydro projects will have difficulty competing with advancing battery technologies. Therefore, most of the new capacity for pumped hydro projects will likely come from retrofits and expansions of existing facilities.

### 2.4.8 Ultracapacitors

Unlike most battery storage systems, capacitors use static electricity instead of electrochemistry to store energy. Capacitors typically have two conducting metal plates with a dielectric, which is an insulated material that separates positive and negative charges that build up between these plates, thus storing energy. Ultracapacitors—also known as supercapacitors—differ from ordinary capacitors in that the plates have a bigger area. The distance between these plates is also smaller; instead of having a dielectric between them, they are soaked in an electrolyte and are separated by a thin insulator. Positive and negative charges build up on either side of this insulator, creating an electric double-layer. In this state, ultracapacitors resemble two regular capacitors side-by-side. Ultracapacitors generally fall into two categories. Small ultracapacitors, which are less than 100 farads, are used in computer memory systems, cameras, audio equipment, and uninterruptible power supplies. Large cylindrical ultracapacitors, which are greater than 500 farads, offer power delivery for automotive, wind power, and grid-scale applications. Large ultracapacitors have traditionally been a small portion of the ultracapacitor market. However, their market size and value have increased in recent years given higher demand for fast frequency response requirements, particularly in the United States and United Kingdom.

Maxwell Technologies has leveraged this market opportunity by supplying ultracapacitor ESSs for power grid applications globally. To date, it has deployed approximately 10 million ultracapacitors for wind pitch control, which utilize stored energy to orient the rotor blades in a wind turbine to maximize energy capture from wind. Today, Maxwell Technologies is looking to further capitalize the fast response capabilities of ultracapacitors through active and reactive voltage stabilization, frequency regulation, and renewables intermittency smoothing applications. Ultracapacitors can also meet islanding needs for microgrids by quickly switching between the grid and a battery or generator during its initial ramp up. Active standalone ultracapacitor projects currently deployed by Maxwell Technologies include a 3 MW system that mitigates voltage sag from crane operations by supplying 20 seconds of reserve power in the Yangshan Deep Water Port near Shanghai, China and an ultracapacitor storage system used to stabilize solar output from short and long-term intermittencies in California. As the storage needs of today's modern grid rapidly change, Maxwell Technologies expects to shift its focus toward hybridized systems, such as its ultracapacitor-battery storage system that captures excess braking energy from trains operated by Southeastern Pennsylvania Transportation Authority Light Rail System.

#### 2.4.9 Hybrid Energy Storage Systems

Navigant Research defines a hybrid ESS as a system that couples two or more energy storage technologies that possess complementary operating characteristics. Hybrid systems are advantageous in that they can provide multiple services to the grid, based on dynamic conditions and specific requirements. For example, U.S.-based Duke Energy is partnering with Aquion Energy, Maxwell Technologies, and Win Inertia to test a hybrid ultracapacitor-battery energy storage system that will smooth solar power output and store this energy for later use. Maxwell Technologies' ultracapacitors will be used to stabilize solar output fluctuations while Aquion Energy's Hybrid ion battery system will store the energy. Win Inertia is providing its trademark SHAD solution, which integrates advanced power electronics and control systems to manage these services. Hybridization significantly extends the lifetime of a system. It also improves the efficiency and lifetime cost of the combined technology and can increase the value proposition of technologies—particularly those that have a higher upfront cost.

# Section 3
# MARKET TRENDS AND DYNAMICS

## 3.1 Market Drivers & Barriers

North America is currently the largest global market for installed energy storage projects (excluding pumped hydro). The region has seen numerous supportive policies, projects, and business model innovations that support the growing market.

On the policy side, the most impactful actions have been taken at the state level to encourage energy storage development. Specifically, mandates and deployment targets directing local utilities to deploy energy storage have spurred market growth in leading states. The first and most impactful mandate came in California in 2013 with the passage of the AB 2514 law that required the state's large investor owned utilities to deploy a total of 1,325 MW of energy storage by 2020. The California Public Utilities Commission (CPUC) then issued a further order in 2017 requiring utilities to procure an additional 500 MW of behind-the-meter for distribution grid connected energy storage. These mandates have played a critical role in California being establishing as one of the leading energy storage markets worldwide.

Following in California's footsteps, similar but smaller mandates and procurement targets have been passed in other states around the country. In 2017 Massachusetts announced a rather modest target of 200 MWh's of installed storage capacity by 2020. Later in 2017 New York surpassed Massachusetts with a much more ambitious target of 1,500 MW of storage capacity by 2025 as part of the state's "comprehensive agenda to combat climate change". The exact structure and impact of these two targets have yet to be seen, with initial deployments of projects expected in 2018 or 2019.

The state of Oregon also instituted a small energy storage procurement mandate for its utilities in 2015, requiring just 5 MWh of capacity to be installed by 2020. However, in 2017 one of the state's largest utilities, Portland General Electric, announced a plan to deploy 39 MWs of energy storage over the coming years. Not only does this amount of storage exceed the utility's requirement, it represents the maximum capacity it is allowed through the 2015 law.

US states have also acted to accelerate the energy storage industry by requiring utilities to evaluate storage alongside other infrastructure investments they must make. In states around the country, including New Mexico, Colorado, Washington, Arizona, and Oregon, utilities are now required to compare the costs and benefits of storage against their traditional investments in power lines, substations, and new generation capacity. In Arizona, two of the state's largest utilities have now announced plans to deploy storage in their integrated resource planning (IRP) documents.

