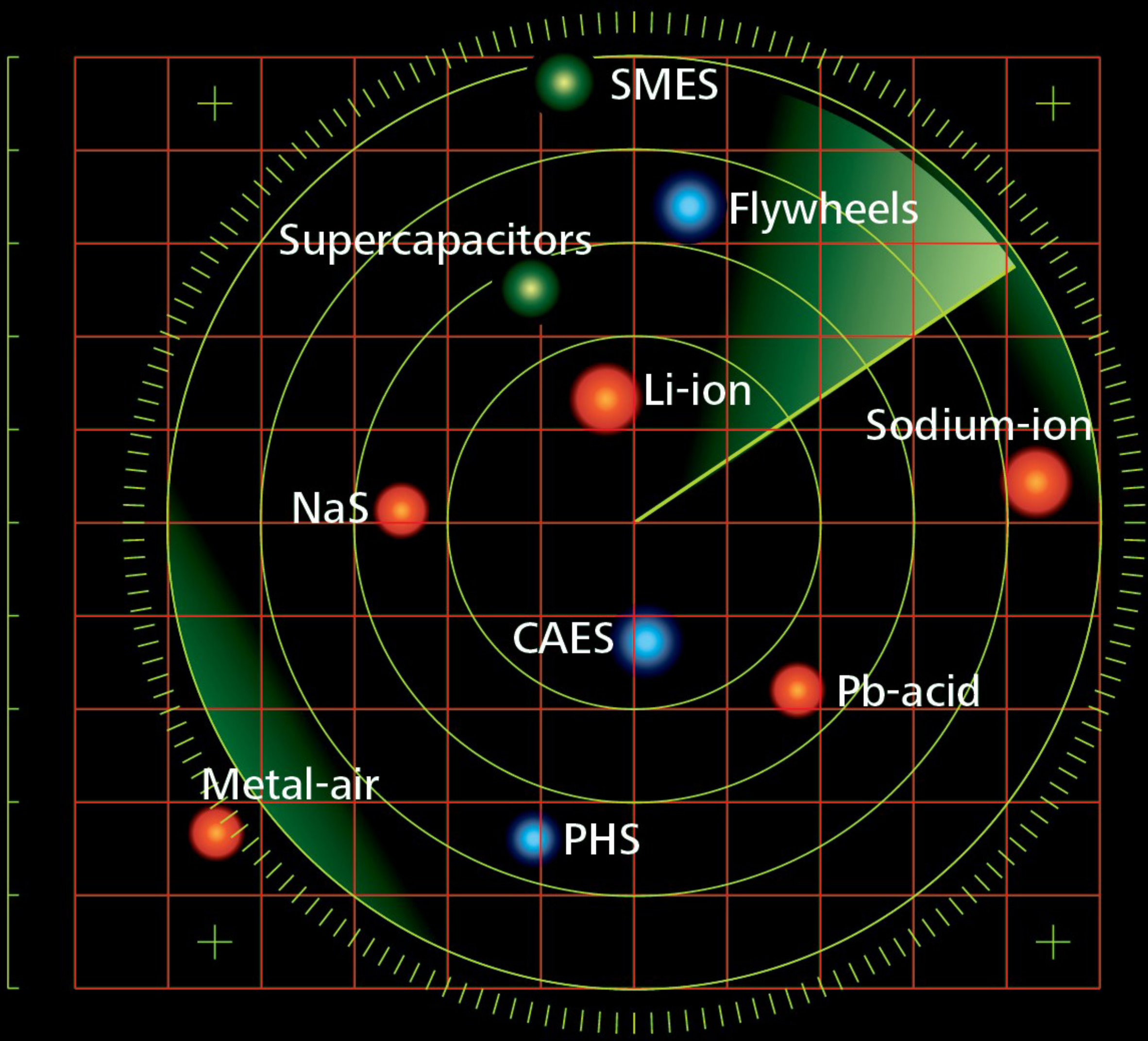
Deloitte.

Energy storage: Tracking the technologies that will transform the power sector



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Executive summary

The world's population is expected to grow by two billion people by 2050 and global energy demand is expected to roughly double during the same period.[1] Concurrently, the power sector is on the brink of a major transformation as more stakeholders look into the possibility of moving away from traditional fossil-energy-based centralized power systems towards the potential of renewable-energy-based distributed generation. However, the penetration of renewable technologies has been hampered by their costs - which are improving - and their intermittency and variability, which reduces availability and induces grid instability. Therefore, the utility industry should consider overcoming these challenges if renewables are to account for more than just a negligible portion of the global energy portfolio.

At present, the emerging consensus[2] is that energy storage is the pivotal technology that will reshape the energy sector by enabling widespread adoption and grid-integration of solar and wind renewables. In the same way that transmission lines affect ***where*** electricity is consumed, energy storage influences ***when*** it is consumed. Thus, commercial and residential consumers are provided the flexibility to become power generators and to select the price point at which they will consume electricity, and utilities and the grid gain the agility to accommodate producers and consumers with disparate temporal behaviors. Regulators are beginning to recognize the value of storage and are creating policies that further improve the business case for adoption.

Recent advancements in materials and manufacturing have improved the economics of storage. Traditional storage technologies such as pumped hydro and compressed air have limited applicability and are losing market share to emerging battery technologies, many of which are leveraging experience in the transportation and consumer electronics sectors to compete in the power sector. In addition to the various technologies that are gaining commercial traction, there are numerous disruptive technologies under development that offer the potential of step-change improvements in performance or cost. The multitude of current and emerging storage options can make it difficult to decide which technology to adopt and when. To assist decision makers, this paper offers a preliminary feasibility assessment that evaluates the business case and benefit/cost ratio of storage technologies within certain customer classes.

The impact of energy storage is far-reaching, as not only does it address the issues that have limited renewable energy's penetration, it fundamentally alters the longstanding relationship between utilities and their customers. The disruptive potential of storage is unlike other energy technologies in that it pervasively extends across the value chain in a way that stakeholders will impact and be impacted by its adoption. To remain a casual observer is to risk disruption, as even non-power companies (e.g., Tesla, Daimler) are entering the market. If the decision is to adopt, there is a need to translate the technical parameters of storage into financial implications to understand the bottom-line impact. If the decision is to not adopt, there is still a need to respect the interdependencies of the ecosystem and evaluate potential impacts to the business and operating model. Either way, the potential of storage requires that stakeholders develop robust strategies that decrease the risk and increase the opportunity.

1 "2014 Energy and Climate Outlook," MIT, 2014.

2 At a recent U.S. DOE "townhall" meeting (February 9, 2015), U.S. Secretary of Energy Ernest Moniz was asked to name a "Blue Sky" technology that has the potential to revolutionize the energy sector. His response: "Distributed Energy Storage." Similarly, a recent survey of electric utilities revealed that energy storage is the top emerging technology that warrants investment. (2015 State of the Electricity Utility Survey Results)

Introduction

Effective use of the world's energy resources depends on having the flexibility to selectively provide energy at choice times, which is the fundamental concept behind energy storage technologies (Table 1) -- the conversion of energy from one state to another (i.e., kinetic to potential or vice versa) so that it can be harnessed at a later date or used in an alternative manner.[3] The temporal flexibility offered by storage can help the power sector accommodate periods of supply/demand mismatch (from brief fluctuations to extended outages) and thereby improve the reliability of the grid, the quality of its electricity, and the profitability of infrastructure investments.[4] From a societal perspective, storage can address the emerging energy demand of rural areas, empower consumers to manage their energy consumption, and strengthen the value proposition of renewable energy installations.

