2015 MITEI Associate Member Symposium

Storage, Renewables and the Evolution of the Grid

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Apurba Sakti
sakti@mit.edu

Francis O'Sullivan
frankie@mit.edu

MIT Energy Initiative, 77 Massachusetts Ave., Cambridge, MA 02139, USA

MIT Energy Initiative

Cover page images: “Phillips AA and C batteries” by Darra, C., “A photovoltaic array and wind turbines at the Schneebergerhof wind farm in the German state of Rheinland-Pfalz” by Kubelbeck, A. and “Yellow Electricity” by Oast House Archive. Creative Commons.

Executive Summary

The structure of the US power system is changing as renewable resources play an increasingly important role in meeting electricity demand, and as consumer adoption of distributed energy solutions grows. Evidence of this dynamic includes the fact that over the past decade the combined annual generation from wind and solar has increased by an order or magnitude to reach 225 TWh in 2015, or some 6% of total US generation. Furthermore, at the start of 2016 the US reached the milestone of having one million solar PV installations in place, with the vast majority being small rooftop mounted units feeding into the distribution-level system. In terms of the need to address climate change, and indeed the desire of many to see a more distributed consumer-centric power system emerge, these recent dynamics have been positive. However, realizing a future power system that is much more renewables reliant will require the addition of a wealth of energy storage services. Some of these services may be provided by the traditional storage options like pumped hydro; however, it is certain that new storage resources will be needed, and in many instances this will require the adoption of new technologies, business models, and changes to existing regulation and market design.

During the 2015 MIT Energy Initiative Associate Member Symposium, the opportunities and challenges associated with the large-scale integration of renewables, the evolution towards a more distributed power system, and the associated storage technology and policy needs were discussed and debated. This engagement highlighted the complex and nuanced nature of the subject; however, there was consensus among symposium participants on several key needs, which if addressed would aid in expanding storage service availability. The first of these relates to understanding they types of energy storage services the grid requires. Today, particularly in the context of storage technology development, there is a greater need for power system specialists and storage technology specialists to work together to guide and align the technical and economic development of storage technologies with the needs in the field. It was emphasized that there is no one-size-fits-all storage solution, and so greater stakeholder communication across the storage and power system value chains will result in more effective and efficient storage solutions being developed.

The second salient takeaway from the symposium discussion was that there is an urgent need for the development of thoughtful regulatory and market design frameworks for the expanded range of storage services that technical development is yielding. In particular, the issue of whether storage is categorized as being generation or demand requires clarification as it will have implications for how the technology participates in markets. There is also need for market reform across all timeframes to ensure the technical benefits that storage can provide the grid can be fully compensated by the market. Regulatory frameworks around storage should also subscribe to the principle of cost-causality, so that the manner in which storage assets contribute to system costs is appropriately quantified. This point was

emphasized since today's regulatory regimes often fail to reflect the fact that storage assets often lower overall system costs, and such be compensated rather than charged for delivering these benefits.

The final point on which there was broad consensus regards the use and nature of support mechanisms to aid in the development and deployment of new storage technologies. All agreed on the merits of continuing and indeed expanding public support for basic and applied research focused on developing better performing and more cost efficient technical options. However, in terms of deployment support, it was emphasized that policies that try to pick winners should be avoided entirely, and market based mechanisms should be used to encourage and support the deployment of the optimal techno-economic storage solution for any given application.

Table of Contents

1. Introduction

Demand for advanced stationary energy storage systems grew by 243% (221MW, 161MWh)[1] in 2015--the largest annual deployment on record--and is forecast to grow significantly over the coming years due to these systems' ability to facilitate large-scale grid integration of non-dispatchable renewable energy sources including solar PV and wind. In this report we summarize the discussion that took place among participants in the 2015 MIT Energy Initiative Associate Member Symposium, exploring the roles that advanced stationary energy storage technologies might play in future power systems that will rely on much greater amounts of intermittent renewable energy generation. The document's sections mirror the symposium's content sessions, and report the salient points made by session speakers and audience participants, along with incorporating additional context and information from MITs ongoing research on these topics.

Following on from this introduction, Section 2 discusses the expanding role being played by intermittent renewable energy resources in contemporary power systems, and describes the challenges associated with the efficient integration of these. In particular, the issues of system reliability assurance, and generator ramping requirements are described. The section also describes the suite of options available to meet these challenges. Section 3 describes and categorizes energy storage services in terms of the system needs that they meet, the energy scales involved, the timeframes over which storage must be provided and the reactiveness and deliverability needed. Sections 4 and 5 follow on by describing the technical pathways available to deliver storage services to the grid. The contemporary deployment of grid-level storage by technology type is reported, and qualitative descriptions of the storage technologies that have seen operational are provided. At the end of Section 5 a very detailed quantitative comparison of the technical characteristics of today's grid-level energy storage technology options is provided. Section 6 briefly discusses the issue of how energy storage technologies map to specific grid applications, and provides a graphic that illustrates how today's technologies intersect with these applications in terms of system scale and the capacity for energy and power delivery. Following this, Section 7 describes a range of use cases for energy storage systems, with a focus on how they deliver economic value. Finally, Sections 8 and 9 explore issues relating to regulation, policy making and market design for energy storage, and how a path forward can be developed, which will allow for the realization of the technical and economic benefits that advanced energy storage systems can offer to the grid.

2. The Rise of Renewables and the Evolution of the Grid

The role being played by intermittent renewable resources in the overall US electricity generation mix has grown enormously over the past decade. In 2006 wind and solar combined produced just over 26 TWh, an immaterial contribution considering the system's overall output was over 4000 TWh. By 2015 these same sources were delivering a combined 230 TWh, and although still only 6% of total annualized generation, the intermittent nature of this output means that in many parts of the grid, wind and solar often meet significantly larger proportion of total instantaneous demand. Going forward, there is no doubt that the relative role played by renewables will continue to grow. One example illustrating this consensus can be seen in Figure 1. It shows the set of eight scenarios for non-hydro renewables generation growth between 2015 and 2040 being used by the EIA in their contemporary power system modeling work. It is notable, that every scenario predicts growth, and some predict very significant growth indeed.

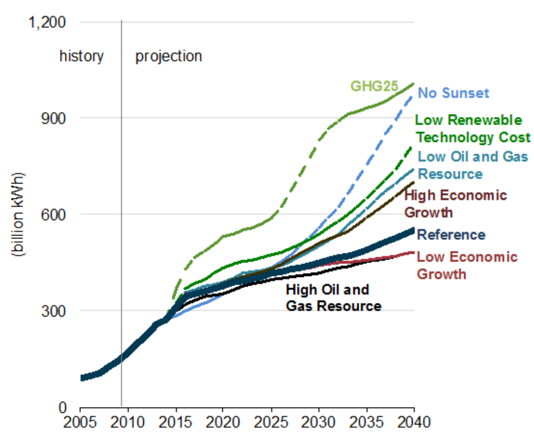

Figure 1: Share of historic and projected electricity generation from renewables in eight cases from 2005-2040 (hydro resources not included). (Source: Chris Namovicz, EIA 2014[2])

Of course, the exact scale of this growth remains to be seen, and accurate prediction of it is exceptionally difficult. Just how quickly things are changing and how difficult these dynamics are to predict is illustrated by Figure 2. The figure show an EIA's assessment of solar and wind capacity growth from late 2013 to 2025. In the figure, the installed solar capacity is shown to increase more than threefold from 7,813MW in 2014 to 25,199MW, while the wind capacity is shown to increase from 60,347MW to 95,373 MW. These represent significant relative capacity additions, particularly in the case of solar. As it happens however, they have already been proved wrong. Actual US solar PV capacity at the end of 2015 has already reached 25GWs. Underestimating the growth of renewables generation capacity is also not just an issue with the EIA. As shown in Figure 3, the IEA have also consistently underestimated renewables adoption. As a result, it is important that any analysis of the future role to be played by renewables--based on the types of projections made by agencies like the EIA and the IEA--is viewed with a healthy degree of skepticism.