Actions are also being taken to support energy storage at the federal level in the US, albeit at a slower pace. The most notable development is the Federal Energy Regulatory Commission's (FERC) Order 841 which seeks to, "remove barriers to the participation of electric storage resources in the capacity, energy, and ancillary service markets." FERC has wide-ranging jurisdiction over the independent system operators (ISOs) that supply electricity to most customers in the US. Current regulations in many of these markets often do not consider the unique technical attributes of energy storage, and in some cases, forbid the technology from providing certain services. Despite the significant impact this ruling is likely to have on the market, few concrete results have yet come to light. The country's ISO's have until the end of 2018 to file their implementation plans, and a further year following that to implement new rules.

There is also a growing level interest from utilities in how storage can be used to improve grid asset utilization and reduce costs by deferring or avoiding the need to upgrade T&D infrastructure. As these systems would be owned by the utility, the cost of storage can be included in their rate base as a necessary investment to ensure grid reliability and asset optimization. To displace some of the technology risks with these projects, utilities often contract competitive warranties and terms, carefully select technology vendors, and work with experienced developers and integrators. Although building ESSs is not within the technical skillset of most utilities currently, it may be practical for larger investor-owned utilities with extensive ESS experience going forward in North America.

Perhaps more important than any policy developments, the increasing competition and pace of new project developments in the US is driving down costs and opening new market opportunities. Likely the most significant project developments in the past two years were the Aliso Canyon energy storage projects, deployed in response to the massive gas leak the threated power plant supplies in Southern California. Faced with the potential for rolling blackouts resulting from the shortage of natural gas supplies, the CPUC fast-tracked the approval of 104.5 MW of battery-based energy storage in May of 2016.

The storage industry capitalized on this opportunity by deploying what were some of the largest ESSs in the world at that time, at record speeds. By early 2017 a total of 8 projects representing the full 104.5 MW and 346.6 MWh had been installed, providing the region's grid operators with sufficient peak capacity resources to avoid outages or load shedding. These procurements dramatically highlighted the advantages energy storage possesses over other resources in terms of speed of deployment and operational flexibility, along with the overall maturity of the industry and technology.

The growth and maturation of the energy storage industry that has been achieved over the past two years has been driven largely by the rapidly decreasing prices for battery technologies. This trend has allowed developers to offer consistently lower prices for new projects, particularly for systems combined with large-scale solar PV plants. Tesla make headlines in late 2016 when it signed a PPA with the Kauai Island Utility Cooperative in

Hawaii to sell energy from a dispatchable solar + storage plant at just 13.9 cents per kWh. Several months later that project was outdone by AES Distributed Energy announcing an even larger solar + storage plant that would sell energy on Kauai for just 11 cents per kWh. These PPA's were competitively priced given the high cost of electricity on the Hawaiian Islands, however they were above the rates paid by most customers in most of the US.

Another major price break through came in May of 2017 when Tucson Electric Power in Arizona announced it has signed a 20-year PPA with developer NextEra Energy for the output of a 100 MW solar plant with 30 MW / 120 MWh of energy storage for just 4.5 cents per kWh. This project remained as the lowest cost, publicly announced solar + storage project in the world for nearly a year. However, in January 2018 Xcel Energy announced it has received bids at record low prices for renewable generation and energy storage projects. Xcel listed a median bid price for solar + storage projects of just 3.6 cents per kWh. With combined solar + storage costs now well below the national average electricity rates, the industry is poised to see major growth over the coming years nationwide.

Though utilities in North America have largely benefitted from the growing market and increasing popularity of ESSs, there still exist several barriers specific to the region. In general, North American utilities are still figuring out the best ways to integrate ESSs into their networks.

Table 2.2 outlines key barriers to the North American energy storage industry.

***Table 3.1 Key Market Barriers: North America***

| Barrier | Description |
|---|---|
| Lack of Adequate Compensation in Submarkets | A consistent pricing or market plan for providing grid storage must be developed, the uncertainty surrounding use case economics inhibits investment<br>Driven in part by the lack of understanding and acceptance of storage from public utility commissions |
| Low Natural Gas Prices | Energy storage competes directly with natural gas plants to provide several grid services<br>Low fuel prices have resulted in new gas plants being built |
| Cost-Competitive Systems | Despite significant decreases, the total cost of storage systems, including all the subsystem components, installation, and integration remains a barrier |
| Industry Acceptance | There still exists some uncertainty about how storage technology will be used in practice and how new storage technologies will perform over time |

*(Source: Navigant Research)*

The North American ESS market continues to grow increasingly competitive. Major solicitations from government, utilities, and private sector companies are well covered and receive significant interest. As this market continues to mature, technology vendors and project developers are working to establish closer relationships with utilities themselves, rather than relying on competitive procurements and mandates. This, in turn, could result in a growing number of new storage assets being utility-owned or contracted to provide services directly to utilities rather than relying on merchant market opportunities.