The potential benefits of energy storage have caught the attention of many stakeholders in the power sector, leading to significant growth. Installations associated with grid and ancillary services are projected to grow by roughly 40x over the next 10 years (538.4 MW in 2014 to 20,800 MW in 2024[5]) due to drivers such as renewable integration, energy demand, asset retirements, and technological innovation. Energy storage among end users (commercial and residential) is expected to see even greater growth of 70x (172 MW in 2014 to 12,147 MW in 2024) due, in large part, to smart grid technology.[6] The range of storage technologies that will fuel these exponential growth rates spans the states of energy and the principles of physics.

Table 1. Energy storage technologies[7]

Kinetic energy			Potential energy		
Thermal technologies	Electrical technologies	Mechanical technologies		Electrochemical technologies	Chemical technologies
Hot water	Supercapacitors	Flywheels	Pumped hydro	Lithium ion	Hydrogen
Molten salt	Superconducting magnetic energy		Compressed air energy	Lead acid	Synthetic natural gas
Phase change material				Redox flow	
				Sodium sulfur	

3 "Energy cannot be created or destroyed but can be converted from one form to another." The Law of Conservation of Energy.

4 "Electrical Energy Storage," International Electrotechnical Commission White Paper, 2011.

5 "Energy Storage for the Grid & Ancillary Services," Navigant, 2014.

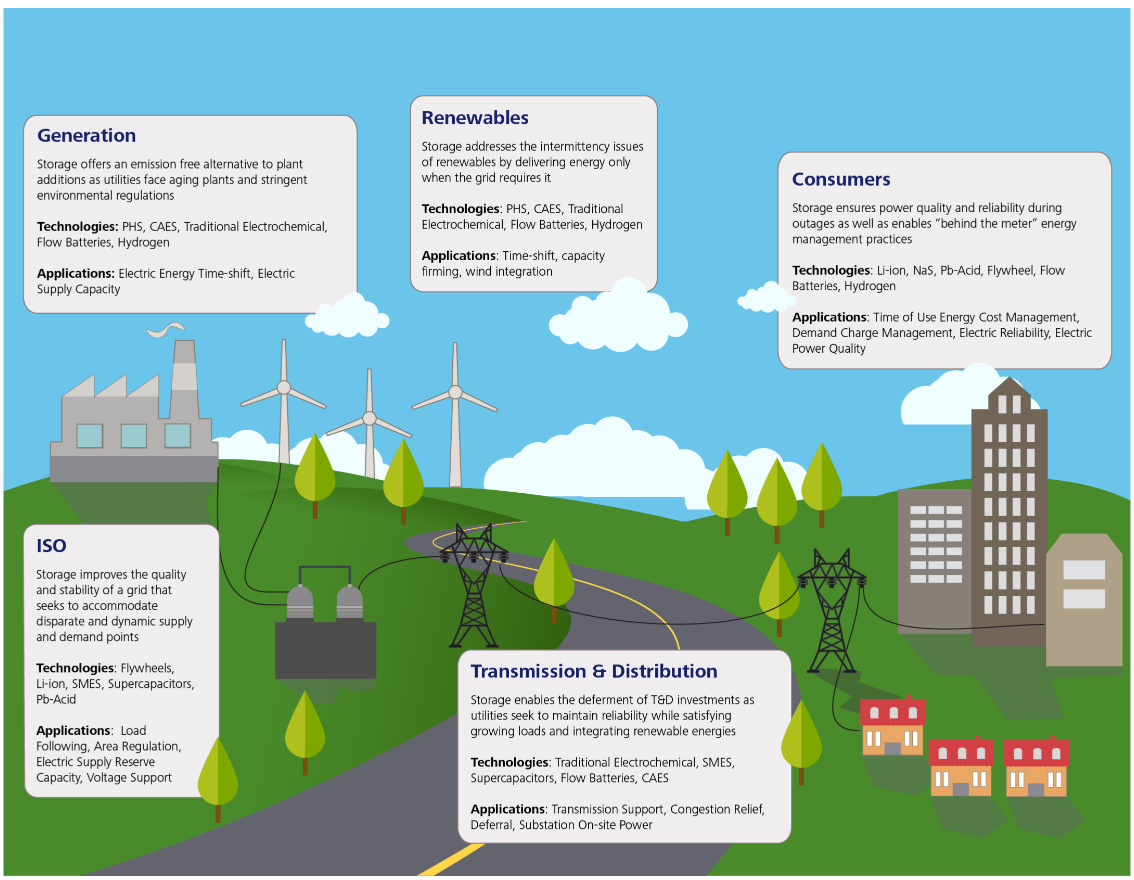
6 "Community, Residential, and Commercial Energy Storage," Navigant Research 2015.

7 "Electricity Storage Fact Book," SBC Energy Institute, September 2013.

Across the value chain

The stability of the power grid depends on various actors working in concert to maintain a balance between electricity supply and demand. Traditionally, electricity assets are categorized based on their function; i.e., generation, transmission, or distribution. Storage systems differ in that they have the ability to balance supply and demand across the segments that comprise the value chain. The new control points offered by storage systems enable operators to selectively respond to fluctuations in grid inputs and outputs. Such functionality is essential to realizing the vision of "smart cities" where producers and consumers are equally informed and equipped to respond to market dynamics in real time. However, many electrical grids were not originally designed to accommodate assets that can both generate and consume electricity. The implications of two-way power flow and the role of energy storage within a modern electricity ecosystem have been studied by many institutions. Potential applications and appropriate storage technologies within each segment of the value chain are illustrated in Figure 1.

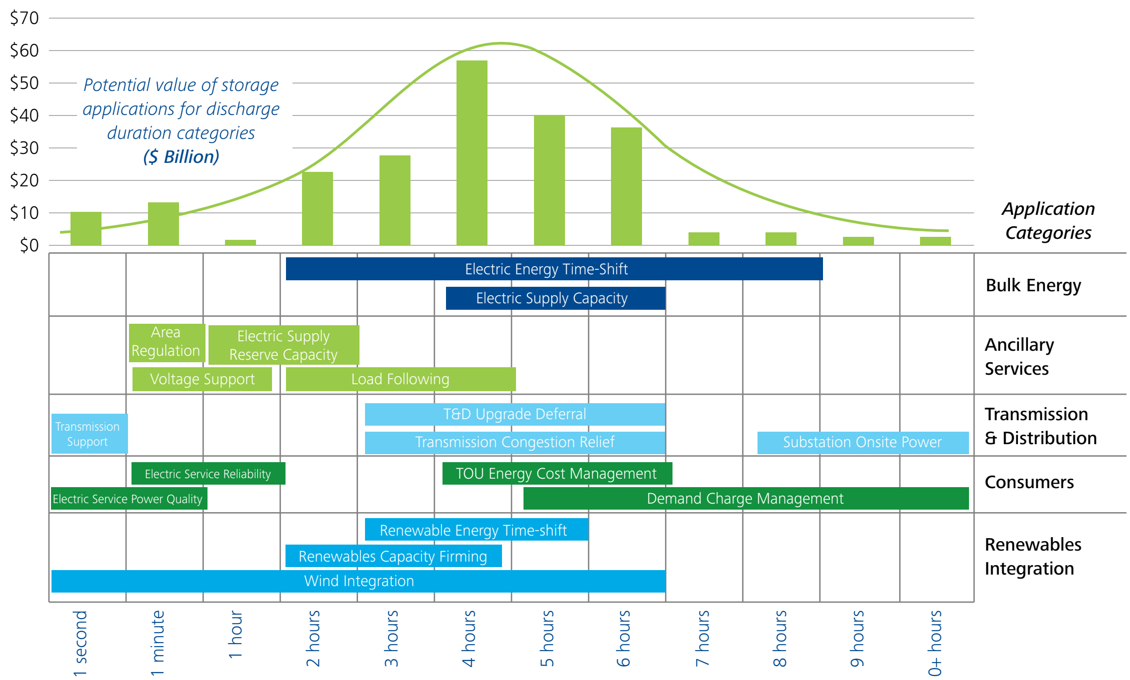
Figure 1. Energy storage across the power sector[8]



[8] "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide: A Study for the DOE Energy Storage Systems Program," SANDIA, December 2010.