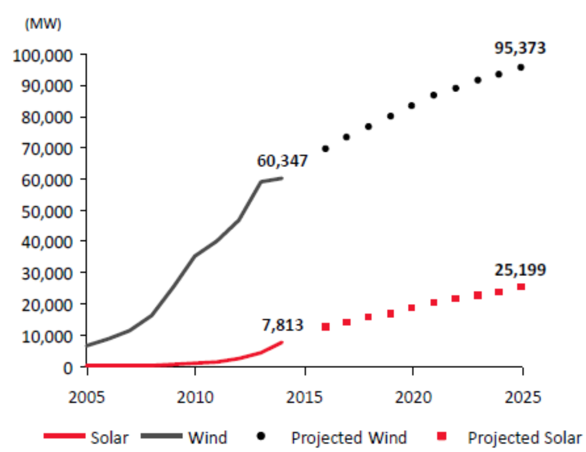

Figure 2: Wind and Solar installed capacity projections in the US (Source: Dan Wishnick-Siemens, EIA 2014[3]).

Irrespective of the precise quantification of new renewables generation additions, the change in the generation mix resulting from the increased deployment of renewables, and particularly solar PV at various system scales indicates an evolutionary trend in the electric grid away from very large centralized generation units to a more fragmented and decentralized mix paradigm, and as a result the management of the electric grid is becoming increasingly complex. The challenges of integrating renewables are beginning to come into sharper relief, both from the technical and market perspectives, and as we move forward there will be a need for enormous new infrastructural investment, which some have suggested could amount to ~$1.5-2 trillion[4]. We discuss these challenges, and pathways to mitigate them in detail in the following sections.

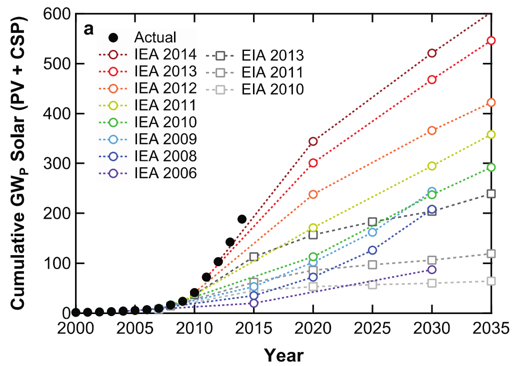

Figure 3: Worldwide cumulative PV and CSP installed capacity projected by the Energy Information Administration (EIA) and the International Energy Agency (IEA) compared to actual data (Source: MITEI Future of Solar Study[5])

2.1 The Challenges of Large-Scale Renewables Integration

Increased levels of generation from intermittent renewable energy sources can yield important challenges for power systems operation and planning. At the most basic level, the fact that generation from wind and solar PV units is not dispatchable means that reserve capacity must be available within the balancing area to ensure supply always meets demand. In systems with low to modest levels of renewables penetration, this can often be a trivial issue; however, as the proportion of instantaneous demand being met by non-dispatchable renewables rises, substantial issues can emerge. First, there is the obvious need for dispatchable backup generation to be available at short notice to ensure system reliability. Many technical options can provide such backup, with hydro and fast acting gas turbine-based generators being obvious examples. However, hydro resources are not universally available, and in all cases there is a cost associated with remunerating backup capacity, which may rarely produce any income from generating power. This is a particularly complex issue for systems operating within RTO/ISO structures, as the market design in place must be robust enough to ensure adequate investment occurs in backup assets.

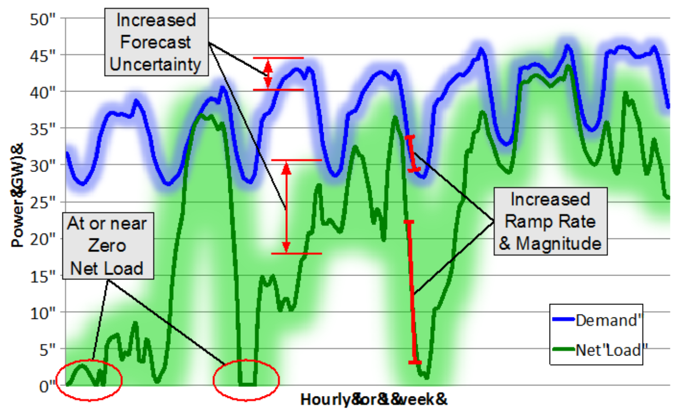

Figure 4: Demand and net load requirements with 40% wind penetration. Times with zero net load as well as steeper ramps are seen. (Source: Palmintier, NREL[6])

Beyond the reliability and reserve issue, very large-scale penetration of renewables also leads to other systemic challenges. First, the fact that output from renewables like wind, and solar PV in particular, vary temporally over the course of the day means that other generators must be capable of "ramping" their outputs at the rate at which the renewables output is rising or falling. An example of just how significant the level of ramping might be is shown in Figure 4, which illustrates an NREL analysis of how the net load (that which must be met by non-renewable sources) could vary over the course of a typical week in the ERCOT system in a situation where 40% of overall average demand was met by wind power. Clearly, this situation requires that very flexible and reactive dispatchable-assets be available to maintain the system in balance. Some systems already have flexible generation assets needed to meet this type of need; however, others do not, particularly those that rely heavily on coal and nuclear units and are not designed to operate across a broad range of generation levels. Substantially increasing the level of renewables such systems can accommodate will require the adoption of new technologies that can provide this enhanced flexibility. We discuss the pathways to address these challenges in the short- and medium-terms in the next section.

2.2 Pathways to address the challenges

By their very nature power systems have some inherent flexibility that allows them to continuously match varying demand with supply. However, as described in the previous section, the increased penetration of intermittent renewable energy resources demands that some power systems add additional operational flexibility.

