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Energy Storage

Opportunities and Challenges

A West Coast Perspective White Paper –

Energy Storage Opportunities and Challenges

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Performed by Ecofys under contract to EDF Renewable Energy with feedback from Advisory Panel members.

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Executive Summary

Judging solely from the number of published reports, interest in energy storage has exploded in the last few years. The new interest appears to stem from the rapid development of variable renewable energy resources, and the perceived need for storage to accommodate the variable nature of these new resources. The need for balancing services, rapid generation ramping, and moving energy from times of excess to times of high demand are expected to increase with high levels of wind and solar energy penetration—exactly the types of services that energy storage can provide. Although some energy storage technologies are mature and ready to serve, many other storage technologies span the range of development maturity with rapid improvements in many technologies underway.

Historically, the economic argument for energy storage technologies hinged on moving energy from low price (e.g., nighttime and weekends) hours to high price (e.g. daytime) hours. In recent years, wholesale market prices have not supported development of energy storage based on the simple arbitrage calculation. Energy storage brings with it a host of other potential value streams:

- Flexible Capacity.
- Ancillary Services (a growing number of them).
- Power Quality, including back-up power.
- Non-wires solutions to transmission and distribution system congestion.
- Emissions Reductions.

Utilities and regulators desiring to compare the economics of energy storage with traditional generators face some special challenges:

- Storage acts as both generation and load.
- Generation is limited by the available energy in storage.
- Value proposition can span across generation, transmission, and distribution systems ("value stacking").
- Limited commercialization of many of the technologies.
- Value proposition includes sub-hourly benefits that may not be captured with standard power system models or methods.
- Lack of standardized and interoperability of communications and controls with existing utility control and communications systems.

The valuation complexities, and the difficulty of the resources realizing their full value through current markets and prices call out for policy intervention. Policies supporting energy storage are being implemented or considered at both federal and state levels. These policies are important for the continued development of energy storage that has seriously lagged behind growth in variable renewable generation. As with any policy intervention, extreme care must be taken to minimize the potential for disadvantaging what would otherwise be least cost solutions.

Many of the services provided by energy storage are available through other means, including: improved markets (bigger, faster, more liquid); demand management programs; more flexible and efficient conventional generation; and smarter controls on renewable resources. Energy storage must compete with these alternatives, but may be the most economical alternative in many situations.

For example, energy storage can provide an economic alternative for relieving transmission congestion in regions where air emissions will not allow conventional generation and transmission expansion is problematic. Energy storage can also make existing utility generation portfolios more efficient by allowing them to run at higher and more constant levels. Another key advantage is that storage provides flexibility while storing. Flexible conventional power plants tend to be displaced as the level of renewable generation increases due to market price pressure. System flexibility from conventional generation drops just as it is most needed—during high renewable generation levels. Energy storage facilities provide flexibility services in both storage and generation modes, preserving the available flexibility when flexible thermal generation would otherwise be economically displaced.

This paper reaches the following conclusions:

1. Complexities in calculating and realizing the value of energy storage provides multiple system benefits that are often not fully quantified, at least partly because of the complexity involved.
2. Energy storage includes both mature technologies and technologies that appear to have much development potential.
3. Energy storage deserves to be evaluated on a par with other resources and integrated into utility resource plans.
4. Barriers to energy storage development suggest policy intervention is merited to promote competition among projects and technologies, and promote market design improvements to more fully reflect the value of flexibility services.
5. Standardized integration with utility system energy management systems may be lagging and merits development.

Today, generation rises and falls to meet demand by tapping existing energy storage available in hydro reservoirs, natural gas production and storage fields, gas pipelines, and coal piles. As reliance on variable generation grows, so will the need for balancing services and opportunities for storage during times of oversupply. Policies supportive of energy storage are providing support for the rapid development of a wide range of promising storage technologies in the development phase.

Longer term, reaching very high levels of variable renewable energy penetration may hinge on being able to store very large quantities of energy (e.g., hundreds of GWh) over periods of weeks or months. Recent utility-scale chemical and thermal energy storage technologies appear to demonstrate the technical feasibility of such applications.

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1 Introduction

Electric generation from variable generation is growing at very high rates in the United States. The increases are largely driven by a combination of effects that include falling prices for wind and solar generation, increasing concern over burning fossil fuels, and government policies. Chief among the latter are state renewable energy standards that require minimum fractions of utility generation derived from new renewable resources.

Power system operators are accustomed to maintaining system reliability against the historical challenges of uncertain and varying demand, along with both planned and unplanned outages. Increasing dependence on variable renewable energy resources provide additional challenges that are raising concerns over the potential need for additional flexibility and optionality in power systems. Among the sources of flexibility and optionality is a wide range of energy storage technologies.

The purpose of this paper is to provide a concise source for information on the value of energy storage technologies and techniques analysts use to quantify that value. As utilities begin considering flexibility in their resource planning processes, it is increasingly important to more fully represent the full value of energy storage technologies. The number of relevant reports and papers on energy storage seems to be growing exponentially, and it is hoped that this report will provide a summary and guide to that information.

Modern power systems could not exist without the many forms of energy storage that are already employed. Because electric power is consumed the instant it is produced, the generation of electricity is normally carefully timed so that it occurs at the same time it is demanded. Storage usually occurs at the fuel level—for example, storing water behind dams, natural gas in fields and pipelines, and in coal piles. When demand goes up, fuel comes out of storage so that electric power can be created when needed.

Getting significant portions of electric power from variable renewable generation has increased pressure on the existing storage capability. A new phenomenon is being increasingly experienced as well—the creation of energy in excess of demand at times. There are two options when that occurs[1], either the energy must be wasted or demand increased. One way of increasing demand is to go to end use devices directly, turning on devices such as chillers or electric heaters. There is storage inherent in some existing energy consuming devices. For example, buildings are natural thermal energy storage devices and it is possible to adjust the timing of energy stored in them as a kind of thermal battery for the grid.