The disparities between electricity supply and demand can span timescales from milliseconds to months. A single technology, however, is incapable of operating across all potential timescales. Some technologies provide power quickly while others can deliver it over an extended period. While the need for storage spans the value chain and includes multiple timescales, many grid-related applications cluster near the multi-hour discharge requirement. In addition, the valuable applications also tend to require technologies that have multi-hour discharge durations, as shown in Figure 2.

Figure 2. Energy storage applications and corresponding value for various discharge durations[9]



While the discharge duration of a technology is important and often governs whether it should be considered for a particular application, there are numerous other chemical and physical characteristics that contribute to the final selection decision, such as: power rating, storage duration, cycling, self-discharge, energy density, power density, efficiency, response time (Appendix A). While these attributes may determine which storage technology may be preferred for a certain application, the fundamental factor that determines the feasibility of implementation is whether the benefits offered by a technology exceed its cost. A business case for storage adoption emerges only when the economics are favorable enough to signify a potential return on investment.

[9] Eyer, Jim; Garth Corey "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide – A Study for the DOE Energy Storage Systems Program," Sandia National Laboratories, February 2010.

Energy storage economics – A view through today's lens

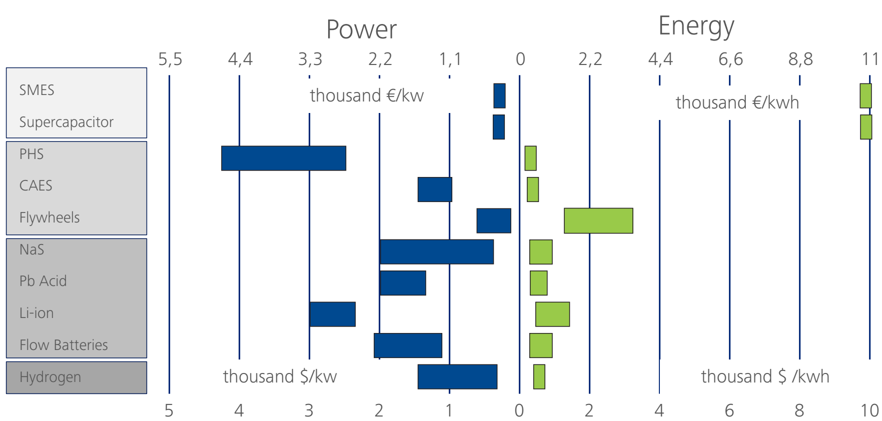
When evaluating the costs and benefits of energy storage for a single application, storage technologies are often prohibitively expensive compared to the alternatives. For example, when offsetting the intermittency of renewable energy such as solar and wind, energy storage is often compared to combustion turbines, which can also flatten the power generation profile of renewable energy systems. Currently, PHS and CAES, both heavily capital-intensive, are the two technologies that are competitive with combustion turbines when the operational parameters associated with renewable integration are considered.[10] Other applications have similar competitive landscapes where storage technologies must unseat incumbent technologies. To justify adoption, either the costs of energy storage technologies need reduced through scale and technological innovation or the benefits need increased through stacking of services.

Storage costs

Whether an energy storage technology is a viable option for a particular application depends on its cost per unit of power or energy. Energy storage technologies typically excel at providing either power or energy, but not both. The costs associated with the provision of power or energy are not necessarily positively correlated and, in fact, flywheels and CAES are two examples in which the cost of energy and power are negatively correlated.[11] Figure 3 shows how the cost per unit of energy and power varies for each of the storage technologies in question.

While Figure 3 represents current technology cost ranges, companies are actively engaging in R&D to reduce the cost of implementing storage systems. The pace at which advancements are made and costs reduced varies from technology to technology.[14] As one might expect, some of the more mature technologies have cost curves that do not decline as significantly as others. For example, PHS is already mature and will experience small cost decreases based on more efficient power station equipment and better construction techniques. Conversely, the cost of hydrogen storage systems could decline rapidly as technological advancements in both production and electrification are achieved. Battery technologies are projected to experience similar cost reductions except in the case of NaS and a few of the Redox Flow batteries, which may experience more rapid cost reductions.

Figure 3. Theoretical capital cost of energy storage technologies[12, 13]



10 "Electricity Energy Storage Technology Options – A White Paper Primer on Applications, Costs, and Benefits," EPRI, December 2010.

11 "Electric Storage Factbook," SBC Energy Institute, September 2013.

12 EPRI, December 2010; "Economic Analysis of Large-Scale Hydrogen Storage for Renewable Utility Applications," SANDIA, Schoenung S., August 2011.

13 Exchange rate as of 2nd April 2015, 1$ = 1,1€ This conversion rate is used throughout the paper.

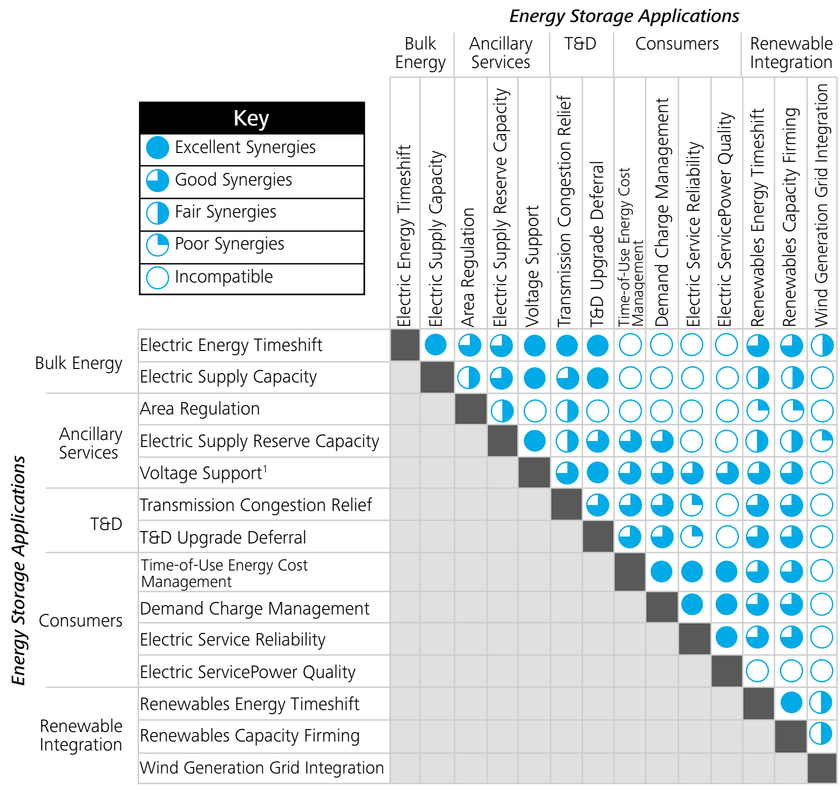
14 The cost projections for the storage technologies used during the analysis are based on business cases conducted by various research institutions, vendor inputs and expert interviews. Supercapacitors and SMES were approximated by a learning curve approach which states that every doubling of their units comes along with a certain cost reduction. (footnote: the reduction depends on the assumed learning rate and was retrieved from IRENA, April 2014, "Electricity Storage – Technology Brief").