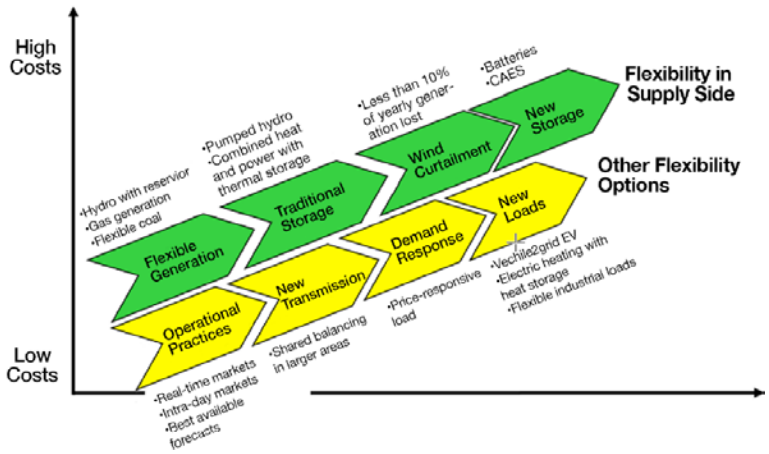

Figure 5: Different methods to increase flexibility in power systems (Botterud ANL, IEA 2013[7])

A number of different pathways are available to provide this increased operational flexibility. Figure 5 illustrates a grouping of these options developed by IEA based on how they integrate into the system and the qualitative ranking of their relative costs Modifications in operational practices tend to be lower cost compared to others approaches since their implementation does not typically require significant additional investment. Examples of such operational practice changes include the development of broader balancing zones within power system interconnections, trading closer to real time, and the expanded use of demand response[8]. Aggregating geographical areas into larger balancing zones can enable a smaller reserve requirement to maintain system reliability as compared to the sum of the reserve requirements needed for a set of smaller zones. Trading closer to real time and intra-day markets helps strike a better balance between the demand and the amount of generation available. Flexibility on the demand side can result from a) price-responsive load, which becomes increasingly attractive with aggregation and b) new forms of load such as increasing penetration of electrified vehicles, flexible industrial loads and from electric heating loads with the ability to store heat energy. On the supply side, the options for delivering system flexibility include a) the addition of generating units with quicker ramp rates like gas-fired turbines and more flexible coal plants b) the expanded use of traditional storage via pumped hydro and from combined heat and power plants c) the active curtailment of variable energy resources such as wind and solar as needed and d) the addition of energy storage assets such as batteries, flywheels etc. Energy storage services and systems are reviewed in detail in the following sections.

3. Energy Storage Services[1]

Energy storage services can be broadly classified in five categories: bulk energy, ancillary, transmission and distribution, renewables integration, and customer energy management. This section provides a list of services that can be provided by storage, their definitions (adapted from the International Energy Agency's *Technology Roadmap: Energy Storage*[9]), and respective performance characteristics (Table 1). In practical usage, a single or several energy storage system technologies may support multiple services.

Bulk energy services provide large-scale and, often, long-duration storage. At the bulk scale, energy storage systems can be used to increase overall grid capacity (seasonal storage), or for price arbitrage, as defined below. Installed capacities are similar to those of natural gas-fired peaking plants.

> *Seasonal storage* refers to longer-term storage of energy, ranging from days to months, for example, thermal energy storage during summer months for use in winter.
>
> *Arbitrage* refers to energy storage during off-peak hours, when electricity prices are low, so that the stored electricity can be sold during peak demand hours for a profit. This may occur within the same energy market or between two separate markets.

Energy storage system assets that provide ancillary services deliver power for short durations, relative to bulk services, but require faster response times (from less than a second to minutes). The following are some of the key ancillary services that energy storage technologies can provide to the grid.

> *Frequency regulation* is the use of storage to dampen the fluctuations caused by momentary differences between power generation and load demand. This is often performed automatically on a minute-to-minute, or shorter, basis.
>
> *Load following*, similar to frequency regulation, is a continuous electricity balancing mechanism that manages system fluctuations. However, in this case, the timeframe of the intervention is longer, ranging from 15 minutes to 24 hours, and is performed either automatically or manually.
>
> *Voltage support* refers to the maintenance of voltage levels in the transmission and distribution system through the injection and absorption of reactive power.
>
> *Black start* capability enables a power station to restart without relying on the transmission network in the event of a wide-area power system collapse.
>
> *Spinning reserve* acts as the reserve capacity (extra-generating capacity) that is on-line and synchronized to the grid with a response time of less than 10 minutes.

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[1] Sections 3-6 have been adapted from Appendix C of 'The Future of Solar Energy' study published by MITEI in 2015.

This reserve is used to maintain system frequency stability during unforeseen load swings or emergency conditions.[10]

Non-spinning reserve is a form of reserve capacity similar to spinning reserve, however, this reserve capacity is off-line, and can be ramped up and synchronized to the grid in less than 10 minutes and maintained for at least 2 hours.[11]

Table 1: Key characteristics of storage systems for selected energy services (adapted from International Energy Agency[9])

Services	Size (MW)	Discharge duration	Cycles (typical)	Response time	Output (electricity '*e*', thermal '*t*')
Bulk energy services					
Seasonal storage	500-2,000	d – mo	1-5 /y	d	e, t
Arbitrage	100-2,000	8-24 h	0.25-1 /d	> 1 h	e
Ancillary services					
Frequency regulation	1-2,000	1-15 min	20-40 /d	1 min	e
Load following	1-2,000	15 min – 1 d	1-29 /d	< 15 min	e, t
Voltage support	1-40	1-60 s	10-100 /d	0.001-1 s	e
Black start	0.1-400	1-4 h	< 1 /y	< 1 h	e
Spinning reserve	10-2,000	15 min – 2 h	0.5-2 /d	< 15 min	e
Non-spinning reserve	10-2,000	15 min – 2 h	0.5-2 /d	> 15 min	e
Transmission and distribution infrastructure services					
Transmission and Distribution T&D investment deferral	1-500	2-5 h	0.75-1.25 /d	> 1 h	e, t
T&D congestion relief	10-500	2-4 h	0.14-1.25 /d	> 1 h	e, t
Renewable and other integration services					
Variable supply resource integration	1-400	1 min – h	0.5-2 /d	< 15 min	e, t
Waste heat utilization	1-10	1-24 h	1-20 /d	< 10 min	t
Combined heat and power	1-5	min – h	1-10 /d	< 15 min	t
Customer energy management services					
Demand shifting and peak reduction	0.001-1	min – h	1-29 /d	< 15 min	e, t
Off-grid	0.001-0.01	3-5 h	0.75-1.5 /d	< 1 h	e, t

Transmission and distribution (T&D) infrastructure services help defer the need for capital-intensive T&D upgrades or investments to relieve temporary congestion in the T&D network.

T&D investment deferral refers to the use of energy storage assets to help defer large investments in the T&D infrastructure by mitigating substation overload for a period of time. Services can also include the permanent removal of overloads due to negative loads that could arise in a PV connected circuit.[12]

T&D congestion relief refers to energy storage assets that temporarily address congestion in the T&D network.

Renewables and other integration services can be used in conjunction with an intermittent renewable energy source (like wind or solar) to address variability, or with other energy sources to improve efficiency.

Variable supply resource integration refers to storage technologies deployed to integrate intermittent electricity generators, such as renewables, into the grid while compensating for the variability in their energy or power output.

Waste heat utilization refers to energy storage resources used to prevent heat energy from being wasted, when the supply (e.g., from thermal power plants) exceeds end-user demand (e.g., building heating/cooling loads).

Combined heat and power (CHP) refers to electricity and thermal energy storage in CHP plants to help bridge demand gaps.

Customer energy management services may be provided by storage systems that tend to have much smaller capacity than those previously mentioned. These systems are generally located at the end of the electricity distribution network.