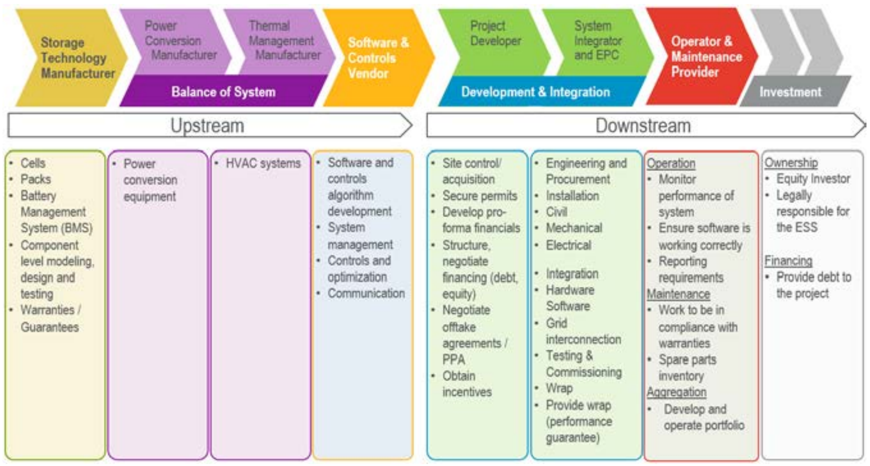
In the distributed energy storage market, North America has been a leading market over the past 2 years, driven by several favorable policies and market conditions. In particular, the C&I energy storage market in the United States is currently the largest and most advanced in the world. However, within the country, the market remains highly concentrated in select states and regions, primarily in California. In California, high electricity rates, TOU- and demand-based charges, and the favorable economics of rooftop solar PV combine with state subsidies through the Self-Generation Incentive Program (SGIP) to build a solid business case for C&I storage. While some of these enabling factors are present in other parts of the region, none have yet to see the level of growth experienced in California.

Another key factor in the early success of the market in California and throughout the region is the growing number of vendors exploring innovative business models to quickly reduce system costs, maximize value, reduce risk for host customers, and enable utility procurements of the assets. Many of these vendors are also pioneering virtual power plant (VPP) aggregation models in partnership with utilities to provide grid services and improve the overall economics of C&I storage. Aggregation-focused business models are designed to either provide services directly to utilities or participate in competitive markets for both energy capacity and ancillary services. These innovations are helping the DESS industry spread to new markets throughout the United States, including Hawaii, New York, Massachusetts, and Arizona.

## 3.2 Market Landscape

Overall the value chain of companies and components involved in a storage project are grouped into upstream and downstream segments. In general, the upstream segment of the value chain involves hardware and storage technology products, while the downstream segment is based around services. For each market segment, the dynamics between who provides which component and service vary considerably. For example, in the residential market, many project developers source hardware components themselves, design and manufacture integrated ESS products, provide software and controls platforms, acquire customers, and integrate systems. In this way, many companies focus their efforts on a single segment of the market to establish offerings targeted specially for certain customers. Other companies have taken an opposite approach by standardizing their products and targeting all four segments of the market, Tesla is a leading example of this model with products and services for each segment. Figure 2-1 below illustrates the standard energy storage value chain.

***Figure 3-1. Utility-Scale Energy Storage Value Chain, Roles and Responsibilities***




*(Source: Navigant Research)*

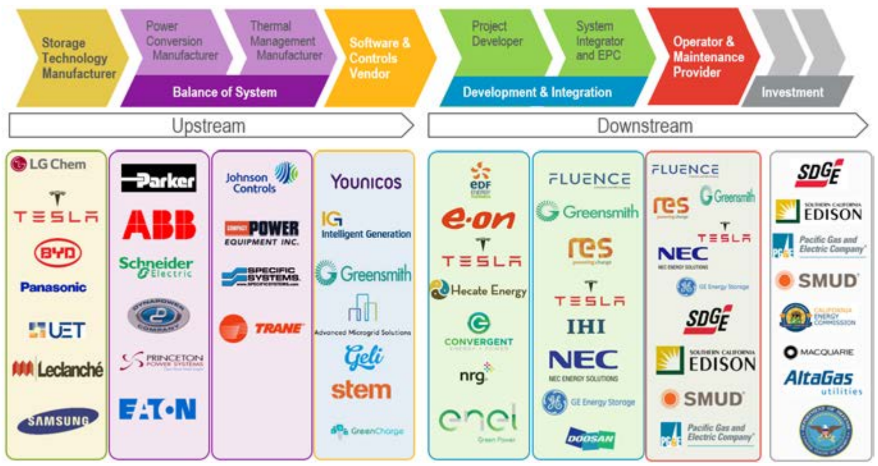
An important factor in the development of the storage market to date has been the increasing manufacturing scale and standardization of hardware components, specifically lithium ion batteries. These products are becoming commoditized as some of the world's largest technology manufacturers such as Samsung and LG have rapidly expanded their production capabilities. This trend has put a greater emphasis on more advanced storage system software, and reducing the costs for downstream project services.

As the energy storage industry continues to develop, the role of the system integrator is becoming increasingly important. Integrators are responsible for maximizing the value of a system by enabling all available revenue streams to be captured, ensuring constant availability, and maximizing system life. This balancing act requires substantial expertise, as the overall ROI of a project relies heavily on the systems integrator. ESSs will increasingly be asked to provide the flexibility to serve multiple different applications ranging from short-duration and high-power ancillary services to long-duration time shifting of energy. Energy storage systems integrators are responsible for managing this complexity by designing and optimizing systems that can provide the maximum value to both the grid and the system owners.

An emerging trend in the storage market is the growing diversity of the backgrounds of leading players. Companies now active in the market have backgrounds in renewable project development, utility ownership, electrical grid equipment and services, battery manufacturing, civil and electrical engineering services, and developing innovative energy management systems (EMSs). This diversity is driving competition in the industry; companies emerging as leaders have leveraged their backgrounds to provide a range of flexible solutions that include full turnkey project development. The greater diversity of companies in the market has also resulted in a growing number of very large multinational corporations. The presence of these large companies with global footprints and significant financial resources is helping to drive maturity in the market by bringing down prices and increasing the reputability of storage technologies.