Electrical energy storage technologies are designed to absorb electrical energy (act like increased demand) directly and release it as electrical energy (act like a generator) at a later time. It is these dedicated energy storage devices that are the topic of this paper. There are numerous such technologies-- some well advanced in their development, others at the beginning. Although batteries are Perhaps the most familiar storage technology, pumped storage has been the technology of choice for grid energy storage and has been around since the advent of hydropower generation in the early part of the last century[2]. Although batteries have been around even longer than pumped storage, costs have generally been prohibitive for utility scale energy storage applications but much progress is possible with new types of batteries showing much promise.

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[1] It is possible to do nothing, but as generation increases beyond demand, at some point the safety and reliability of the power system are put at risk.

[2] The first pumped storage device was the Connecticut Light & Power Rocky River Plant in 1929. See 2013 Electricity Storage Handbook, Sandia National Laboratories.

Despite the increasing need for energy storage and the substantial progress that has been made, utility-scale development of new electric energy storage technologies has not kept pace with the advent of variable renewable generation. Wind and solar nameplate capacity additions totaled nearly 16,500 MW in 2012[3], but energy storage additions amounted to just 125.8 megawatts of nameplate generating capability and 935 MWh of storage capacity[4].

The complex interplay between the power system, market structures, and generally low wholesale market prices has complicated the fair valuation of energy storage. Historically, the economics of electric energy storage that justified the construction of the nation's fleet of pumped storage facilities hinged on the wholesale electric market price spread between nighttime and daytime. Value was determined on the basis of the cost of the energy purchased for storage at night and the value received from selling the energy back during the day. However, with low-priced natural gas and an influx of zero (or negative) variable cost renewable generation wholesale market prices are no longer high enough to make an economic case for energy storage based on diurnal price spreads. It is expected that this value will rise again as variable renewable resource penetration increases and zero- or negative market price ("oversupply") events increase along with it.

Short-term market prices are not the only basis on which resource addition decisions are made. In fairness, today's wholesale market prices generally don't make a case for generation additions at all. New generation is being added for other reasons—to meet renewable energy requirements or ensure system adequacy and reliability. A more complex valuation of energy storage is clearly merited. The value analysis of energy storage is complicated by the fact that it acts as both generation and demand and can provide multiple value streams at one time.

Energy storage brings with it a number of unique values. For example, there are no direct emissions associated with the operation of most storage technologies. Some devices can supply on-peak power, effectively converting variable renewable energy into peaking capability without adding emissions to the system[5]. Modern power conversion electronics allow the devices to provide fast acting reserves that can have relatively high value when compared to generation technologies. A storage device with 50 MW of generating capability may be able to provide bi-directional reserves equivalent to 100 MW from a conventional generator.

The value of energy storage, combined with the challenges in realizing that value because of development risk and regulatory hurdles, suggest the need for policies to encourage energy storage development. Policy development is underway in a number of places:

- The Federal Energy Regulatory Commission (FERC) has been working to encourage ancillary service market reforms such as requiring pay for performance and recently approving a frequency response obligation for balancing authorities.

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[3] US DOE, 2012 Renewable Energy Data Book, NREL, October 2013.

[4] Source: DOE Energy Storage Database-- http://www.energystorageexchange.org/. Total does not include thermal demand management storage.

[5] Some studies show small increases in carbon emissions at lower levels of renewable penetration, as energy storage provides additional demand for high-carbon production (i.e., coal) plants during low demand periods when they would otherwise be displaced. However, the studies of high penetration renewables (roughly 30% or more) show lower levels of emissions overall as renewable energy that would otherwise be curtailed due to lack of demand makes up for the effect on high carbon plants.

- The California Public Utilities Commission mandated procurement of up to 1,325 MW of cost-effective energy storage.
- The Puerto Rican Power Authority recently established a minimum requirement for energy storage in solar energy developments[6].

All these issues are explored below, and it is hoped that the exploration helps analysts, planners, decision makers, regulators and policy developers considering the intriguing opportunities energy storage has to offer.

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6 See listing of current policy efforts at: http://www.energystorageexchange.org/policies

2 Energy Storage Attributes

At the most basic level electric power generators convert non-electrical energy sources (fuels) into electric energy that is delivered to the power grid. The reality, however, is more complex. Generators have many attributes that affect their relative contribution to meeting needs in complex power systems. Important attributes of traditional generators include:

- Maximum output ratings.
- Capital, fuel, and operations and maintenance costs.
- Ability to operate at different levels and rate of change in output (controlled or otherwise)
- Outage rates.
- Energy conversion efficiency (e.g., heat rate) at different output levels.
- Environmental effects.
- Inertia, or rotating mass

Power systems typically employ from several to several hundred individual power generators, each of which provides its own set of attributes that are woven together to provide power on a reliable and economic basis.

Energy storage devices have many of the same attributes of conventional generations and some others that can make valuation more complex. Most prominent among the unique attributes is that energy storage devices act both as electrical generation and load on the system. Unlike many other generating technologies (hydro being the main exception), generation from energy storage devices is energy-limited—maximum output can be maintained for a limited period based on the amount of energy previously stored. Some technologies may have cycling limits as well.

Against some of the challenging aspects, energy storage's ability to act as a load at times brings with it important benefits—environmental, economic, and operational that can make energy storage a desirable or vital component of an energy system.

Important attributes especially relevant to energy storage devices include:

- Power Rating storage and discharge rates (e.g., MW)
- Energy Storage Capacity (e.g., MWh)
- Efficiency
- Ramp Rate
- Performance degradation with time or use
- Capital Costs and utilization rates (i.e. efficient use of capital)
- Physical size (storage medium energy density)
- Operation and Maintenance Costs
- Emissions
- Cycling Limits

These attributes are important in characterizing energy storage technologies. For example, the usefulness of a technology that can reach its maximum storage and discharge ratings quickly, but has a storage capability only of a few minutes may be suited to providing fast-acting regulating reserves, but not for moving energy from one season to another. In other words, the suitability of a technology varies depending on the task to which it is put.