Demand shifting and peak reduction refers to energy storage technologies or strategies that facilitate shifts in demand at times of peak energy demand to reduce the load level.

Off-grid refers to technologies that help customers not connected to the electricity grid meet electrical demand needs with variable supply (from locally available fossil or renewable energy resources), thereby ensuring a more reliable power supply.

4. Existing Energy Storage System Technologies

Electrical energy can be stored in numerous ways that differ in cost, performance, and technological maturity. Figure 6 shows a number of storage technologies that have either been deployed or are in the demonstration phase, organized by their storage function and as a percentage of U.S. and global electricity generation capacity (expressed in gigawatts or GW). The United States has approximately 240 gigawatt-hours (GWh) of energy storage capacity, which represents about 2.3% of overall U.S. electricity generation capacity. Of this total, most storage capacity in the United States—95%—is provided by pumped hydroelectric (pumped hydro) systems. Compressed air energy storage (CAES), -flywheels, rechargeable batteries, and molten salt-based thermal storage are the other mature storage technologies. Electrochemical capacitors and superconducting magnet energy storage (SMES) are promising technologies in the demonstration or advanced research phase. A brief description of each of the above technologies follows.

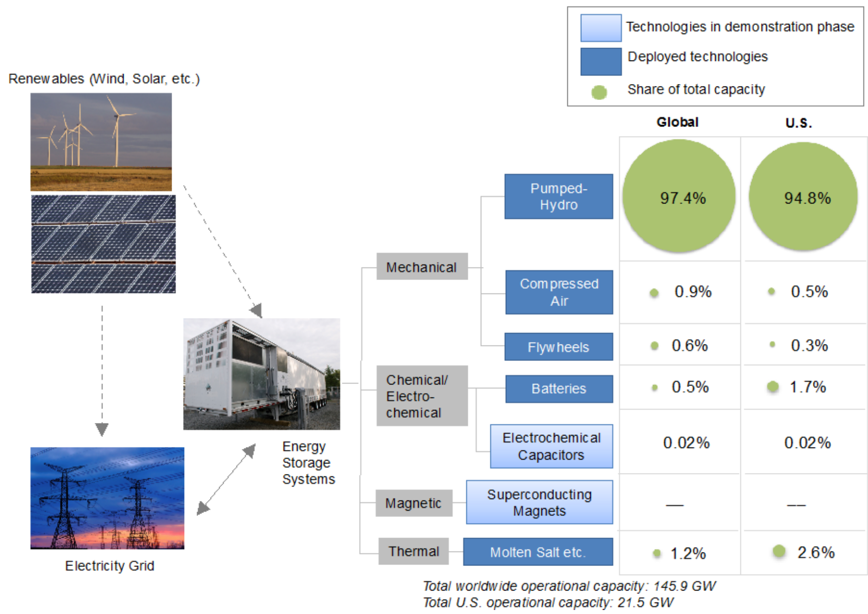


Figure 6: Grid-related energy storage technologies deployed or in the demonstration phase[2] (as of Feb 2016) **Note:** Already deployed technologies are indicated by a dark blue box, while those in the demonstration phase are shown in light blue. The percentage of total storage capacity each energy storage system technology represents is both listed and indicated with a green bubble of corresponding size. The reported percentages were derived from data obtained from the U.S. Department of Energy (DOE) Global Energy Storage Database.[13] Images are from the Creative Commons website.[14,15,16,17]

Pumped Hydroelectric Energy Storage

Pumped hydro systems operate by moving water between two reservoirs at different elevations, thereby converting between electrical, kinetic, and potential energy to store and deliver electricity. To store energy, water is pumped to the higher elevation reservoir, while to recover the stored energy—either at times of higher demand or for economic reasons such as price arbitrage—the water is allowed to flow down through a turbine to generate electricity. Pumped hydro is a mature energy storage technology, with 270 pumped hydroelectric storage stations currently in operation globally that together provide over 120 GW of electricity generating capacity.[18]

[2] Thermal storage technologies include chilled water thermal storage, ice thermal storage, and heat thermal storage. More information on these types of systems can be found in the DOE Energy Storage Database.[13]

Pumped hydro is best suited for bulk power management applications given its ability to operate at high power ratings, with module sizes up to the GW range, and given its ability to provide relatively stable power output for long periods of time, typically tens of hours. In contrast to rechargeable batteries and flywheels, pumped hydro has a relatively slow response time (typically 0.5–15 minutes). However, the introduction of variable speed pumping enables a new level of flexibility that allows pumped hydro to deliver a broader range of services, such as frequency regulation through faster response times.[19] Variable speed is achieved by decoupling the magnetic field of the stator from that of the rotor, unlike a conventional single-speed pump-turbine in which the stator and rotor remain coupled.[20] Pumped hydro, however, suffers from constraints arising from its dependence on suitable geographical settings as well as from constraints related to licensing requirements, environmental regulations, and uncertainty in long-term electric markets.[21]

Compressed Air Storage

Compressed air energy storage (CAES) works by capturing and storing air, typically in vast underground geological formations, when electricity production capacity exceeds demand or when generation is economical. The compressed air is then released via a gas turbine to generate electricity at times of peak demand or to capture the benefits of arbitrage. There are currently two commercially operating CAES systems in the world: a 290 megawatt (MW) plant in Huntorf, Germany, built in 1978, and a 110 MW plant in McIntosh, Alabama that was commissioned in 1991. In both cases, compressed air is stored in excavated salt caverns.[18] Several companies are now working on developing smaller CAES systems that store compressed air in above-ground tanks and employ more efficient compression and conversion technologies to reduce system losses (e.g., isothermal compression).[22,23,24] Others are exploring a broader range of geological formations as storage media for compressed air; porous rock, for example, may provide large-capacity storage opportunities and is also more geographically abundant.[25] Efforts are also being made to develop underwater CAES where the air is first compressed onshore and then stored in subaqueous formations in high-strength polymer/glass bags.[26,27] Like pumped hydro, traditional CAES targets bulk power management applications but also requires specific geographic conditions, which limits location and scalability. When compared to other energy storage system technologies (Table 2), CAES plants often have lower than desirable roundtrip efficiencies (e.g., 27% for the McIntosh plant[28]).