Across the energy storage value chain select leading players have emerged as the most successful to date. This mix of companies includes both major multinational firms including technology manufacturers and utility holding companies, alongside start-ups and companies focusing solely on energy storage. Figure 3-2 illustrates some of the leading players in the utility-sale storage market in the USA.

***Figure 3-2. Utility-Scale Energy Storage Value Chain, Leading Players***




*(Source: Navigant Research)*

## 3.3 Energy Storage System Pricing

Falling costs for Li-ion battery systems have been a driving force in the growth of the stationary energy storage industry over the past 2 years. The decreases in prices around the world exceeded many predictions made several years prior as a result of the rapid increase in manufacturing capacity, and intense competition resulting in low margins for technology providers. Prices for other emerging technologies such as flow batteries have also fallen significantly, with further reductions expected over the coming years. As the industry continues to mature, much of the focus will shift from decreasing hardware costs to reducing the soft costs of a project including system integration and installation, along with balance of system and auxiliary hardware.

Over the coming decade it is projected that ESS prices will reach an equilibrium point as supply meets and demand and prices have decreased sufficient to enable the market to expand by serving new applications and customers. In the near-term continued reductions in hardware (battery and inverter) costs are expected to continue as manufacturing volumes increase and products are standardized and commoditized. There is also expected to be decreases in balance of system and integration costs as the industry gains experience, decreasing necessary customization, along with installation times and costs.

However, towards the later part of a 10-year pricing forecast, it is expected that there will be a diminishing rate of decrease in system costs as economies of scale are reached and there is sufficient demand to stabilize prices.

# Section 4
# METHODOLOGY

## 4.1 Navigant Research Forecast Methodology

Navigant Research uses an applications-driven forecasting methodology to determine the deployments of energy storage in given markets based on the application or specific services those systems will provide. This methodology allows forecasts to be compiled for both the market penetration for each application considered within the energy storage market (i.e., the total addressable market) and what percentage will be delivered by energy storage. This is meant to reflect the competing technologies that will be addressing similar or identical markets to ESSs, such as demand response and natural gas peaker plants. For each individual application included in these forecasts, Navigant Research has determined appropriate market penetration rates for each country which are based on several factors. The initial percentages assigned to each application within each individual country are intended to reflect regulations and market conditions based on inputs:

- Grid requirements for spinning/non-spinning reserve
- Renewable deployment forecasts
- Rates of renewable energy curtailment
- Grid stability (System Average Interruption Frequency Index [SAIFI])
- GDP
- Population growth
- Wholesale electricity prices
- Electrical load/demand growth

Once the total addressable market for each application and country are calculated, the forecasts for energy storage deployments are then determined. The percentage of ESS penetration reflects the current maturity of the energy storage market in each country, for a given application, and is based largely on the existing and announced ESS projects and the number of vendors active in the market. Currently, many countries have ESS penetration rates near 0% given the lack project of activity to date.

Growth rates are then applied to both the market penetration rate and the ESS penetration rate over the forecast period and correspond to an accurate characterization of the market over the forecast period. For example, in most cases, frequency regulation will grow quickly in the next several years in certain countries and will then plateau when the market is saturated, which is the natural course for this type of application. This does not affect the initial market volume—only the growth rate over time. There are considerable differences in the growth rates assigned to the market and energy storage penetration rates for each application. The market rates are often flat or only increase slightly as the need for a single grid service in a country is not likely to grow significantly. On the other hand, ESS penetration rates typically ramp up very quickly, with some markets expected to see exponential growth rates for the market share of energy storage compared to competing technologies.

Navigant Research then determines the appropriate baseline figures that will represent the capacity installed given the market penetration figures. These baseline figures include the annual generating capacity additions in a country, levels of T&D infrastructure investments, and forecasts for wind and solar deployments. Splits for each application and country are then determined based on which technologies will be strongest within each market due to factors such as existing manufacturing or intellectual property capabilities, performance and operating characteristics, local industrial policy, and existing and planned installations.

To calculate energy capacity (MWh) for each segment of the market, Navigant Research assigns a discharge duration for each technology and for each application within regions. The duration assumptions can vary within a given technology for different applications. For example, the duration assumptions for Li-ion systems range from 0.5 hours to 4 hours depending on the application. In contrast, pumped storage systems always have an assumed duration of 10 hours. This approach results in more granular forecasts for energy capacity specific to each technology and application.

Finally, revenue for project deployments is calculated based on average CAPEX assumptions for each technology and application. These assumptions are based on costs for current projects and interviews with industry stakeholders on the trajectory of system costs over the coming decade.

## 4.2 Copper Intensity

With many storage applications just now entering the commercial operation phase, energy storage installations have yet to conform to standard configurations. Though energy storage installations come in a wide array of sizes and configurations, and best practices have now evolved with regard to defining storage configuration, common pieces of equipment will likely be needed to interconnect energy storage to the electric grid. Such equipment includes:

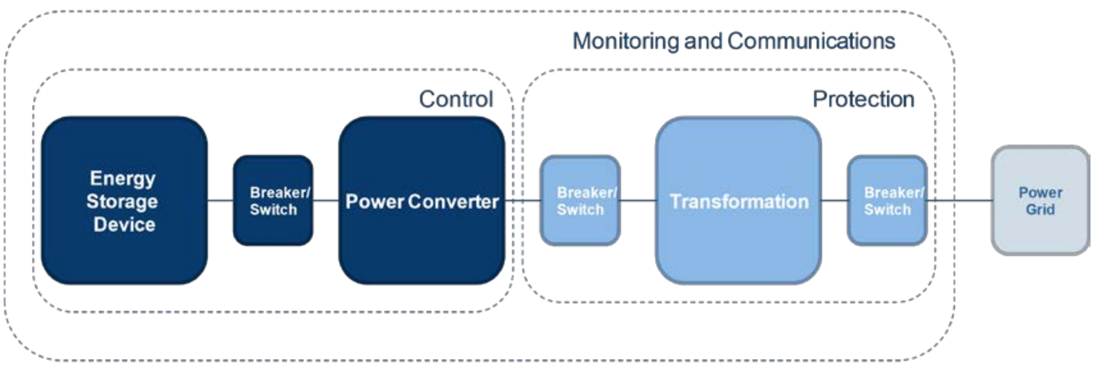
- Transformers
- Interrupting devices (breakers and switches)
- Protection and communication systems
- Monitoring and control systems
- Inter- and intra-system wiring