Storage benefits

The potential benefits offered by storage technologies are monetized by organizations through increased revenues or reduced costs – both budgeted capital and operating expenses. In addition, storage offers other less quantifiable benefits, such as integrating renewable energy and reducing greenhouse gas emissions.[15] While these "societal benefits"[16] are important, it is difficult to rationalize an investment based solely on externalities. Instead, implementation of energy storage technologies depends on the extent to which a technology can provide a valuable service at a cost that is attractive compared to the alternatives. Storage technologies differ from other systems across the grid in that they can efficiently provide multiple services, thereby improving their economic viability. While the benefit/cost ratio for a single application may not be favorable, an amalgamation of applications provides multiple revenue streams for the same investment. The effectiveness of this concept of "stacking services" depends on the extent to which synergies exist among the applications being stacked (Figure 4).

The siloed nature of the power sector presents a challenge to stacking services. That is, the current regulatory environment does not create a means for each beneficiary to compensate the technology. The Director of the Energy Storage Association, Matt Roberts, suggests that "if the value that energy storage offers across the value chain is summed it exceeds the cost of the storage system, yet markets that allow a system owner to capture all the value streams as compensation are still evolving."[18] As a result, services are typically stacked within each customer segment.

Figure 4. Complementary energy storage applications[17]



15 "Decision Adopting Energy Storage Procurement Framework and Design Program" Order instituting Rulemaking Pursuant to Assembly Bill 2514 to Consider the Adoption of Procurement targets for Viable and Cost-Effective Energy Storage Systems, Public Utilities Commission of the State of California, October 21, 2013.

16 "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide," Sandia, February 2012.

17 Eyer, Jim; Garth Corey "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide – A Study for the DOE Energy Storage Systems Program," Sandia National Laboratories, February 2010.

18 Deloitte Interview with Matt Roberts, Director, Energy Storage Association.

Benefit/cost ratios

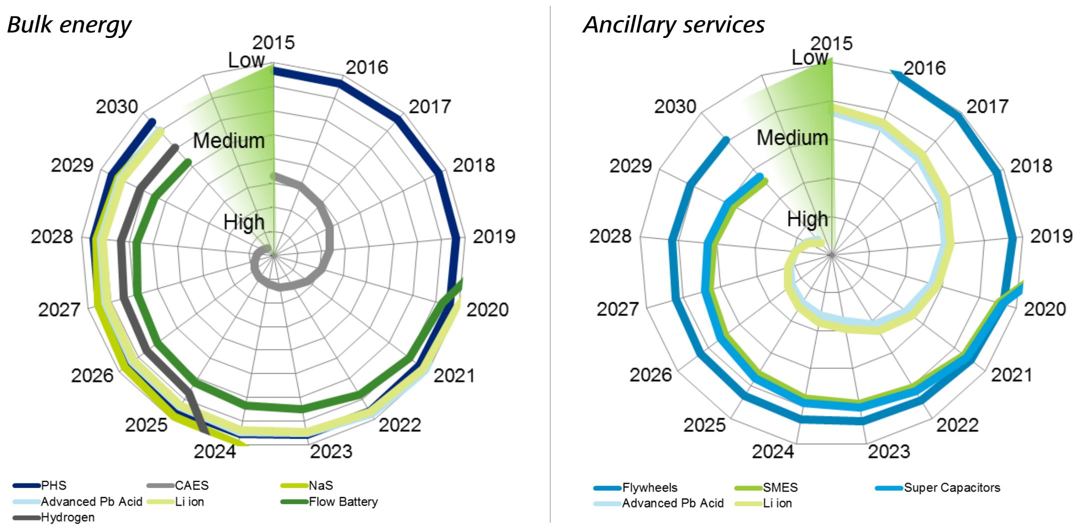
Because the costs and benefits of energy storage are in continual flux, potential users are often unaware of which technologies to consider during adoption decisions. In principle, technologies that should be on a customer's radar are those whose benefits exceed their costs. This is the initial step to determine the technologies that are feasible before down-selecting a technology that is optimal. The charts in Figures 5, 6, 7[19] assist in determining the feasibility of storage technologies by depicting when specific technologies are likely to warrant consideration within a certain customer class. In other words, the charts illustrate how the potential suite of storage solutions might evolve over the next 15 years for specific customers. The charts provide a general indication of the year in which a storage technology becomes feasible compared to its peers and should attract the attention of customers. In addition, as a technology gravitates toward the center of the radar charts, it offers a greater benefit relative to its cost compared to the technologies at the periphery of the circle, but the ultimate selection will depend on whether a technology aligns to the adoption criteria, which varies among customer classes.

[19] Key information related to Figures 5,6,7:

- The curves represent average values, which is important because the ranges associated with both cost and benefit vary wildly depending on innovation and market forces.
- The graphs indicate the year in which a technology with an average cost is suitable for an application with an average value. Companies with low-cost technologies or markets with high value applications can shift the results.
- Regulatory factors such as government incentives in the form of rebates artificially change the benefit/cost ratio of a technology, thereby affecting the results in the charts.
- The analysis considers the feasibility of technologies within certain customer classes, and in this way imposes borders between segments. The borders are consistent with the siloed nature of the global power sector, yet progressive regulatory changes are enabling storage technologies to deliver benefits across the value chain, which improves economics and impacts the charts.
- The scales of each customer class differ, which makes it difficult to make comparisons. For example, a "High" benefit/cost ratio is not equivalent across all classes. The scale within each class is relative to the technologies and applications associated with that class.
- Certain technologies are in developmental phases and are not immediately ready for commercialization. Such technologies appear on the radars during the timeframe in which commercial use is anticipated.
- Each graph considers the value and cost of energy- and power-based applications. The line captured within each radar chart represents the greater of the opportunities presented by energy and power.
- Sources
  - "Electricity Energy Storage Technology Options," a white paper primer on Applications, Costs, and Benefits, Electric Power Research Institute, December 2010.
  - Eyer, Jim; Garth Corey "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide – A Study for the DOE Energy Storage Systems Program," Sandia National Laboratories, February 2010.
  - "Grid Energy Storage," U.S. Department of Energy, December 2013.