Flywheel Storage

Flywheel energy systems store rotational kinetic energy via a spinning rotor-disk in a vacuum chamber. The rotor speed is increased or decreased to store or deliver electricity. Flywheels can respond in less than a second but are significantly more expensive than other storage technologies described in this appendix. Thus, they are typically deployed for niche applications that require very fast response times and shorter discharge durations. Flywheels are currently commercially deployed primarily for frequency regulation (e.g., Beacon Power's 20 MW flywheel installations for the independent system operators of New York and California, NYISO and CAISO[13]). Given their suitability for shorter discharge-time applications, flywheels currently comprise only about 0.2% of total electricity storage capacity in the United States. Flywheel energy storage systems suffer from high self-discharge rates; these high discharge rates arise from frictional losses that can amount to as much as 100% of the energy stored per day.[29]

Molten Salt Energy Storage

Molten salt energy storage employs high-temperature liquefied salts (450°C – 600°C) to store thermal energy. After heating in parabolic solar troughs, the molten salt is stored in an insulated chamber until electricity is required, at which time the molten salt is used to generate steam to drive a turbine. Molten salt energy storage currently accounts for 2.4% of operational energy storage capacity in the United States, and promises energy storage at much lower cost compared to other technologies. Present research initiatives are focused on further cost reduction through technology improvement, such as the development of capsules for salts that facilitate operation with one storage tank instead of two.[30] Another emerging technology worth mentioning here is pumped heat energy storage (PHES). PHES systems store electricity by first converting it to thermal energy using a heat pump cycle; this thermal energy is later converted back to electricity using a power cycle. The efficiency of such systems depends on the difference between the operating temperatures of the heat pump and power cycles and can be as high as 65%–70%.[31] In some cases, efficiencies as high as 72%–80% have been reported with costs comparable to those of pumped hydro storage.[32]

Batteries

Rechargeable electrochemical cells transform electrical energy into chemical energy (and vice versa) through redox (reduction and oxidation) processes that occur at negative (lower potential) and positive (higher potential) electrodes with a working ion, such as lithium, transferring between the two. Batteries typically consist of several individual cells, arranged in series or in parallel, and can be sized and sited without geographical constraints. Of the technologies discussed in this document, batteries are perhaps the most versatile. Their applications can range from frequency regulation to T&D grid support, though system chemistries and design generally target specific applications.[33] Due to a range of technical and economic challenges, however, battery storage presently comprises only about 0.2% of global grid storage capacity and 0.9% of U.S. capacity. Of the numerous battery chemistries and configurations that have been developed, lithium-ion (Li-ion), sodium sulfur (NaS), and lead-acid batteries are considered mature while technologies such as advanced lead-carbon and flow batteries are still in the demonstration phase.[34]

Lithium-Ion Batteries

Li-ion batteries operate by shuttling lithium ions (Li^+) between the positive and negative electrodes in a "rocking chair" mechanism as the cell is charged and discharged. The positive electrode material is typically a transition metal oxide or phosphate with a layered or tunneled structure on an aluminum foil current collector, while the negative electrode typically consists of graphite or another layered material on a copper foil current collector. The charge and discharge processes involve the insertion and extraction of lithium ions into and out of the atomic layers within the active materials. Near ubiquitous in portable electronics and emerging electric vehicles (EVs), Li-ion batteries have high energy (and power) densities, high roundtrip efficiencies, and rapid response times, which makes them well suited for power management applications for uninterruptible power supply or frequency regulation. Though changing, Li-ion battery deployments have been limited by relatively high system costs, constraints on cycle life, and safety concerns (e.g., flammable electrolytes). The application of new high capacity electrode materials, optimization of electrode coating thicknesses, and improvements in manufacturing capabilities are expected to play a major role in bringing down costs in the future.[35,36,37]

High Temperature Batteries

Molten sodium sulfur (NaS) batteries operate at high temperatures (310°C – 350°C)[38] so as to take advantage of the increased conductivity of the sodium-conducting alumina ceramic that separates to two liquid electrodes: sodium (Na) as the negative electrode and sulfur (S) as the positive electrode. During charge and discharge processes, sodium ions (Na^+) shuttle across the membrane and reversibly alloy with sulfur (Na_2S_5). NaS batteries have high energy densities but limited power capabilities as compared to Li-ion batteries. For this reason they are generally employed for longer duration applications (4–8 hours). While high efficiency and abundant, low-cost active materials make this technology attractive, thermal management, cell and component reliability, and system safety are challenges.[39] Continued research and development (R&D) efforts aim to reduce operating temperature and to employ alternative, less expensive Na^+ conductors. Like NaS batteries, sodium-nickel-chloride batteries (also referred to as ZEBRA batteries) are high-temperature devices that operate around 270°C –350°C.[38] Charging involves the transformation of salt ($NaCl_2$) and nickel (Ni) into nickel chloride ($NiCl_2$) and molten sodium (Na) while discharging reverses the process.

Lead-Acid Batteries

Widely employed for starter-lighter-ignition applications in vehicles, lead-acid batteries employ a lead oxide positive electrode and a lead metal negative electrode in a sulfuric acid electrolyte. During charge and discharge, these electrodes are both reversibly converted to lead sulfate. While relatively inexpensive, due in part to large-scale manufacturing and recycling, traditional lead-acid batteries are hampered by low practical energy density as a result of limited electrode utilization (e.g., 20%–30% for grid energy applications[40]). This shortcoming has prompted efforts to develop lead-acid carbon and advanced lead-acid batteries. Lead-acid carbon batteries replace the bulk lead negative electrode with a high surface area carbon material, which leads to longer lifetimes and higher energy density due to deeper discharge capabilities. Advanced lead-acid batteries are conventional lead-acid batteries that incorporate technological improvements, such as a solid electrolyte-electrode configuration or a capacitive storage negative electrode.[34]

5. Emerging/Pre-commercial Batteries and Other Energy Storage System Technologies

Flow Batteries

Unlike the rechargeable batteries described above, which have enclosed architectures, redox flow batteries store energy in flowable solutions of electroactive species. The solutions are housed in external tanks and pumped to a power-generating electroreactor. This architecture offers several advantages including the ability to decouple power (reactor size) from energy (tank size), a high ratio of active to inactive materials, simplified manufacturing, long service life with full charge/discharge cycles, and improved safety. However, due to their low energy density and integrated design requirements, flow batteries are best suited for MW-scale energy storage with longer duration (greater than 4 hours). First developed in the 1970s, numerous flow battery chemistries have been explored including iron-chromium, bromine-polysulfide, vanadium-polyhalide, and all-vanadium systems. In addition, several hybrid systems have been pursued, where one or both electrode reactions involve a deposition/dissolution process, such as zinc-bromine and soluble lead-acid systems. Though only sporadically investigated for the past 40 years, the renaissance of renewable electricity generators has spurred R&D to lower costs and improve energy density, including efforts to develop high-performance electroreactors, new electrolyte formulations, and new tailored redox molecules.[41]

Aqueous Hybrid Ion Batteries

Aqueous hybrid ion (AHI™) intercalation battery system, invented and manufactured by Aquion Energy, a company that spun out of Carnegie Mellon University in 2010 uses cheap, non-toxic materials: manganese oxide cathode, a cotton separator, a carbon composite anode, and sodium sulfate electrolyte. It is reportedly optimized for discharge durations greater than 4 hours and has high cycle life. They are currently available in 2kWh battery stacks and 25kWh battery modules with a 100% state-of-charge (SoC) window[42]. The company is currently shipping products and current installations include a 1MWh residential project in Kona, Hawaii[43].

Liquid Metal Batteries

Spun out of MIT in 2010, Ambri's liquid metal batteries use liquid components. Their initial chemistry comprised of magnesium and antimony liquid metal layers separated by a liquid electrolyte. During discharge, magnesium ions traverse through the electrolyte to form a Mg-Sb alloy, which is reversed during the charging process. Efficiencies up to 60-89% have been reported[44]. High melting points of both magnesium and antimony required the operating temperature of the cell to be near 700°C. Ambri is in the process of commercializing a newer, undisclosed, chemistry that has a lower operating temperature. A 2014 Nature letter[45] by members of the group proposed a lithium-antimony-lead battery that can operate at a much lower temperature of 450°C. The company is scheduled to deliver 2MWh of batteries for demonstration in 2016.