To develop estimates of the magnitude of copper demand associated with installed applications of energy storage, Navigant estimated representative configurations based on previous studies by KEMA, manufacturer interviews and industry experience. Navigant also used copper intensity ranges from published research, interviews with storage developers and interviews with copper experts.

The ranges address two sources of uncertainty:

- Configurations
    - o A variety of potential applications, from low-voltage to high-voltage installations, means that there can be a variety of electrical equipment associated with storage installations. Furthermore, best practices are yet to develop.
- Electrical equipment copper intensity
    - o Electrical equipment offers a range of copper intensities, depending on sizes, but also depending on market offerings. Based off a previous study by KEMA, Navigant used reasonable ranges for the devices to note impacts on total tonnage.

***Figure 4-1. Storage Installation Methodology and Copper Content***




| | | | | | |
|---|---|---|---|---|---|
| Copper content varies by storage technology. Large generators used for pumped storage or CAES and internal connections for battery technologies largest copper contributors. | Low voltage interrupting devices typically have very small amounts of copper Some installations may have a large enough quantities to contribute significant copper. | Copper content determined by inverter size and quantity. Applications such as Transmission and Ancillary services require larger inverters for larger systems. | Distribution level switchgear assemblies utilize copper for internal bus bar connections. Lower voltage equipment also typically uses more copper. | Transformations to low or mid-level voltages (collector systems) and dist or trans (interconnection to grid) contribute significant amounts of copper. Cu content depends on voltage level, size and quantity of transformers. | High voltage circuit breaker copper use primarily for breaker contacts. |
| Monitoring and Communications utilize small copper conductors. Trends moving to wireless and fiber optic communication. Protection devices typically utilize copper alloys for contacts, minimal copper usage. Control utilize smaller copper conductors. Largest Cu contributor – Instrument transformers and sensors. Lower voltage sensors use less copper. | | | | | |

*(Source: KEMA and Copper Development Association)*

*Table 4-1. Copper Usage by Energy Storage Market Segment, World Markets*

| Market Segment | Copper Content Assumption (tons/MW) | Notes |
|---|---|---|
| Utility-Scale | 0.01-3.0 | Depends on the installation configuration, type of electrical equipment, and storage type |
| Distributed | 0.01-0.25 | Other distributed storage could offer high copper intensity, but majority of these installations (e.g., thermal energy storage) offer the lowest copper intensity |

*(Source: Navigant Research)*

*Table 4-2. Copper Usage by Energy Storage Technology, World Markets*

| Technology | Copper Content Assumption (tons/MW) | Notes |
|---|---|---|
| Advanced Lead-Acid | 0.01 | Limited Use in Battery Pack |
| CAES | 0.18-0.26 | Generator and Compressor Motor |
| Flow Battery | 0.27 | Battery Pack |
| Flywheel | 0.23 | Module Only |
| Lithium Ion | 0.22 | Battery Pack |
| Sodium Batteries | 0.25 | Battery Pack |
| Pumped Hydro | 0.11-0.16 | Generator Only |
| Ultracapacitors | <0.01 | Little-to-no Use of Copper |
| Other Advanced Batteries | | Varies by Battery Type |

*(Source: Navigant Research)*

# Section 5
# ENERGY STORAGE MARKET PENETRATION

## 5.1 Copper Demand Forecasts by Technology

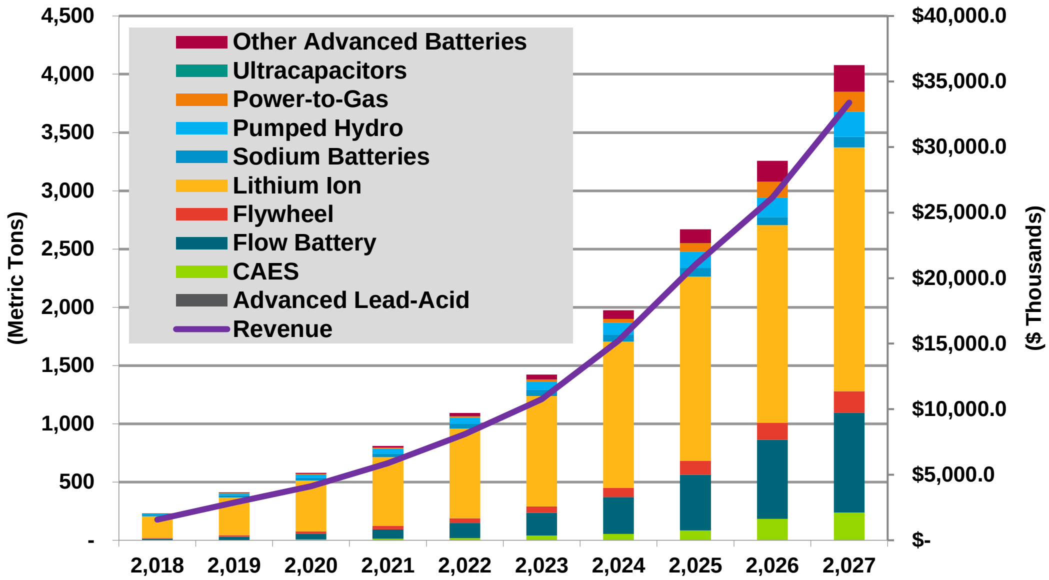
Navigant Research analyzes 10 key technology segments within the utility-scale energy storage market and four technology options within the distributed energy storage market. Each technology has been commercially deployed and is validated by the Navigant Research's proprietary Energy Storage Project Tracker. Technology forecasts are based upon existing installations as well as new project announcements, government mandates, technology roadmaps, among other market factors. Copper revenue forecasts were based on current prices for copper (pricing listed by the London Metal Exchange as of April 2018). Navigant Research did not attempt to project future commodity prices.