2.1 Attributes and Services

Conventional power generating equipment has a number of operating characteristics that are important in distinguishing among them, and choosing the best technology for a particular need. For example, relatively low capital cost, but high operating cost resources are more suited to meeting short periods of peak demand or responding to contingencies. Conversely, higher capital cost resources with low operating costs tend to be more suited to continuous use—selling power around the clock to recoup the large investment.

Similarly, energy storage technologies have various attributes that are importantly tied to the services they are best suited to provide. Energy storage has a cost per installed kilowatt of generating capability as do generators. However, energy storage also acts as a load and the maximum power level going into the storage system can be different from the maximum rated generating power.

An important distinguishing attribute of energy storage technologies is the cost per unit of energy storage (kWh). Technologies with relatively high per-unit storage costs tend to be best suited to provide shorter time period services such as frequency control. Many such technologies are specifically optimized to provide such services. At the other end of the spectrum are technologies with relatively low costs per kWh of storage. Relatively low energy storage costs enables moving large amounts of energy through hours, days, or longer.

Figure 2.1 shows a range of technologies and rough ranges of applicability. Power and energy ratings are not fixtures of the technologies, but more an indication of their current state of development and relative energy and power costs. The vertical extent of each colored parallelogram represents the range of power levels to which a specific technology has typically been applied. The horizontal extent shows the range of energy storage levels to which the technologies have been applied. Generally, lower storage cost (i.e., cost per kWh) show up on the right side of the chart, higher cost technologies on the left. Technologies with low costs on a power basis (i.e., cost per kW) show up nearer the bottom of the chart.

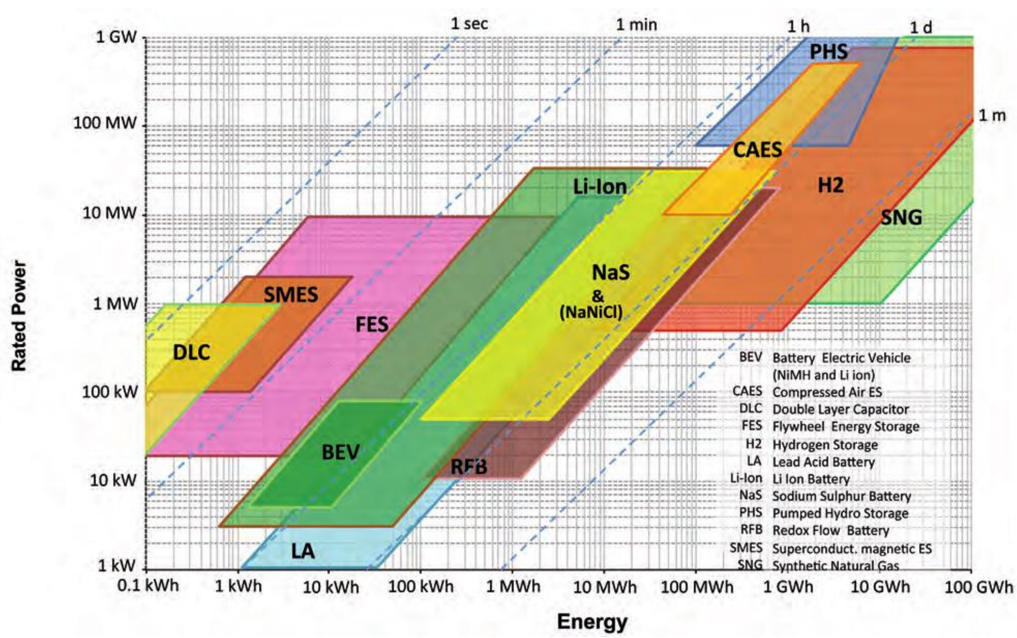

Figure 2.1: Comparison of storage technologies with respect to power and energy storage duration (Source: IEC Electrical Storage Whitepaper).

Other important attributes are shared with conventional generation, such as speed of response, black start capability[7], reactive support, etc. These attributes are important as well, depending on specific needs for which a particular storage device is being considered. For example, reactive support may be important in power quality applications in specific locations where other attributes of storage may also be of value (e.g., low emissions).

The relative attributes of technologies suggest services to which they may be best suited. Figure 2.2 shows one sorting of technologies and services. Applications for storage are shown on the left side of the figure, characterized by the storage capability (in minutes of discharge at maximum rated power), and maximum rated power. The right side shows technologies on a similar basis to visualize matching technologies to specific applications.