Hybrid Zn-air Batteries

EOS Storage Technologies have commercialized a version of zinc-anode batteries that uses air as the cathode, which subsequently increases the capacity and energy density of the technology. EOS reports hybrid reactions that increase the cell efficiency to 95%[46], and a roundtrip efficiency of 75% for their Aurora 4MWh units in full depth-of-discharge applications[47]. Currently undergoing demonstration, EOS recently partnered with NEC Energy Solutions to develop next generation energy storage solutions[48].

In addition to these technologies, other battery chemistries, including lithium-sulfur and semi-solid flow are at various stages of development and may eventually provide lower-cost alternatives to existing technologies.

Electrochemical Capacitors

Electrochemical capacitors (also referred to as supercapacitors) store charge in the electrical double layers present between two porous, high-surface-area electrodes and a common electrolyte rather than through the faradaic redox reactions common to batteries. In general, this leads to higher roundtrip efficiencies, fewer parasitic side reactions, and faster response times but these benefits come at the expense of energy density. Thus, electrochemical capacitors demonstrate higher power densities, longer useful lifetimes, and lower energy densities as compared to rechargeable batteries. Present electrochemical capacitor technologies generally target high-power, short-duration applications such as frequency regulation. If longer discharge times are required, these technologies generally become cost-prohibitive. Ongoing research efforts to develop pseudo-capacitors that combine faradaic and non-faradaic storage mechanisms as well as flow-based cell architectures may eventually serve to enhance energy density.[49,50]

Superconducting Magnet Energy Storage

Though still in the demonstration phase, superconducting magnetic energy storage (SMES) offers high roundtrip efficiencies in addition to providing long cycle life and high power density. SMES systems consist of a superconducting coil, a power conditioning system, and a refrigeration unit. Electrical energy is stored inductively in a solenoid in the form of magnetic energy. Cryogenic temperatures (less than 4.2 Kelvin when liquid helium is used) must be maintained to facilitate the flow of electric current with minimal resistance. Low energy density and high manufacturing cost make this technology more suited to supplying short bursts of electricity in applications like uninterruptible power supply.

6. Mapping Energy Storage Systems to Applications

The particular attributes of each energy storage system technology, described in the preceding section, make each technology suited to provide certain services that address particular application needs. Relevant considerations include charge and discharge durations, specific power and specific energy characteristics, response time, lifetime and, roundtrip efficiency. Table 2 summarizes the key attributes of various energy storage system technologies, as well as their technological maturity level. Attributes such as discharge duration, power capability, and response time, as well as system cost, tend to drive market share and installed capacity of these technologies. Other than pumped hydro, which is attractive due to its relative low cost and bulk-storage attributes, and which currently represents over 97% of worldwide energy storage capacity (Figure 6), most of the energy storage system technologies included in Table 2 have economics that are currently too costly to enable *widespread* deployment. Figure 7 maps the energy storage system technologies to the types of services they can provide based on the performance attributes summarized in Table 2. These applications can be divided into three broad segments according to their associated discharge time and system power requirements: ancillary/customer energy management, T&D infrastructure/renewable integration, and bulk energy services.

Table 2: Comparison of existing energy storage system technology attributes and associated deployment constraints and challenges

	Pumped Hydro	CAES	Flywheels	Batteries: NaS	Batteries: Li-ion	Batteries: Lead-acid	Batteries: Flow	Batteries: Sodium-nickel-chloride (ZEBRA)	Super-conducting Magnets	Electro-chemical Capacitors	Molten Salt
Capital Cost ($/kWh)	200-300	100-200	1,800-3,000+	450-1,750	400-1,750	550-2,550	300-1,600	500-1,500	-	-	-
Primary Applications	Bulk, Anc.	Bulk, Ren. Int., Anc.	Anc.	T&D, Ren. Int., Anc.	T&D, Ren. Int., Anc.	T&D, Ren. Int., CEMS	T&D, Ren. Int., Anc.	T&D, Ren. Int., Anc.	Anc.	Anc.	Ren. Int.
Response time	s-min	s-min	< s	< s	< s	< s	s	< s	< s	< s	min
Lifetime (y)	50-60	25-40	~20	15-20	5-15	~15	5-20	10-14	20+	4-12	~30
Cycles	20k-50k	5k-20k	> 100k	2.5k-4.5k	1k-10k+	2.2k-4.5k	> 10k	> 2,000	100k+	100k+	-
Maturity	Deployed	Deployed	Deployed	Deployed	Deployed	Deployed	Demo	Deployed	Demo	Demo	Deployed
Roundtrip Efficiency (%)	75-85	27-54	70-80	85-90	75-90	75-90	60-75	85-90	70-80	85-98	65-80
Capacity (MWh)	1,680-14,000	1,080-3,600	0.0005-0.025	≤ 204	0.25-25	0.25-500	0.01-250	0.01-10s	-	-	-
Discharge duration	6-10 h	8-26 h	s	~6 h	0.25-1 h	0.25-10 h	2-5 h	h	s	ms-min	h
Power (MW)	280-4k	3-400	0.002-20	0.5-50	1-100	0.01-100	0.03-50	0.005-10s	0.1-10	0.001-1	~150
Key challenges	Geog. limits	Geog. limits	Cost	High operating temp.	Cost	Environ. impacts	Energy density	High operating temp.	Cost	Cost	Suitable only with CSP

Note: The data presented in the table are taken from various sources.[51,22,28,29,52,53,54,55,56] Boxes for some of the attributes have been shaded to help the reader distinguish between values. Darker shades of green indicate increasingly desirable properties, red shading indicates undesirable properties, and gray shading indicates that no information is available. Capacities, discharge durations, and power represent typical ranges of installations. CAES capacities include underground as well as aboveground air storage. Flywheel capacities include planned flywheels. The upper limit given for NaS battery capacity (204 MWh) is based on the Rokkasho wind project in Japan. Primary applications for the different storage technologies are labeled Ren. Int. for renewable integration, Anc. for ancillary services, T&D for transmission and distribution services, and CEMS for customer energy management services.

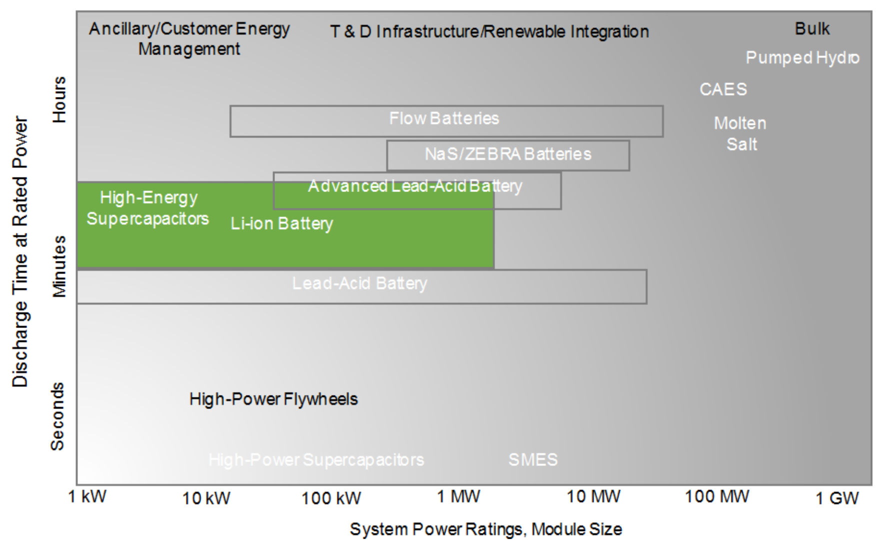


Figure 7: Existing energy storage system technologies and associated applications