### 5.1.1 Utility-Scale Energy Storage

Utility-scale energy storage is expected to be the largest market segment for copper in this study, going from 229.6 metric tons in 2018 to 4,077.5 metric tons in 2027. Copper for lithium-ion batteries is expected to be the majority of this market, representing a cumulative 59.9% of new advanced energy storage copper additions throughout the forecast period. Total copper revenue is expected to go from $1.6 million in 2018 to $33.4 million in 2027, representing a compound annual growth rate (CAGR) of 40.4%.

Flow batteries are also expected to be a prominent energy storage technology for copper usage, going from 13.1 metric tons in 2018 to 857.1 metric tons in 2027, representing a CAGR of 59.1%. In total, flow batteries are expected to be a cumulative 17.1% of the entire utility-scale market through the forecast period.

***Chart 5-1. Copper Intensity by Technology: Utility-Scale Energy Storage, World Markets: 2018-2027***



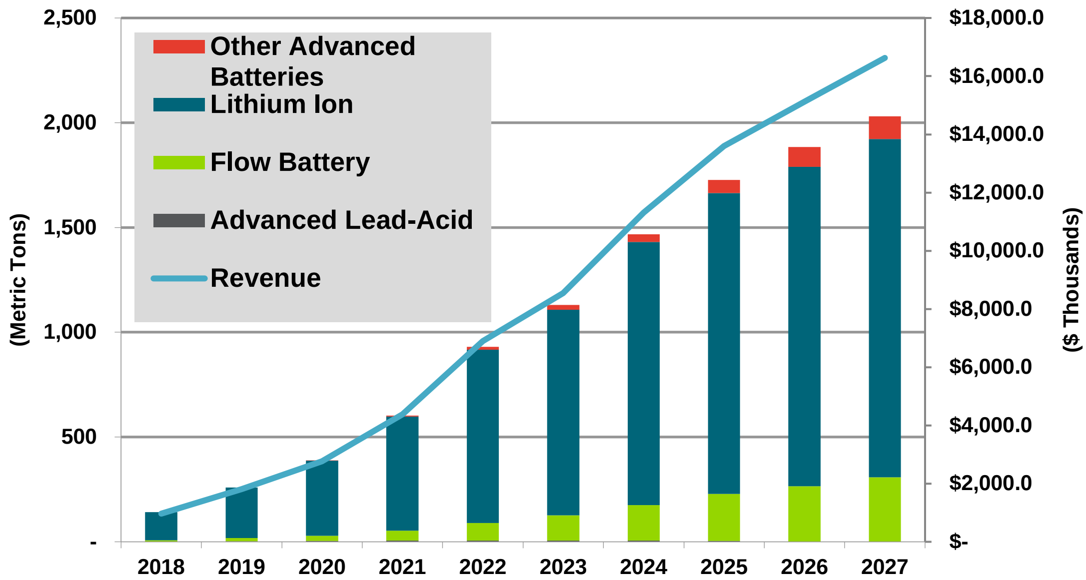

*(Source: Navigant Research)*

## 5.1.2 5.2.2 Distributed Energy Storage

Copper for distributed energy storage is expected to account for approximately a cumulative 39.0% of both energy storage market segments, going from 141.2 metric tons in 2018 to 2030.6 metric tons in 2027. Copper revenue for distributed energy storage is expected to go from $967.4 thousand in 2018 to $16.6 million in 2027, representing a CAGR of 37.2%

Lithium-ion batteries are expected to have the largest impact on the copper market for this segment, reaching a cumulative 8.9 thousand metric tons and a CAGR of 31.9% through the forecast period. Copper for flow batteries are expected to be the fasted growing technology within the distributed energy storage market with a CAGR of 53.0% from 2018-2027.