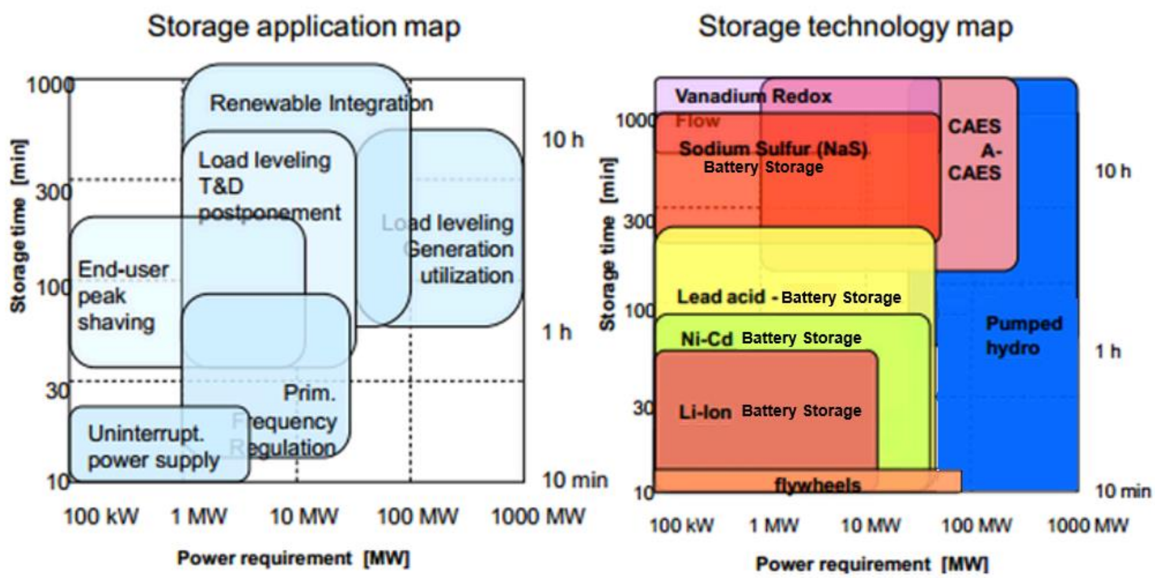

Figure 2.2: Mapping of energy storage attributes and suitability to various services. (Adapted from Utility Scale Energy Storage Systems, State Utility Forecasting Group, June 2013)

Important distinguishing attributes to consider in technology choice for potential energy storage applications include:

- Cost on both power and energy bases
- Response time
- Discharge duration
- Depth of discharge and frequency of discharge
- Efficiency
- Operating ranges and characteristics (e.g., minimum generation levels, efficiency at different levels of operation).
- Performance degradation over time and use

[7] Black start capability is the ability of a generator to begin operation without station service. This can be important for recovering from, or operating through power system outages.

- Environmental footprint
- Reactive Support

Other attributes are important in distinguishing energy storage from conventional power plants as well. For example, some of the technologies have very rapid response times and short discharge periods, which can be beneficial in power system stability applications. Foremost among the differences is that energy storage technologies have little to no local emissions associated with them, which can be extremely beneficial in transmission congestion applications where generation needs to occur in sensitive urban air sheds. To receive similar flexibility from traditional fossil fuel generation would require them to run inefficiently creating greater combustion emissions than normal.

3 Brief Survey of Energy Storage Technologies

This section provides a brief overview of various energy storage technologies, including general descriptions of the technology, costs, and technological maturity. Unless otherwise noted, the tables in this section rely on *Utility Scale Energy Storage Systems: Benefits, Applications, and Technologies*, by the State Utility Forecasting Group, June 2013. Cost figures are expressed in 2010 dollars. This is not the only source for this information, but it is an internally consistent source covering a broad range of technologies.

The broadest definition of energy storage includes any system for absorbing energy in some form at one time and releasing at a later time. The focus of this paper is on electric energy storage devices in which electrical energy is absorbed at one time and released at some later time under control of an operator. Most such technologies convert electrical energy into another form for storage. Storage technologies can be grouped by the similarities of the interim storage medium. Figure 3.1 shows such a classification scheme. The technologies discussed in this section are grouped according that scheme.

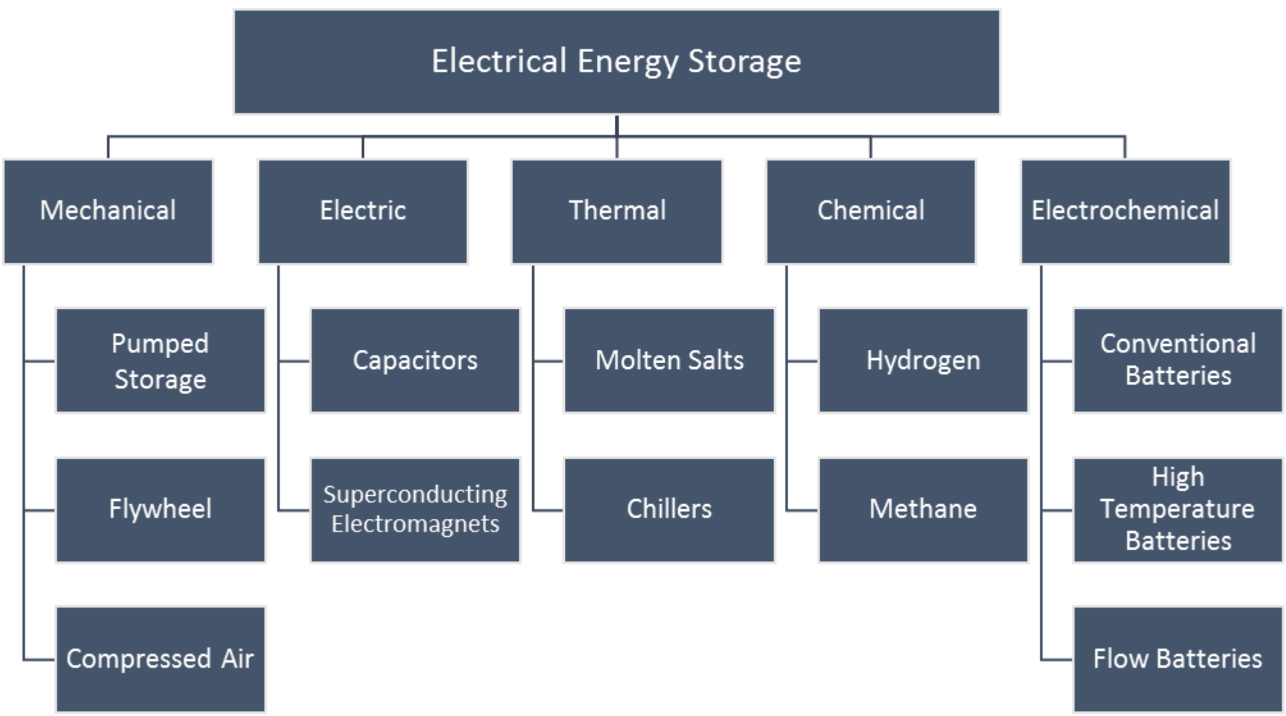

Figure 3.1: Classification scheme for energy storage technologies

Also included is a section on intermediary communication and control systems that allow power system operators to interact with energy storage resources. Although energy storage is very similar to other generating technologies, there are important differences that may require software and analytical tools that need to be seamlessly integrated into existing utility energy management systems.