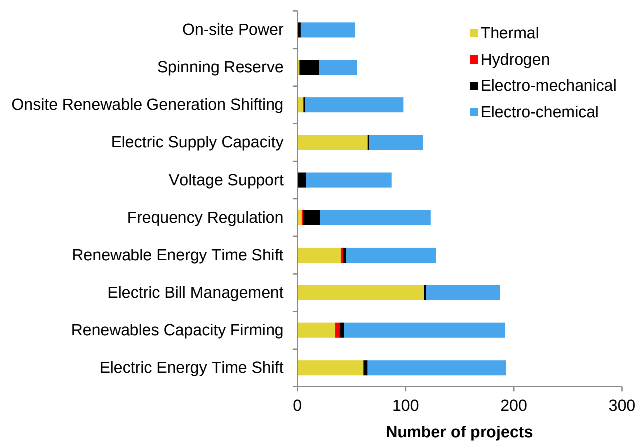
Note: Applications have been divided roughly for purposes of general comparison into three categories: ancillary/customer energy management services, T&D infrastructure/renewable integration, and bulk energy services. The technologies have been shaded based on capital cost information from Table 2. *Source:* Adapted from original figure in Sandia National Laboratory report.[57]

7. Economics and Current Business Models

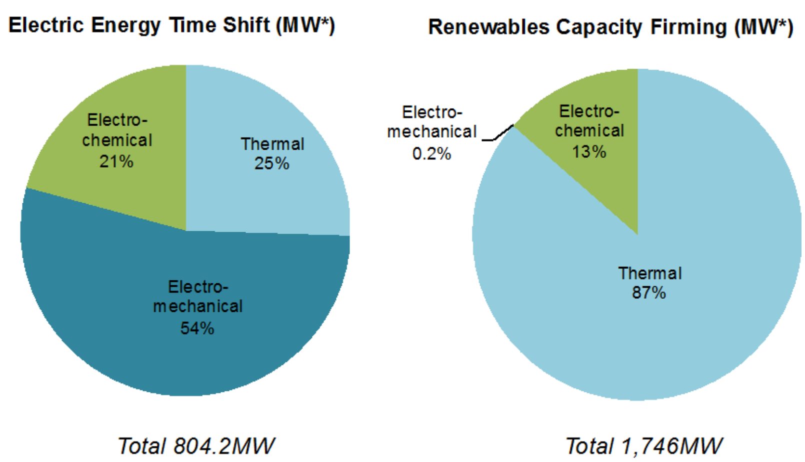
Recent technical progress in energy storage system options, coupled with the growing need to integrate renewable energy and better utilize power system assets is leading to a range of new value creation opportunities for energy storage. One area of current focus is the use of storage for line loss and congestion mitigation, issues that can result in very significant costs for system operators. As an example, the projected cost of congestion at PJM's top-10 most congested nodes alone in 2019 will amount to around $271M.[58] By deploying battery-based systems, PJM may be able to reduce these losses in a much more economically efficient manner than would be possible if they chose other approaches such as building new lines. Energy storage may also be able to help improve system asset utilization. For example, in systems like that of New England where 50% of the peaking power combustion turbines have a capacity factor of less than 2%[59] batteries may be able to substantially reduce the investment necessary in rarely dispatched generating units. Additionally, energy storage systems can provide a host of other services that are of economic value as described in Section 3. It is no surprise then that the estimates for the size of the global energy storage market are optimistic: ~$114B worldwide with $25B in the US alone by 2017 (Lux Research), $35B worldwide by 2022 (Navigant Research), and €281B by 2030 (Boston Consulting Group)[60]. The Electric Power Research Institute (EPRI) estimates an annual revenue potential of ~$143,000 per year from 1MWh of energy storage in the CAISO market[61].

Today, as Figure 8 shows, the majority of advanced energy storage projects in operation in the US are for time-shifting and renewable energy integration applications. However, the actual capacity of the projects for renewable energy applications, at 1,746MW is more than twice the capacity of those for time shifting applications at 804MW[62]. The majority of projects use electrochemical energy technologies (Figure 8a); however, capacity-wise, electromechanical and thermal storage installations are higher (Figure 8b). Electromechanical and thermal energy storage projects are usually centralized given their larger capacities as compared to the more distributed nature of electrochemical storage installations.

When it comes to current business models (Figure 9), apart from non-electricity services for software and technology developers, three major service provider types seem to be emerging: i) those that offer **network-services** such as firm capacity, operating reserves and network constraint mitigation for DSO, ISO and industrial customers ii) those that offer **end-user and system co-optimization** services such as firm capacity, operating reserves and network constraint mitigation for residential, commercial, institutional, and municipal customers together with the ISO or the DSO and iii) those that provide **end-user optimization** services such as firm capacity for residential, commercial, institutional, industrial and municipal customers[63]. These business models are expected to evolve in the near future with more effective regulations and pricing signals as discussed in Section 8.



(a)



(b)

Figure 8: (a) Top-10 use cases for energy storage projects in operation in the US, and **(b)** Capacity breakdown of the installations by energy storage technology type for the top two use cases: electric energy time shift, and renewables capacity firming. *(*Projects have multiple use cases*). Pumped Hydro storage not included. (Source: DOE Energy Storage Database)

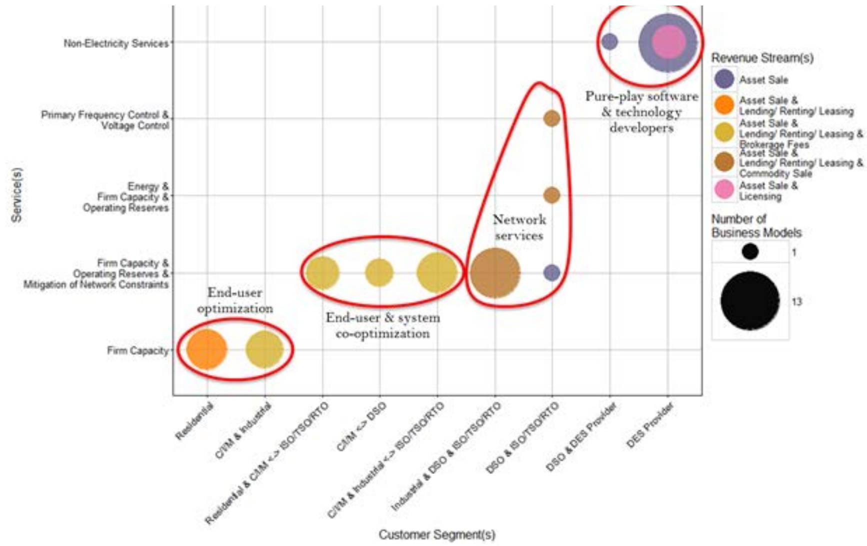


Figure 9: Taxonomy of electrical and thermal storage business models (Burger and Luke, working paper)

As more work is taking place to assess the potential value that advanced energy storage systems can deliver, the value potential of distributed storage systems is receiving particular attention. Recent analysis looking at distributed storage deployment carried out for OnCor highlighted significant value streams from storage deployment on a system-wide societal perspective (Figure 10)[65]. The analysis assumed an installed cost of $350 per kWh for electrochemical energy storage systems and indicated that up to 15GWh of grid-integrated energy storage could be cost-effective for the state in the ERCOT system[66]. Customer-level benefits in the form of lower electricity bills and improved reliability were reported to exceed costs. However, the study also highlighted that single merchant developers, relying solely on wholesale market prices for electricity, miss out on capturing 30-40% of the system wide benefits of storage systems that result from reliability, transmission, and distribution functions. Regulatory mechanisms that allow for storage unit operators to capture all the monetizable value streams of energy storage systems, be it from the wholesale market or from the T&D systems, are required.