***Chart 5-2. Copper Intensity by Technology: Distributed Energy Storage, World Markets: 2018-2027***




*(Source: Navigant Research)*

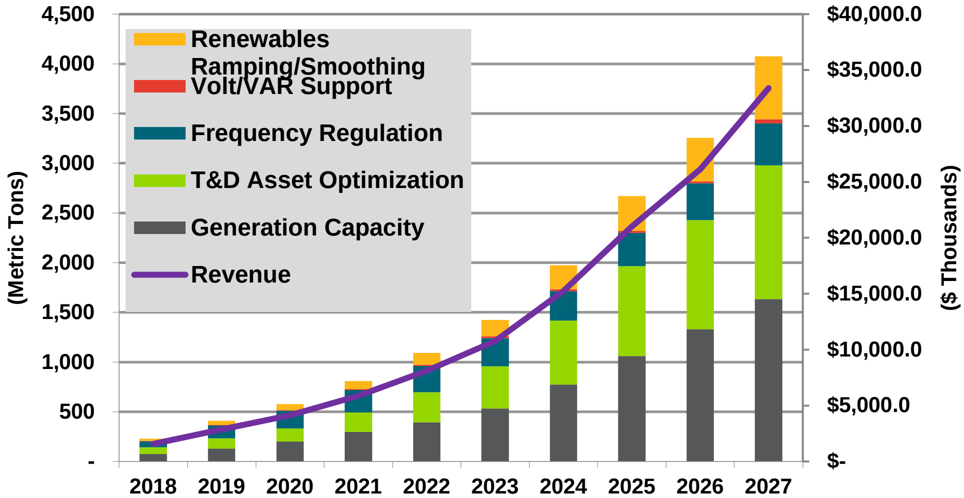
## 5.2 Copper Demand Forecasts by Application Segment

Navigant Research divides the utility-scale energy storage market into five separate use case applications: generation capacity, T&D asset optimization, frequency regulation, volt/VAR support, and renewables ramping and smoothing. Each application requires different power-to-energy ratios, so copper intensity will vary. Distributed energy storage is divided into two separate applications: C&I energy storage and residential energy storage. These systems are similar in architecture, but C&I systems are on average about five to ten times larger than residential systems.

### 5.2.1 Utility-Scale Application Segments

Navigant Research anticipates that generation capacity will be the most copper intensive application within the utility-scale energy storage market segment. Copper for generation capacity is expected to go from 73.8 metric tons in 2018 to 1,634.5 tons in 2027, representing a CAGR of 41.1%. T&D asset optimization comes in closely behind generation capacity in terms of copper intensity, going from 68.8 metric tons in 2018 to 1,343.3 metric tons in 2027, representing a CAGR of 39.1%. Renewables ramping/smoothing, volt/VAR support, and frequency regulation are expected to have CAGRs of 44.2%, 30.6%, and 24.3%, respectively through the next 10 years.

***Chart 5-3. Copper Intensity by Application: Utility-Scale Energy Storage, World Markets: 2018-2027***

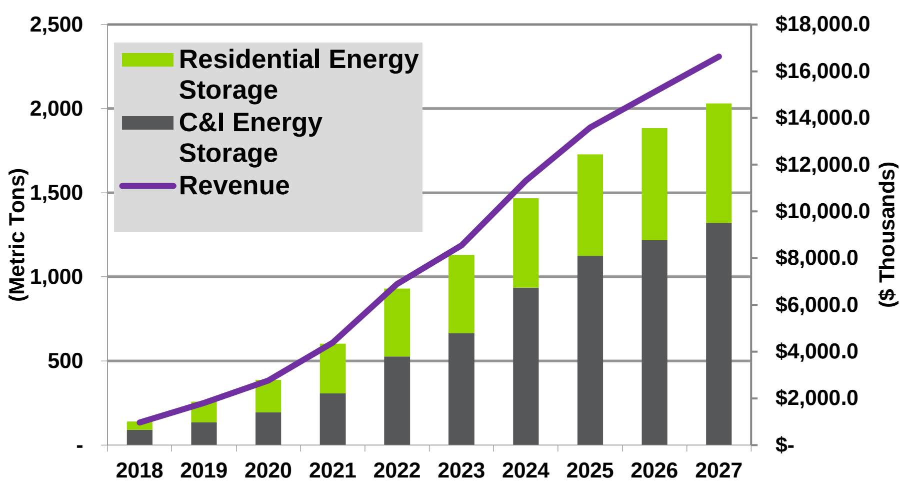



*(Source: Navigant Research)*

### 5.2.2 Distributed Application Segments

Within the distributed energy storage market, Navigant Research anticipates that C&I energy storage will be the largest and fastest growing portion accounting for approximately 61.8%. C&I energy storage is expected to go from 91.1 metric tons in 2018 to 1,319.9 metric tons in 2027, representing a CAGR of 34.6%. Copper for residential energy storage is anticipated to grow at nearly the same rate (CAGR of 34.3% from 2018-2027), but will only account for approximately 38.2% of the distributed energy storage market.

***Chart 5-2. Copper Intensity by Application: Distributed Energy Storage, World Markets: 2018-2027***




*(Source: Navigant Research)*

# Section 6

# RESULTS OF COPPER DEMAND ANALYSIS

## 6.1 Summary of Findings

Navigant Research predicts that the Asia Pacific region will be the leading region for energy storage, and consequently the most copper intensive region through 2027. While it is currently smaller than the North American market, some of the most developed electricity markets exist in the Asia Pacific region. Energy storage deployments to date, both for utility-scale and distributed applications, have been in select markets, namely Australia, Japan, South Korea, and China. The world's largest battery OEMs reside in this region, which further influences battery deployment.

Additionally, new markets are beginning to emerge in the Asia Pacific region with different dynamics and potential for storage both for utility-scale and distributed storage. For example, India aims to decrease its dependence on imported resources and become a global leader in the solar PV industry. India's rapid population growth, particularly in urban areas, is also driving the need for increased investment in T&D infrastructure across the country. Several other Asia Pacific countries have the potential to leapfrog more developed storage markets. Countries such as Vietnam and Indonesia are faced with rapidly growing electricity demand and the need for new infrastructure. These countries have also recently enacted aggressive new renewable energy development targets.

The North American market, primarily comprised the United States and Canada, is projected to be the second largest market through 2027. Federal support across both countries has created favorable landscapes for storage across the region. This consequently led new manufacturers and developers to enter the market with North America as their primary focus in the short term. Europe is also predicted to be a leading market because of its progressive policies supporting renewables and emissions reductions. Many European utilities have worked for years to integrate renewable generation in their energy mix which has called for increased energy storage deployments.