The equivalent of energy storage can be accomplished in many end use applications. Energy consuming activities in which the timing of the power consumption can be varied is essentially an energy storage application. Examples include pre-cooling of buildings to reduce daytime demand, utility control of electric water heaters, and timing the use of municipal water pumping or irrigation systems. These fall under the category of demand management and are not the focus of this paper.

3.1 Mechanical

3.1.1 Pumped Hydro Storage

Pumped hydro storage (pumped storage) is the most prevalent and mature energy storage technology, with 129 GW of installed capacity worldwide, 22 GW of which is in the US. Pumped storage is a very versatile technology capable of providing valuable benefits from intra-hour through multiple-day time periods. Pumped hydro stores energy by using electricity to pump water from a lower reservoir to an upper reservoir and recovering the energy by allowing the water to flow back through turbines to produce power. Pumped storage technology is very similar to traditional hydro power plants, and the first pumped storage plant was constructed in 1929.

Pumped storage technology has a long economic life span typically more than 50 years, low O&M and lack of cycling degradation. Pumped hydro requires very specific siting requirements. Initial investment costs tend to be high. The 22 GW of installed capacity in the US has historically been used primarily as an energy management technology, ideal for load leveling and peak shaving.

Round trip efficiency variously reported between 70 and 85%, with most references falling in the 75-82% range. Costs are highly situational, depending on size, siting and construction. Pumped storage's low O&M, long life, and lack of cycling degradation sets it apart from other energy storage technologies.

Table 3.1 Pumped Hydro Characteristics Summary

Technology	Maturity	Cost ($/kW)	Cost ($/kWh)	Efficiency	Cycle Limited	Response Time
Pumped Hydro	Mature	1,500 - 2,700	138 - 338	80-82%	No	Seconds to Minutes

3.1.2 Compressed Air Energy Storage (CAES)

In compressed air energy storage (CAES), energy is stored by running electric motors to compress air into enclosed volumes. The electrical energy is recreated when the stored compressed air is fed into the inlet of a combustion turbine. The combustion turbine consumes some fossil fuel in its operation, but the compressed air at its inlet reduces the work of the combustion turbine that can generate almost three times the energy of a similarly sized conventional gas turbine.

There are two utility-scale CAES systems in existence, the first built in Germany in 1978 (60 MW compressor, 321 MW generator, 4 hour discharge), and the Alabama Electric Cooperative McIntosh plant built in 1991 (50 MW compressor, 110 MW generator, 26 hour discharge)[8]. Both resources rely on burning some fossil fuel in the generation phase. Pacific Gas and Electric, in collaboration with EPRI and support from the US Department of Energy, is working on siting, designing and demonstration testing of a 300 MW CAES plant with 10-hour storage capability.

The energy efficiency of CAES units ranges from 40-75%. Units require five to 15 minutes to start up, and then can ramp up at a rate of 10% every 3 seconds in discharging mode and 20% per minute in charging mode.

When air is compressed it heats up. In conventional CAES the compression energy that goes to heating the air is lost to the atmosphere. A second generation CAES technology is under development that captures the heat energy during compression and returns it by heating the air as passes to the combustion turbine inlet. Another approach to improving CAES efficiency involves compressing and expanding the air slowly such that it nearly maintains the same temperature.

Storage of air can be done in underground caverns or in above ground storage tanks. Underground storage can be relatively less costly, but is dependent on the availability of specific geological conditions at site.

Table 3.2 Summary characteristics of compressed air energy storage.

Technology	Maturity	Cost ($/kW)	Cost ($/kWh)	Efficiency[9]	Cycle Limited	Response Time
Compressed Air (Underground)	Demo to Mature	960 - 1,250	60 - 150	60-70%	No	Seconds to Minutes
Compressed Air (Aboveground)	Demo to Deploy	1,950 - 2,150	390 - 430	60-70%	No	Seconds to Minutes

3.1.3 Flywheels

Flywheels store electrical energy by speeding up inertial masses (rotors). Typically rotating masses rest on very low friction bearings (e.g., magnetic) in evacuated chambers designed to reduce friction as much as possible. Energy is transferred in and out using a motor-generator that spins a shaft connected to the rotor.

The rotor is the main component of the flywheel. Rotor characteristics such as, inertia and maximum rotational rate, determine the energy capacity and density of the devices. The motor-generator and associated power electronics determine the maximum power of the flywheel, allowing for power and energy capacities to be decoupled.

Flywheels used for power applications range from 100 kW to 2 MW with discharge times from 5 seconds to 15 minutes. Energy storage flywheel modules store 0.5 to 1 kWh of energy. Flywheels have round trip efficiencies of 70 to 80% with 1 to 2% of rated power standby losses.

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[8] Vasconcelos, J, et al; *Electricity Storage: How to Facilitate its Deployment and Operation in the EU*, 2012, Think.

[9] Efficiency taken from Fuchs, G., Lunz, B.; Leuthold, M.; Sauer, D. U.; Technology Overview on Electricity Storage; Smart Energy for Europe Platform GmbH (SEFEP), June 2012.

Flywheels are generally considered short discharge duration devices with instantaneous response time, making them a common choice for uninterruptible power supplies as well as power quality applications.

As frequent cycling and continuous operation wear down mechanical components, life expectancy of flywheels is a concern. Flywheels have an expected life cycle of 100,000 charge-discharge cycles, limited by mechanical wear.