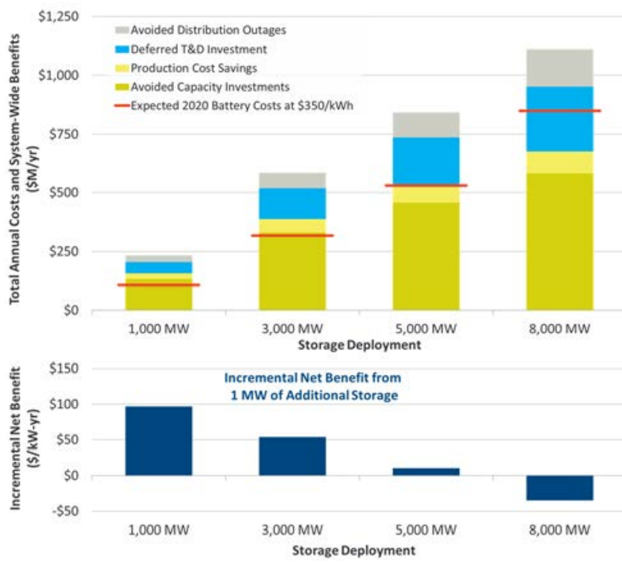


Figure 10: Total benefits and costs of distributed energy storage systems exceed expected storage costs in 2020 (Source: Pfeiffenberger, Brattle Group[67])

8. Regulation, Policy and Market Design

Throughout the symposium, participants emphasized the fact that energy storage assets can deliver several value streams to power systems, but that capturing all of that value is complex and highly sensitive to regulation and market designs. Three aspects of regulation, policy-making and market design were highlighted as key issues be addressed[68]: i) the definition of storage and whether it should be categorized as a generation or demand asset, ii) designing the market for all timeframes: long-term capacity, day-ahead, and ancillary services, iii) grid-tariffs based on the principle of cost causality. These issues are discussed below.

Energy storage assets provide a host of different services given their ability to supply electricity while discharging, thereby acting as *generation*, and as *demand* by consuming electricity while charging. Hence, storage does not clearly fall into the category of either *generation* or *demand*. Restructuring of the electricity market and its unbundling requires that network companies do not own generation assets. As such, defining storage, as a *generation* or *demand* asset is critical to which agents can own and operate them and the different business models that will allow it to be fully compensated for the range of services it is capable of providing. In the light of such confusion, there have been calls to categorize storage as a separate asset, but such a measure may not lead to a complete solution as indicated by FERC Order

784. Defining storage in such a manner that allows it to competitively participate in the market, based on price signals, for the different services it provides seems to be one way to getting to the heart of this issue.

When it comes to the design of markets, reforms are needed at all timescales to increase the efficiency of a grid that is evolving as more distributed resources become part of it. In the longer-term, for capacity markets, the duration thresholds for which generators need to be able to produce and provide electricity needs to be revisited for storage since most storage technologies are limited in their ability to operate for longer durations, which also is a function of their state-of-charge. For day-ahead markets, the ability to economically schedule storage assets based on their states of charge and cycle life and allowing bid revisions is something that can increase the efficiency of an evolving grid. In the shorter-term ancillary services markets FERC orders 755 and 784 removed barriers that impeded storage from participating as well as allowed for payments for performance reflecting the accuracy and speed of response.

In the case of grid charges, the principle of cost-causality and how a storage asset contributes to the cost drivers of the network should be used to assess the appropriate charges. At present, in some systems, energy storage assets pay grid-charges both while charging and discharging. However, that is almost certainly not an efficient allocation of the costs since, in most cases, energy storage helps reduce rather than add to congestion-related problems. A more-efficient grid-tariff design would be based on the actual usage profile of the user.

9. Path forward

As can be seen from the materials and discussion summarized in this document, the symposium successfully explored a very broad range of complex issues that are relevant to the growing role that energy storage plays in contemporary power systems, and how that might evolve over the coming years and decades. From the many messages articulated during the event a few salient points emerged that are worth considering as the path forward for storage is mapped out. The first of these relates to the technologies themselves and how their potential is exploited. Participants made clear that there is urgent need for greater communication between those developing storage technologies, those charged with deploying them on the grid, and those whose role it is to develop the regulation and policy frameworks within which this deployment will take place. Power systems engineers need to better articulate the types of services they would like from storage assets, and storage technology developers must do a better job at matching technologies to applications, and at making clear what their systems can and cannot practically achieve.

Regarding regulation, policy and markets, the symposium participants were unanimous in their belief that a great deal of work remains to be done before we can claim to have a set of fit-for-purpose regulations and market structures that ensure the potential storage can offer is fully realizable. Participants pointed out that the core question of what is it we trying to achieve with the deployment of storage has also not yet been fully answered. Certainly, it is clear that we ought to be looking to use these technologies to improve the technical and economic efficiency of the grid, and that regulation and markets should support that goal. Where things get a little more opaque is with regards to the role storage plays in emissions mitigation. Participants all acknowledged the crucial role storage technologies can play in integrating more renewable generation. However, there was a broad consensus that picking storage technologies as winners through direct focused deployment support was unwise and that a much more effective approach would involve internalizing the cost of emissions into the cost of power and then allowing a technology-agnostic market decide the optimal outcome in terms of the generation technology and storage technology mixes.

The symposium participants acknowledged that the likelihood of a universal regulatory paradigm that fully internalizing the cost of emissions from the US power system was very low indeed and so acknowledged the need for thoughtful development and deployment support for storage. It was highlighted that support in the form of incentives is needed when an industry is in its nascency as has been seen in the case of solar and wind. To that end, the participants highlighted that support policies should correctly differentiate between the public or private nature of the technology benefits and should not result in rent transfers, something that has occurred in the case of solar's support mechanisms. Currently, energy storage systems are profitably participating in the ancillary services markets, but the size of this is small Given that, symposium participants emphasized that if storage is to play the larger role it could in the broader power market, the appropriate definition of storage along with the design of market mechanisms and grid-tariffs, as discussed in Section 8, will be crucial.

As a final note, it was highlighted by several participants that if the market for energy storage technologies does take off as expected, countries that are late in joining the party will likely lose out.

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