## 6.2 Key Assumptions

Navigant Research believes that over time, the amount of copper present in advanced battery systems will decrease significantly. Copper is used as the primary current collector from the anode during discharge, as well as other balance of system components. The energy storage industry uses less than 1% of all copper consumed by the global economy; while there may be a brief increase in copper usage in the energy storage industry, Navigant Research expects the overall amount of copper present in cells to decrease through 2027. Copper prices tend to be extremely sensitive to the economy at large, so prices often fluctuate in symphony with global economic growth or lack thereof.

A new material that offers significant advantages over a preexisting material can lead to dramatic and swift changes in the industry. To date, recent energy storage research has heavily focused on utilizing materials that are abundant and low cost. As a result, next generation energy storage, particularly electrochemical batteries, have a lower volume of pricey metals like copper and a higher volume of less expensive metals like silicon and iron. Navigant Research consequently employed a copper content deescalator for Li-ion, flow, sodium batteries, and other advanced batteries. Li-ion batteries are one of the most copper intensive energy storage devices in this study and are the vast majority of new deployments across regions. This consequently causes the overall growth rate for both utility-scale and distributed storage to slow from 2022-2027.

Going forward, Navigant Research expects the overall volume of copper in an individual storage device to decrease. This decrease will not outpace the growth of the energy storage industry, so the total amount of copper utilized for energy storage is projected to increase. Navigant Research expects that most materials that go into new energy storage devices will not endure supply squeezes, even as the industry is likely to quintuples in size over the next through 2027. It is expected that the available reserves of relatively rare materials, such as lithium, manganese, and copper, can be expanded relatively easily if high-growth scenarios prove to be the reality.

## Section 7
# ACRONYM AND ABBREVIATION LIST

BEMS .......... Building Energy Management System

BTM .......... Behind-the-Meter

C&I .......... Commercial & Industrial Building

CAES .......... Compressed Air Energy Storage

DESS .......... Distributed Energy Storage System

DoD .......... Depth of Discharge

DR .......... Demand Response

EMS .......... Energy Management System

ESS .......... Energy Storage System

EV .......... Electric Vehicle

FERC .......... Federal Energy Regulatory Commission

LCO .......... Lithium Cobalt Oxide Battery

LFP .......... Lithium Iron Phosphate Battery

Li-ion .......... Lithium Ion Battery

LMO .......... Lithium Manganese Oxide

LTO .......... Lithium Titanate Oxide

NaMx .......... Sodium-Metal Halide Battery

NCA .......... Lithium Nickel Cobalt Aluminum Battery

NMC .......... Lithium Nickel Manganese Cobalt Battery

O&M .......... Operations & Maintenance

PPA .......... Power Purchase Agreement

R&D .......... Research & Development

T&D ........ Transmission & Distribution

TOU ........ Time-of-Use Rates

VPP ........ Virtual Power Plant

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# Section 10
## SCOPE OF STUDY

This report provides an overview of the stationary energy storage market in North America, with a specific focus on estimating the amount of copper that will be utilized in the industry. The market overview and forecasts focus on the three major market segments for grid-connected energy storage: utility-scale, commercial & industrial, and residential. This report provides details on the market dynamics including a discussion of the leading energy storage technologies across all three major market segments. Drivers, barriers, and the competitive landscape in the market are explored to provide context on the forecasts for overall energy storage deployments and the demand for copper in the industry.

## SOURCES AND METHODOLOGY

Navigant Research's industry analysts utilize a variety of research sources in preparing Research Reports. The key component of Navigant Research's analysis is primary research gained from phone and in-person interviews with industry leaders including executives, engineers, and marketing professionals. Analysts are diligent in ensuring that they speak with representatives from every part of the value chain, including but not limited to technology companies, utilities and other service providers, industry associations, government agencies, and the investment community.

Additional analysis includes secondary research conducted by Navigant Research's analysts and its staff of research assistants. Where applicable, all secondary research sources are appropriately cited within this report.

These primary and secondary research sources, combined with the analyst's industry expertise, are synthesized into the qualitative and quantitative analysis presented in Navigant Research's reports. Great care is taken in making sure that all analysis is well-supported by facts, but where the facts are unknown and assumptions must be made, analysts document their assumptions and are prepared to explain their methodology, both within the body of a report and in direct conversations with clients.

Navigant Research is a market research group whose goal is to present an objective, unbiased view of market opportunities within its coverage areas. Navigant Research is not beholden to any special interests and is thus able to offer clear, actionable advice to help clients succeed in the industry, unfettered by technology hype, political agendas, or emotional factors that are inherent in cleantech markets.

# NOTES

CAGR refers to compound average annual growth rate, using the formula:

$$CAGR = (\text{End Year Value} \div \text{Start Year Value})^{(1/steps)} - 1.$$

CAGRs presented in the tables are for the entire timeframe in the title. Where data for fewer years are given, the CAGR is for the range presented. Where relevant, CAGRs for shorter timeframes may be given as well.

Figures are based on the best estimates available at the time of calculation. Annual revenues, shipments, and sales are based on end-of-year figures unless otherwise noted. All values are expressed in year 2018 US dollars unless otherwise noted. Percentages may not add up to 100 due to rounding.

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©2018 Navigant Consulting, Inc.
1375 Walnut Street, Suite 100
Boulder, CO 80302 USA
Tel: +1.303.997.7609
http://www.navigantresearch.com