Table 3.3 Summary characteristics of flywheel energy storage.

Technology	Maturity	Cost ($/kW)	Cost ($/kWh)	Efficiency	Cycle Limited	Response Time
Flywheels	Deploy to Mature	1,950 - 2,200	7,800 - 8,800	85-87%	>100,000	Instantaneous

3.1.4 Other Mechanical Storage

A number of other mechanical energy storage systems have been proposed and are being investigated. Most of the technologies involve raising masses against gravity. One such proposal is based on rail cars hauling stone or sand up inclines in electric cars with motor-generators. Other proposals use hydraulic fluids to lift masses, or water to float buoyant masses.

3.2 Electrochemical Energy (batteries)

Electrochemical energy storage technologies convert electricity to chemical potential for storage and then back again. Batteries can be broken down into three main categories: conventional, high temperature, and flow. Basic battery technology has a history longer even than that of pumped storage, though cost effective means of storing bulk energy in batteries has been a challenge. Unlike some other storage technologies, batteries have exhibited limited cycling times owing mainly to electrode fouling and electrolyte degradation. Advanced batteries are also the major focus of research into improving storage technology, with advances in materials and designs taking place at a rapid rate.

3.2.1 Conventional Battery Technology

Conventional batteries contain anode and cathode electrodes in a sealed cell with separated by a substance called an electrolyte. During the charging cycle the electrolyte is ionized, during discharge an oxidation-reduction reaction recovers the energy. There is a wide range of battery types named for the electrolyte employed. Common ones include lead-acid, nickel-cadmium and lithium-ion.

<u>Lead Acid</u>

Lead acid is the most technologically mature of the battery technologies. It remains popular due to its low cost, despite toxicity, low specific energy and power, short life cycle and maintenance requirements. Lead acid is generally best suited to power quality applications. Round trip efficiency is between 75 and 85% and expected life, depending on technology is between 3-10 years. About 35 MW of lead acid batteries are deployed for power applications worldwide.

<u>Nickel-Cadmium</u>

Nickel-Cadmium batteries have around 27 MW of installed capacity around the globe. They have relatively low round trip efficiency, between 60 and 70% and cadmium is highly toxic. Although they are more expensive than lead-acid they are still an attractive technology, as they are technologically mature and offer a longer life span than lead-acid of around 10-15 years.

Lithium-Ion

Lithium-Ion technology is used extensively in consumer electronics due to their high energy density, low standby losses and tolerance to cycling. They are making major inroads in the electric vehicles market and are also being considered for utility functions. One business model has been proposed to use electric vehicle batteries in utility applications after their useful life in vehicles has been realized. Another business model replaces batteries instead of recharging them at "charging stations." While in the charging station, the batteries can be connected to the grid, providing grid services.

Lithium-ion batteries still face significant cost barriers and some versions do not tolerate deep cycling well. Nevertheless, the technology has demonstrated the ability to provide a very wide range of grid benefits. They boast round trip efficiencies between 85 and 95% with a lifetime of 10 to 15 years. As they are still a relatively young technology for grid applications, cost estimates vary widely.

3.2.2 High Temperature Batteries

High temperature batteries, or molten salt batteries, are similar to conventional batteries, but are based on reactions that only occur at elevated temperatures. Common chemistries are sodium sulfur (NAS) and sodium nickel chloride with sodium sulfur much more common. The electrolyte is solid in either case, with NAS operating temperatures between 300° and 360°C and sodium nickel chloride at around 270°.

NAS batteries are suitable for energy and/or power applications, generally long duration energy storage. This includes load leveling, arbitrage, "islanding," and renewables output smoothing, although their fast response time (1 ms) and the ability to provide pulse power make them suitable for a very wide range of applications.

NAS batteries are still in the early stages of commercialization, especially on the grid scale. Thus far most of the grid applications are in Japan. Round trip efficiency is generally high (70 to 90%), although the parasitic energy required to maintain the batteries in a molten state may reduce this somewhat.

Energy outputs range up to tens of MWh, with discharge capacities from 50 kW to 100 MW. NAS batteries have a relatively high energy density, 100 250 Wh/kg with a power density of 260 W/kg, allowing for small footprints.

Due to their early stage of commercialization costs remain high and as with many other battery technologies, there are toxicity concerns. There are also safety concerns due to the high operating temperatures and explosive nature of sodium when exposed to water. Costs are currently around 600 $/kWh[10], with projections that this will eventually drop towards 250 $/kWh.

Sodium nickel chloride batteries get their nickname ZEBRA from Zero Emission Battery Research. They have a rated power between 5 and 500 kW, with up to 100 kWh of energy. Round trip efficiency is between 85 and 90% with a 20 ms response time and expected cycle lives of up to 3,000 at 8% discharge depths.

3.2.3 Flow Batteries

Flow batteries use similar electrochemical reactions to conventional and high temperature batteries, but the electrolyte material is stored in external tanks. During charge and discharge cycles the electrolyte is pumped into the cell stack. This construction allows for a decoupling of power and energy as well as eases chemically managing or replacing the electrolyte.

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[10] S. Schoenung and W. V. Hassenzahl, "Long- vs. Short-Term Energy Storage Technologies Analysis," Sandia National Laboratories, Albuquerque, 2003.

However this construction method increases the cost and maintenance of flow batteries, as well as efficiency losses associated with pumps and other ancillary equipment.

There are two types of flow batteries: hybrid and redox. Hybrid flow batteries use electro-active components deposited as a solid layer, then the battery cell contains one battery electrode and one fuel cell electrode, with the energy limited by the size of the battery electrode. Redox flow batteries are a reversible fuel cell with the electro-active components dissolved in the electrolyte. The energy is related to electrolyte volume and power is related to the electrode area in the cells. Common redox flow battery chemistries are zinc bromine and vanadium.