Bulk energy and ancillary services

Figure 5. Energy storage radar charts for bulk energy and ancillary services



Bulk energy

Bulk energy storage involves shifting the energy production of current generators such that utilities can “buy low” and “sell high” within daily or seasonal markets. In addition, bulk energy storage systems can stave-off the need for the generation capacity offered by peaking plants.[20] Currently, PHS and CAES are the feasible options for bulk energy storage; however, both depend on the availability of suitable topology or geology, which is often limited. In addition, financial challenges emerge when rationalizing the large capital expenditures that are required to scale PHS and CAES systems to maximize efficiency, especially in the case of CAES plants, which lack operational data to mitigate the risk of a 40 year investment, even though they seem to be the most viable technology, as reflected in Figure 5.[21] Conventional batteries such as NaS and Pb-Acid emerge as viable options that are likely better-suited for small- or medium-size applications due to their scaling and lifecycle limitations. Similar technical constraints occur for Li-ion systems, which have much higher efficiencies and power densities, and are pushed by the automotive sector to become cost-effective, making them much more appealing than other conventional battery types. Flow batteries may emerge and even supplant existing technologies as they achieve commercial deployment. Since bulk storage requires relatively large amounts of energy with frequent discharges throughout the year, replacement and O&M costs are significant factors. Among the viable technologies, however, there are trade-offs between replacement and O&M costs because mechanical systems often require more maintenance during their lifetime, while electrochemical systems are more expensive to replace. Finally, hydrogen storage would be well-suited for bulk applications in the future, as the hydrogen could potentially be used in conventional gas-fueled power plants. Currently, however, this opportunity is constrained by the tradeoff between infrastructure modifications required to accommodate high blending percentages of hydrogen.[22]

20 In addition to storage and combustion turbines, capacity resources include demand response, energy efficiency, and distributed generation.

21 Interview with Dirk Uwe Sauer, Professor, ISEA RWTH Aachen, Electrochemical Conversion and Storage.

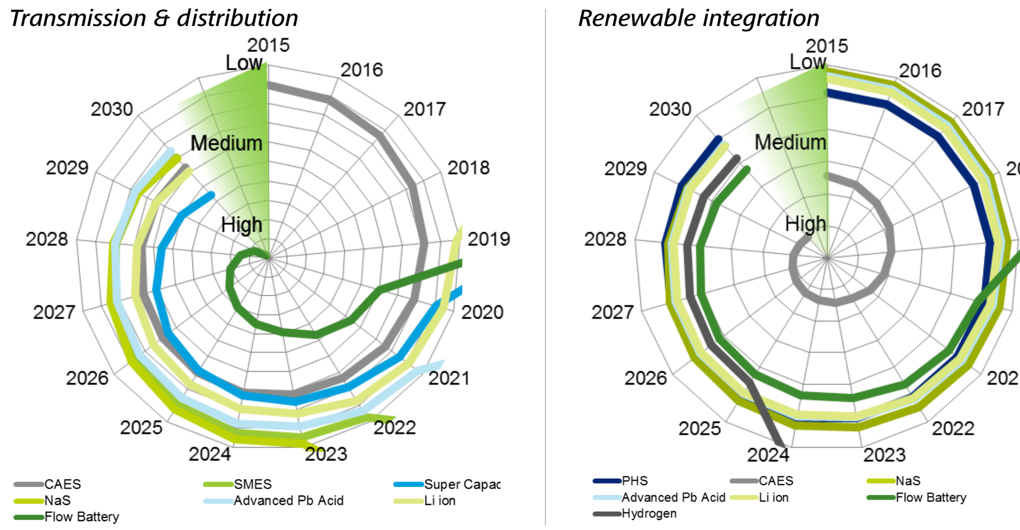
22 Hydrogen could be used in a current natural gas infrastructure given certain mixing (blending) percentages are met. If the thresholds are not respected costly infrastructure modifications have to be implemented. Methanation could override this issue but has even higher total cost as additional conversion steps are required.

Ancillary services

Energy storage technologies are uniquely suited to provide ancillary services, which are currently being performed by generators that are not designed for this purpose. Moreover, the provision of ancillary services impairs the primary function of traditional power generation assets by requiring that they operate at suboptimal levels in order to respond to changes in the grid. Energy storage, on the other hand, offers responsive technologies that can accommodate the need for frequent but relatively short discharges. Currently, battery technologies such as Li-ion and Pb-acid are the most economically viable storage options, with flywheels on the cusp of feasibility.[23] (Flywheels provide an advantage in both their extended lifetime and minimal maintenance costs.) Supercapacitors and SMES are currently immature but offer the potential for extremely high efficiencies and long lifetimes upon achieving commercialization.

Transmission & distribution and renewable integration

Figure 6. Energy storage radar charts for transmission & distribution and renewable integration



Transmission & distribution

Energy storage can improve the stability and performance of transmission assets as well as defer the need for additional infrastructure by alleviating traffic congestion along transmission lines during peak times. Conventional battery technologies are currently being used within the T&D space with researchers at Sandia National Laboratories estimating that "100,000 battery storage systems (are installed) at utility substations in the U.S."[24] In addition, above-ground CAES appears to be a viable option for T&D applications in instances where space is less of an issue. Within the T&D segment there are also applications that require sub-second responses (e.g., transmission support) that will make SMES and supercapacitors desirable technologies. Going forward, flow batteries will present an intriguing option based on the potential benefit/cost ratio once they achieve commercial maturity.

Renewable integration

Storage technologies are essential for renewable energy systems to realize their full potential. Renewable power is often produced at inopportune times, resulting in an undesirable price or possible curtailment. Storage can improve the economics of renewable systems, yet the appropriate storage technology depends on the renewable installation, as PV and wind differ both in technology and size. CAES and PHS are initial energy storage options because they are apt to accommodate the daily and seasonal intermittency issues of renewables. However, PHS and CAES have siting constraints,

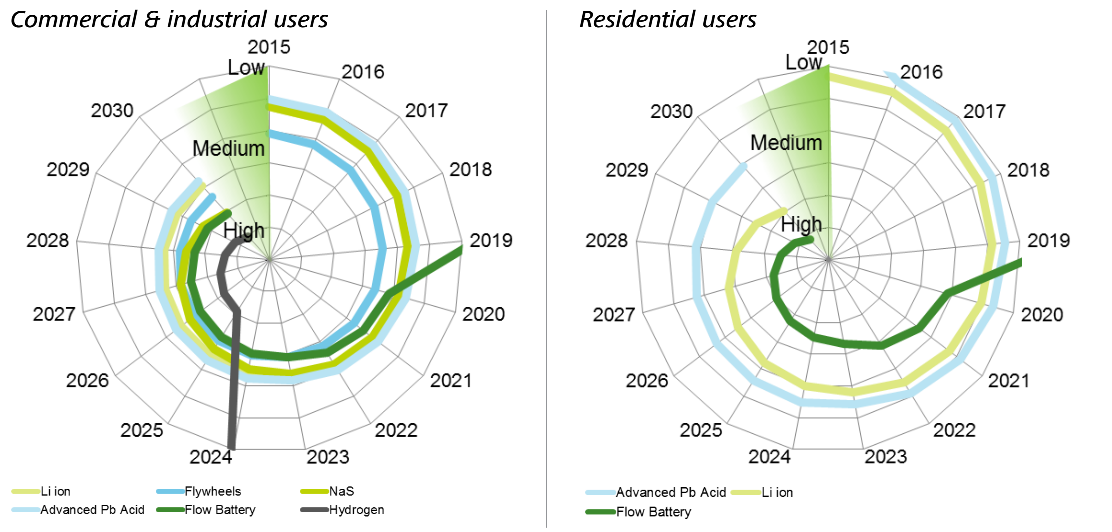
23 Current sample projects, Pb Acid: Kaua'i Island Utility Cooperative, designed to mitigate the variability of the island grid, monitoring the power supply and correcting for frequency and voltage deviations, Li-ion: United Kingdom, England, Bedfordshire, Leighton Buzzard, Smarter Network Storage, services to distribution network operators and transmission system operators.