Vanadium redox batteries have demonstrated their compatibility with PV and wind generation, load leveling, and power quality and reliability, including spinning reserve. In conjunction with a supply driven generating facility they can be used for time shifting as well as forecast hedging. Current commercial units are around 5 kW in size, although some demonstration units are around 250 kW and expected rated power is between 100 kW and 10 MW. Each liter of electrolyte provides 20 to 30 Wh at full charge. Size is a concern, as a flow battery generally has twice the footprint of a similar electrochemical storage device.

Flow batteries are most suited for energy applications such as peaking and spinning reserve. Their full power discharge ranges from four to ten hours. Life expectancy is 10 to 15 years, with the internal membrane the limiting factor, although refurbishment can extend the lifetime to 20 years. Efficiencies are in the 60 to 70% range with nearly instantaneous response times for the battery itself (0.35 ms), although the pumps and power electronics have a slower response time, overall one can expect a response of several milliseconds.

Costs are difficult to estimate as the cell stacks and electrolyte volume are decoupled, but range from $1.1 million (250 kW, 4 hr.) to $4.9 million (1 MW, 8 hr.), with costs expected to fall significantly as the technology matures.

Zinc bromide batteries are still in the early stages of development, but have the potential for low cost and high energy density. However the zinc builds up unevenly on the electrodes and as a result the battery must be fully discharged every 5 to 10 cycles.

As bromine is extremely corrosive the limiting factor in lifetime of the units is not charge cycles but simply hours the storage system has been in operation, with estimates of around 6,000 hrs. The corrosive property is potentially a human and environmental hazard as well.

Zinc bromine batteries are best suited for applications requiring high energy density instead of high power density such as bulk energy storage.

Table 3.4 Summary characteristics of electrochemical energy storage technologies.

Technology	Maturity	Cost ($/kW)	Cost ($/kWh)	Efficiency	Cycle Limited	Response Time
Lead Acid Batteries	Demo to Mature	950 - 5,800	350 - 3,800	75-90%	2,200 - >100,000	Milliseconds
Lithium-ion Batteries	Demo to Mature	1,085 - 4,100	900 - 6,200	87-94%	4,500 - >100,000	Milliseconds
Sodium Sulfur	Demo to Deploy	3,100 - 4,000	445 - 555	75%	4,500	Milliseconds
Flow Batteries (Vanadium Redox)	Develop to Demo	3,000 - 3,700	620 - 830	65-75%	>10,000	Milliseconds
Flow Batteries (Zinc Bromide)	Demo to Deploy	1,450 - 2,420	290 - 1,350	60-65%	>10,000	Milliseconds

3.3 Chemical Energy Storage

Chemical energy storage relies on electric energy to create fuels that may be burned in conventional power plants. An advantage of synthetic methane (and hydrogen to some degree) is that it can be injected into the existing natural gas storage infrastructure. Another strength of chemical storage over some of the other technologies is the high energy density (kWh/liter) of chemical storage compared to most of the other technologies. Figure 3.2 shows energy densities for some of the more common chemical storage agents compared with other storage media.

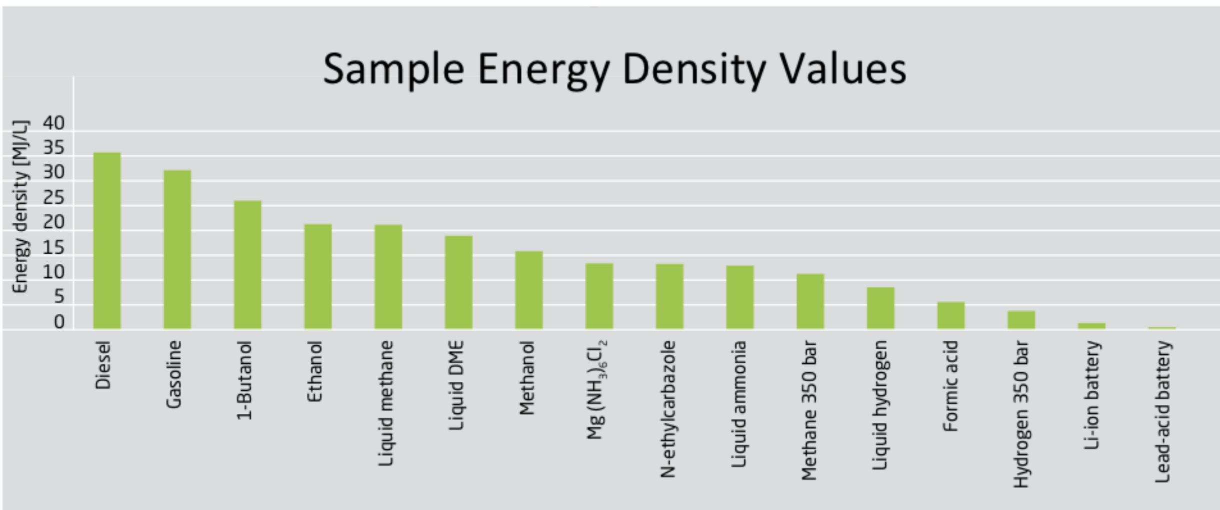


Figure 3.2 Relative energy densities of some chemical storage media compared with some battery technologies. (Source: *DTU International Energy Report 2013: Energy Storage Options for Future Sustainable Energy Systems*, November 2013.)

Synthetic gas processes are referred to as "Power to Gas" technologies. The prevalent power to gas processes begin with water electrolysis that splits water into hydrogen and oxygen. The hydrogen may then be stored and burned directly, or first is combined with carbon to create synthetic methane. Methane is the major component if natural gas and is fully compatible with the existing storage, transmission, distribution, and generation infrastructure for natural gas power plants. In other words, it can be injected into the natural gas grid without restriction. Figure 3.3 illustrates the power to gas energy cycle.