24 "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide," Sandia, February 2012.

which can limit the technology's application depending on the location. CAES would best fit windy, coastal areas with underground caverns, such as Northern Germany, which would assist with the integration of both on- and offshore wind energy.[25] As batteries mature, they will be leading the energy storage market in small- to mid-sized installations. Flow batteries offer interesting options in cases where traditional batteries may have lifecycle issues. Finally, chemical storage technologies such as hydrogen could be an appropriate choice as they offer additional flexibility in how the energy is ultimately used (electricity, heat, or transportation).

Consumers

Figure 7. Energy storage radar charts for consumers



Commercial, industrial, and residential consumers

Consumers of electricity stand to benefit from energy storage technologies, as the smart grid enables users to selectively adjust their energy consumption patterns. Specific storage technologies will vary depending on whether the customer class is residential or commercial. As one might expect, residential applications are smaller in scale, and safety and simplicity are critical. Li-ion and Pb-acid are viable options for residential energy applications in the near term. Redox storage technologies offer intriguing potential once commercialized. Sodium-sulfur and Advanced Pb-acid batteries are currently viable options for commercial and industrial consumers, as are flywheels for power-based applications. Hydrogen and flow batteries offer advantageous benefit/cost ratios with high-quality energy densities and storage capabilities as they mature to commercialization. Hydrogen storage, however, requires an additional electrification system if blending percentages are not met (i.e., special hydrogen turbines or fuel cells, which increases both capex and maintenance costs). Both residential and commercial consumers will look to flywheels and certain types of batteries capable of short discharge durations to maintain their electric service power quality.

To maintain electric power quality, residential and commercial consumers will look to flywheels, as well as certain batteries, that are capable of rapid discharge. Such batteries can serve a dual purpose by satisfying both energy and power applications.

The results presented within the radar charts and the actions taken within each customer class will be affected by the extent to which innovations alter a technology's cost curve and regulations change the value of an application. The remaining sections are dedicated to exploring these two variables (innovations and regulations) and their contribution to the near- and long-term evolution of storage.

[25] "Druckluftspeicher-Kraftwerke," BINE Informationsdienst, 2007.

Technological innovations – A look into what the future might bring

The near-term research goals for each storage technology vary. Pumped hydro companies are seeking to improve the components used for retrofitting existing installations. CAES research is addressing the challenge of heat loss during compression through adiabatic and isothermal concepts, which offer the potential to realize significant gains in overall compressed air efficiency. Flywheel companies are continually pursuing alternative materials that can withstand high rotational speeds and decrease the frictional losses associated with bearings. Battery developers are pursuing low-cost materials as well as materials that offer improved performance over current chemistries. Finally, hydrogen storage companies are seeking to improve the efficiency of the electrolysis process by which hydrogen is derived.[26] In Germany, the Strategy Platform Power-to-Gas which is supported by the German Energy Agency (DENA), research institutes, and private sector actors (including the three biggest utilities), aims to prove the commercial viability and the systemic value of chemical storage technologies.[27] However, none of the 31 demonstration projects that are in operation or under development is currently cost-competitive.[28]

Reducing the cost of storage systems, across all categories, will require a concerted materials and systems engineering effort to reduce the cost of the storage technology as well as the significant cost associated with the balance of plant (BOP) components.[29] Both storage technologies and BOP components stand to benefit from advanced manufacturing concepts, which leverage strategies related to materials, processes, and ecosystems to improve manufacturing methods.[30] Specific technologies such as additive manufacturing, automation, robotics, and sensors—collectively referred to as "smart or digital manufacturing"—are revolutionizing manufacturing strategies across sectors and can improve the efficiency

JCESR[35]

"Energy storage technologies are currently adequate for personal electronics, but not well suited for large grid-scale applications as they are expensive and must serve diverse grid needs spanning the energy-power spectrum [or grid needs from high energy to high power]. Significant improvements in performance and cost are needed to tailor next-generation storage technologies to grid needs."

— George Crabtree, Director

Tesla[33]

"It can theoretically be scaled infinitely, all the way up to industrial and utility level…. Our goal is to fundamentally change the way the world uses energy. It sounds crazy, but we want to change the entire energy infrastructure of the world to zero carbon"

— Elon Musk, Tesla CEO, on the Powerwall potential

26 "Electricity Storage Fact Book," SBC Energy Institute, September 2013.

27 "Power to Gas. Eine innovative Systemlösung auf dem Weg zur Marktreife," Strategieplattform Power to Gas, December 2013.

28 "Thesenpapier Wirtschaftlichkeitsaspekte," Strategieplattform Power to Gas, June 2012.

29 In the case of battery storage systems, BOP components can account for 60 to 70 percent of the cost of the system. "Grid Energy Storage," U.S. Department of Energy, December 2013.

30 The National Science and Technology Council characterizes advanced manufacturing as "a family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, e.g., nanotechnology, chemistry, and biology. It involves both new ways to manufacture existing products, and the manufacture of new products emerging from new advanced technologies." "A National Strategic Plan for Advanced Manufacturing," Executive Office of the President, National Science and Technology Council, February 2012.

33 Tesla CEO Elon Musk's Powerwall reveal event held on April 30, 2015.

35 Deloitte interview with George Crabtree, Director, Joint Center for Energy Storage Research.

of the processes by which BOP components are manufactured. Tesla, for example, plans to take advantage of the full suite of advanced manufacturing technologies in the construction and operation of their "Gigafactory," a $5B (€4.5B) investment that will attempt to leverage the advantages associated with economies of scale for battery production. Tesla's factory will employ a variety of technologies and techniques that are collectively expected to reduce the cost of their Li-ion systems by one-third, to less than $250/kWh ((€227/kWh).[31] Recently, the company has announced its intention to unveil a battery pack for residential storage that will likely benefit from the cost reductions offered by the Gigafactory. While such progress is impressive, many in the space believe that energy storage requires revolutionary (not evolutionary) advancements if it is to truly compete with inexpensive gas in the pipeline for grid-scale applications.[32]

Disruptive technologies

If the energy storage industry is to realize its full potential, cost curves require a step-change compared to current projections that extrapolate modest historical trends. The Department of Energy (DOE) has recognized the need for more significant advancements and consequently has begun to explore technologies "beyond Li-ion"[34] by establishing the Joint Center for Energy Storage Research (JCESR) at Argonne National Laboratory.

The organization has established the goal "5-5-5," which is to develop technologies that have five times the current power density, at a fifth of the cost, in five years.[36] The opportunity beyond Li-ion is believed to be large as there are various conceptual designs and numerous material candidates, which collectively can produce upwards of 100 new batteries.[37] The incremental advancements associated with Li-ion have been due to improvements to the components comprising the battery (i.e., anode, cathode, or electrolyte), which work in concert to achieve the desired effect. With that said, if one desires to develop a battery that is 5X better, each of the components require a 5X gain in performance. The challenge to battery development lies in identifying materials for each component that offer significant gains and are compatible with each other. Progress will be achieved as options are systematically explored and risks are reduced to a level that encourages others to enter the market and innovate.

Accelerating the development timeline is a formidable task considering that Li-ion batteries took 20 years to produce from concept to commercialization. Today, technology developers can exploit tools and techniques that were not available 20 or 30 years ago. High-performance computing and nanoscience enable studies at the atomic and molecular scale that weren't possible in the 1970s and '80s when Li-ion batteries were first developed. High performance, massively parallel computers have advanced by a factor of 1,000 each decade[38] as have the algorithms required to design and simulate the properties of materials at the elemental level. Physics-based models have improved to the point that technology developers can now model complex operating conditions and rapidly iterate designs to determine proper design configurations. Such advancements are enabling scientists to accelerate the identification of advanced anodes, cathodes, and electrodes that are mutually compatible.[39] For example, researchers working on the electrolyte genome project at Lawrence Berkeley National Laboratory have reviewed roughly 5,000 forms of electrolytes over two years and identified 10 to 20 that appear interesting.[40] Tomorrow's technology will further improve the exploration process and, in turn, accelerate the development continuum.

31 "Tesla's high-stakes gamble," The Economist, September 22, 2014.

32 Pyper, Julia "GE Ventures Exec: Grid-Scale Energy Storage Can't Compete With Low-Cost 'Gas in the Pipeline', " Green Tech Media, October 8, 2014.

34 m-sulfur and lithium-air as well as non-lithium chemistries.

36 While not the subject of this report, one could imagine how any advancements related to increasing power density and reducing costs would impact the transportation sector in its pursuit of deploying electric vehicles.

37 Interview with George Crabtree, Director, Joint Center for Energy Storage Research.

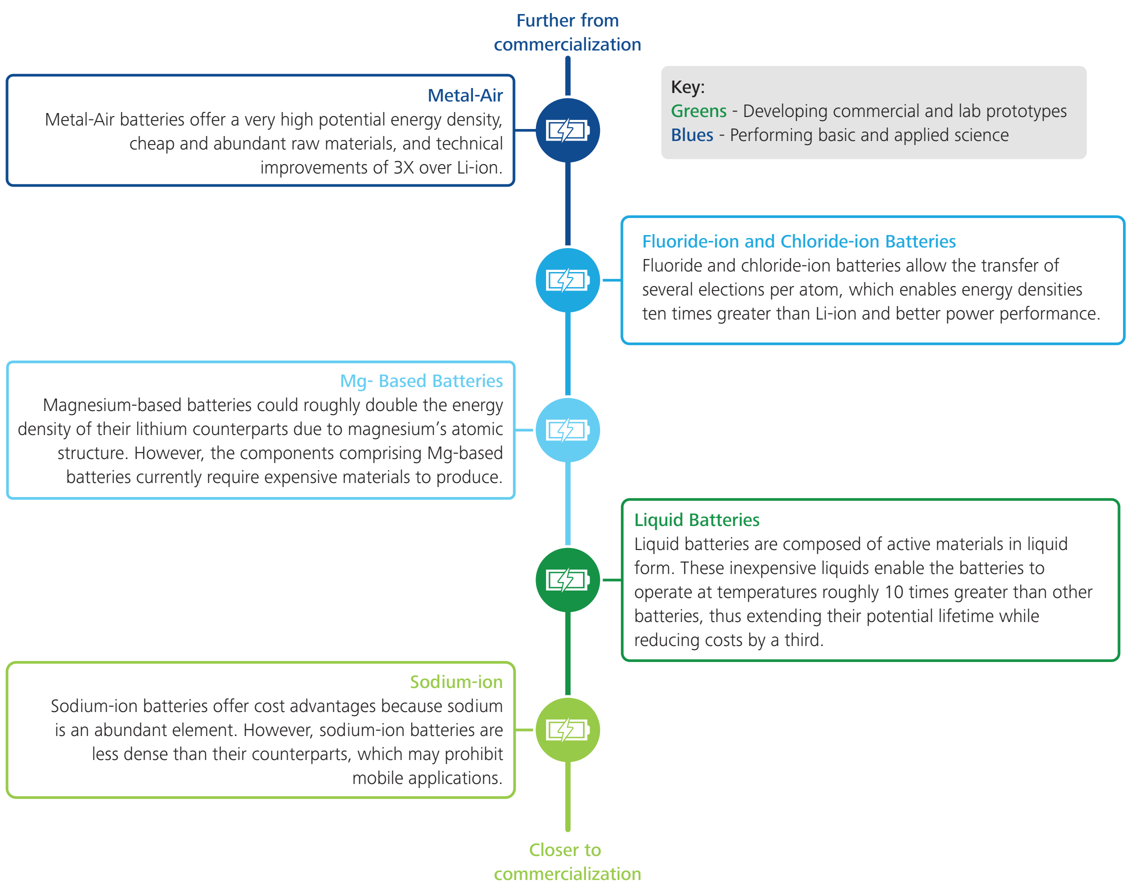
38 "50 years of artificial intelligence," Lungarella M. et al, 2007.

39 This is not unlike the high-throughput testing used by pharmaceuticals to accelerate the drug discovery process. Researchers can simulate thousands of configurations and apply their limited resources to those that theoretically offer the greatest potential for success.

40 Interview with George Crabtree, Director, Joint Center for Energy Storage Research.

Over the next 10 years, the truly disruptive energy storage technologies will likely be electrochemical as new materials are developed and innovative component configurations are identified. Some of the novel electrochemical technologies being explored are shown in Figure 8.

Figure 8. Potential "game-changing" technologies[41, 42, 43, 44]



Of the technologies mentioned in Figure 8, Sodium-ion and its various derivatives are the closest to achieving market penetration. Aquion Energy, a start-up, is manufacturing a type of Sodium-ion battery currently experiencing commercial success. The technology associated with liquid batteries is maturing, due in large part, to the work of Donald Sadoway of MIT, who is developing prototypes capable of achieving reduced operating temperatures and extended lifetimes. The maturation of the remaining battery technologies—magnesium-ion, fluoride- and chloride-ion, and metal-air—will depend on the rate of R&D funding. Each technology comes with specific challenges related to the chemistries of its components—commercialization will take time. In the case of magnesium-ion batteries, for example, JCESR has identified an anode, cathode, and electrolyte that could be compatible, but it will take many years to build a prototype and scale it to a commercial size.

41 "NY BEST: Metal-Air Batteries," EOS March 2012.

42 "TR10 Liquid Battery," MIT Technology Review, April 2009.

43 Interview with George Crabtree, Director, Joint Center for Energy Storage Research.

44 "European Energy Storage Technology Development Roadmap towards 2030," EASE, April 17, 2014.

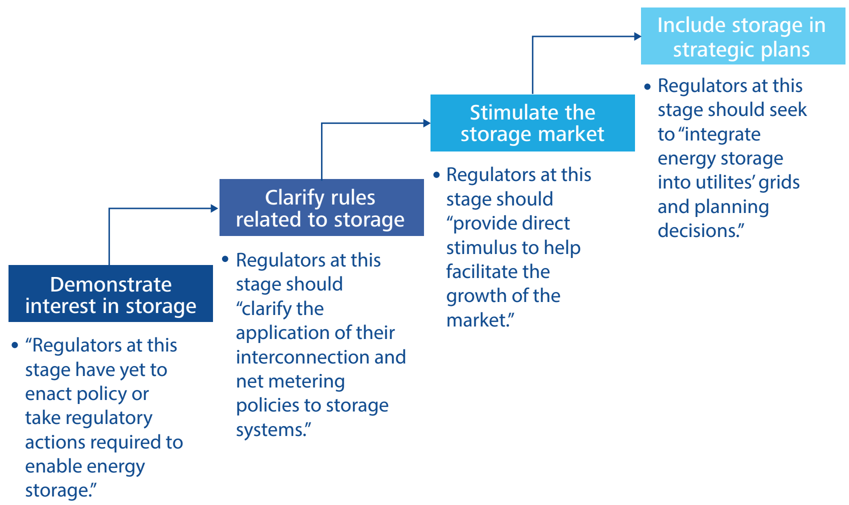
Regulatory considerations – A need for reform

The regulatory maturity of a market will influence the value and utility of storage systems. In fact, regulatory policies may supersede technological advancements in terms of influencing storage adoption. For example, PJM[45] recently adopted capacity performance rules that enable storage technologies to be more fairly compensated for their value, resulting in the growth of installations in a region where neither the market nor the technology has changed.

Energy storage policies, even in mature markets, vary greatly. Both the US and Europe have struggled to incorporate energy storage in their respective regulatory frameworks due to its ambiguous nature – being a generator and a consumer. An additional issue is the fact that it is often difficult to determine the origin of the energy being stored, which can improve economics through bonuses or premiums if the energy is renewable in nature.[46] The Interstate Renewable Energy Council recently reviewed US policies related to energy storage and found many efforts among regulatory bodies can be categorized by the following four stages.

Very few regions have progressed to the final stage where energy storage is explicitly included in strategic procurement plans. Only California has made strides, with the California Public Utilities Commission (CPUC) recently approving a decision that requires its three utilities to procure 1.3 GW of energy storage systems.[48] A Texas utility company has proposed adding 5 GW of battery storage to the grid.[49] The challenge, however, is a regulatory one because Texas does not allow T&D utilities to own generation assets such as storage. This is another case where the technology and market are conducive to adoption of energy storage, yet regulatory barriers are impeding progress. However, just as PJM has adopted progressive policies, other regions may act to create, clarify, or update their policies to accommodate storage systems so that consumers may benefit from improved service and reduced rates.

Figure 10. Hierarchy of possible regulatory temperament[47]



Energy Storage Association[50]

"While the value proposition is evident, rewarding the value of energy storage has historically been difficult, yet evolving policies will likely generate more favorable market structures in the next couple of years."

— Matt Roberts, Director

45 A regional transmission organization in the US that serves the Mid-Atlantic region.

46 stoRE "European Regulatory and Market Framework for Electricity Storage Infrastructure," June, 2013.

47 "Deploying Distributed Energy Storage: Near-Term Regulatory Considerations to Maximize Benefits," IREC, February 2015.

48 "California's Energy Storage Mandate: Electricity Advisory Committee Meeting," CPUC June 17, 2014.

49 "Oncor Wants to Spend $5.2 Billion (€4.73 Billion) on Energy Storage," Power, November 11, 2014.

50 Deloitte Interview with Matt Roberts, Director, Energy Storage Association.

Implications - A call to action for stakeholders

Over the past decade, the power sector has evolved due to the emergence of alternative generation technologies. Renewable energy has become increasingly price-competitive and regulators have crafted favorable policies to ease implementation. However, just as renewable technologies have altered how electricity is produced, energy storage has the potential to fundamentally change the manner in which electricity is consumed. Storage enables renewable integration by better matching supply and demand. By making distributed generation possible, storage is decoupling the traditional value chain of the power sector. The resulting question for the coming years is: What degree of decentralization will be achieved? The answer will vary by region and be driven by a complex set of technical, financial, and political issues such as the need for energy additions, the availability of financing, the penetration of renewables, the price of natural gas, and the threat of climate change.

The opportunity for energy storage is vast, yet realizing its full potential will require a concerted effort among stakeholders to enable the evolution towards a distributed energy future. Each entity across the stakeholder spectrum will play a role in developing the business case to enable the power sector to seize the opportunities presented by energy storage.

Developers

Developers should validate performance, reduce costs, improve efficiencies, understand the merit of their technology (think competitive advantage vis-à-vis substitutes), position themselves in the market (think applications), and actively start developing their market (think stakeholder management and industrial partnerships).

Adopters

Adopters, such as utilities, should assess the potential for stacking storage applications, share lessons learned, and develop new business models that minimize investment risks, while consumers need to understand the value proposition of storage, and the extent to which storage improves the performance of renewable energy systems and smart appliances.

Regulators

Regulators should assess the fit of different storage technologies with the target energy mix they have in mind, and consider the policies that will enable and even incent storage adoption within their jurisdiction – keeping in mind that regional differences in the economy, public opinion, resources, generation mix, and energy demand matter.

If the energy transition has taught us anything, it's this: Disruptive technologies in combination with compelling long-term economic logic can turn seemingly rock-solid sectors upside down. Industry players that ignore such an evolution risk their very existence. Smart players will not only anticipate the storage revolution but drive it. To stay ahead of the curve, organizations should consider the implications of the storage revolution to their business or jurisdiction. Those that view energy storage as an integral asset to the electricity system and proactively incorporate it into strategic plans are more likely to realize the full value that storage offers.

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Appendix A: Characteristics of energy storage technologies

Technologies	Power rating (MW)	Storage duration (h)	Cycling or lifetime	Self-discharge (%)	Energy density (Wh/l)	Power density (W/l)	Efficiency (%)	Response time
Super-capacitor	0.01-1	ms-min	10,000-100,000	20-40	10-20	40,000-120,000	80-98	10-20ms
SMES	0.1-1	ms-min	100,000	10-15	~6	1000-4000	80-95	< 100ms
PHS	100-1,000	4-12h	30-60 years	~0	0.2-2	0.1-0.2	70-85	sec-min
CAES	10-1,000	2-30h	20-40 years	~0	2-6	0.2-0.6	40-75	sec-min
Flywheels	0.001-1	sec-hours	20,000-100,000	1.3-100	20-80	5,000	70-95	10-20ms
NaS battery	10-100	1min-8h	2,500-4,400	0.05-20	150-300	120-160	70-90	10-20ms
Li-ion battery	0.1-100	1min-8h	1,000-10,000	0.1-0.3	200-400	1,300-10,000	85-98	10-20ms
Flow battery	01-100	1-0h	12,000-14,000	0.2	20-70	0.5-2	60-85	10-20ms
Hydrogen	0.01-1.000	min-weeks	5-30 years	0-4	600 (200 bar)	0.2-20	25-45	sec-min
SNG	50-1.000	hours-weeks	30 years	negligible	1,800 (200 bar)	0.2-2	25-50	sec-min

Electrical Mechanical Electrochemical Chemical

Appendix B: Abstract

The power generation sector is on the brink of a major transformation, driven in large measure by the increasing adoption of renewable energies such as wind and solar by both utilities and commercial and residential consumers, as well as by efforts to modernize the electric grid. Electricity storage is considered the pivotal technology critical to enabling this transformation. This paper provides a broad view of the value proposition for all types of power generators of storage technologies today, as well as projections into the future economics and business implications of various storage technologies currently in development. The paper will serve to assist decision makers across many aspects of the economy—from traditional utilities to companies and consumers who increasingly wish to use alternative and renewable energies to generate their own power—as they evaluate the business case for storage technologies, and seek to narrow the field of economically feasible technologies such that an optimal solution can be chosen.

Appendix B: Acronyms

List of acronyms

Acronym	Definition
BOP	Balance of Plant
CAES	Compressed Air Energy Storage
DOE	United States Department of Energy
EC	European Commission
EU	European Union
Fe/Cr	Iron Chromium (flow battery)
GE	General Electric
JCESR	Joint Center for Energy Storage Research
LCOE	Levelized Cost of Energy
Li-ion	Lithium ion (battery)
NaS	Sodium Sulfur (battery)
NASA	National Aeronautics and Space Administration
O&M	Operations & Maintenance
Pb Acid	Lead Acid (battery)
PHS	Pumped Hydro Energy
PV	Photovoltaic
R&D	Research & Development
SMES	Superconducting Magnetic Energy Storage
SNG	Synthetic Natural Gas
T&D	Transmission & Distribution
Zn/Br	Zinc Bromide (flow battery)