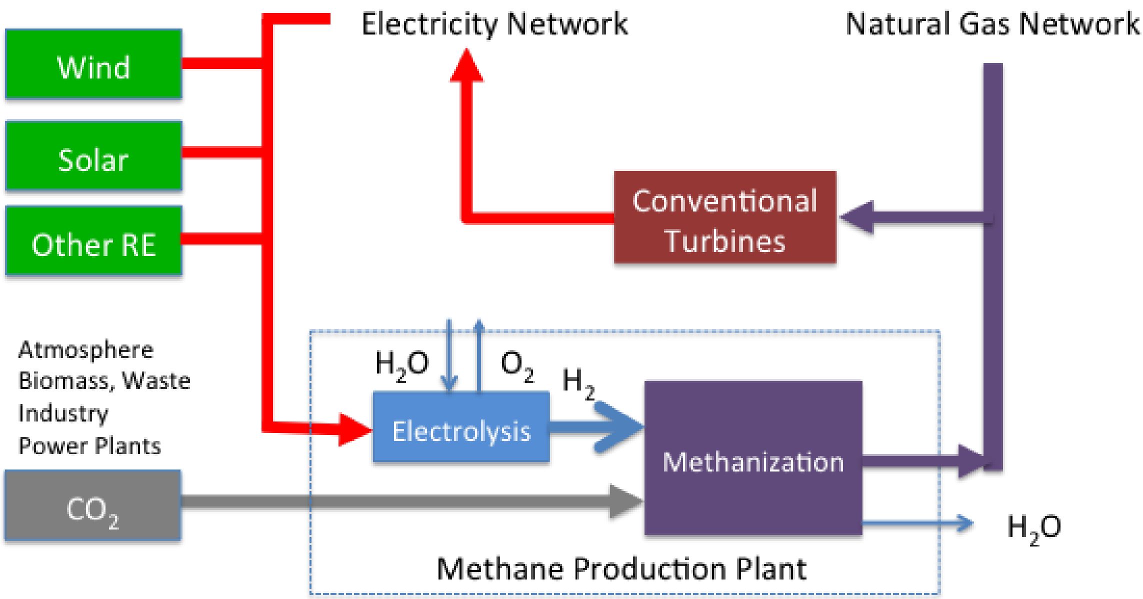


Figure 3.3 Illustrating the energy cycle for a chemical storage in the natural gas system. Note that physical storage occurs in the existing natural gas system.

The storage capacity of the gas grid serves as the storage medium, capable of storing large volumes of energy for weeks, months, or even years. Converting electrical energy to gas may also play a role in indirectly powering transportation with electric power for natural gas vehicles. Audi opened a 6 MW facility in June 2013 in Germany—sourcing the needed electric power from renewable resources. The round-trip energy efficiency of power to gas may be as high as 30 to 45%[11].

Table 3.5 Summary characteristics of methane energy storage.

Technology	Maturity	Cost ($/kW)	Cost ($/kWh)	Efficiency	Cycle Limited	Response Time
Power to Gas	Demo	1,370-2,740	NA	30-45%	No	10 Minutes

Note that cost per kWh is listed as NA. This is because the storage relies on the existent natural gas grid.

3.4 High Temperature Thermal Energy Storage

High temperature thermal energy storage has been used to store heat from concentrating solar facilities for use after the sun sets. Abengoa's Solana 280 MW solar power station in Arizona began operating in October 2013 with six hours of thermal energy storage. Close on its heels is SolarReserve's 110 MW Crescent Dunes power tower solar thermal plant in Nevada that will have 10 hours of storage and is scheduled for completion in 2014. Heat from the concentrating solar mirrors is transferred to a molten

[11]Round-trip conversion efficiency is based on estimated electricity to methane conversion efficiency of 75-80% and combined cycle thermal plant reconversion to electricity.

salt solution and stored in insulated tanks. When the sun goes down, heat from the stored molten salt solution is transferred to produce steam that powers a conventional steam boiler.

While the Solana plant does not have the ability to store electrical energy, it demonstrates the ability to store thermal energy on a large scale for use in electric power generation. It is conceivable that high temperature electric resistance heating capability could be added to such a system to enable full electric energy storage capability. Storage occurs by using electric power to heat a thermal storage medium, and power is produced through a conventional steam turbine fueled by stored heat. The relatively low efficiency (25-35%) may be offset by relatively low capital costs if the resistance heating capability is added to an existing solar thermal plant.

Combining existing or proposed solar thermal power plants with electrical energy storage may present favorable economics. Electric resistance loads are relatively low capital costs on a per kilowatt basis and can act dynamically without any moving parts. These properties may provide a source of relatively low cost balancing reserves— capable of responding rapidly to widely varying input power levels.

Table 3.6 Summary characteristics of thermal energy storage technologies.

Technology	Maturity	Cost ($/kW)	Cost ($/kWh)	Efficiency	Cycle Limited	Response Time
High Temperature Thermal Storage	Demo to Deploy	NA	NA	~30%	No	Storing: Seconds Generating: Minutes

3.5 Combustion Turbine Inlet Cooling Storage

The first stage of both single cycle and combined cycle combustion turbines involves compressing inlet air to feed to the combustion chamber. The compression phase is a factor in the efficiency of the technology. Because cooler air is more dense, it is a relatively common practice to boost both the efficiency and maximum output of the devices by providing some cooling to the inlet air—especially in summer peaking locations. Inlet air cooling is most commonly provided using evaporative cooling techniques. Although less common, active cooling using chillers is employed, especially in warm humid climates where evaporative cooling is less effective. Where chillers are used, it is common to employ thermal storage so that the electric chillers can run at night when power is less costly and chilling is more efficient due to lower ambient air temperatures.

Although not mentioned in most energy storage references, turbine inlet cooling represents a form of energy storage—power goes into the chillers (typically at night) and returns as higher maximum turbine output capacity and energy when the turbine operates. This is a commercially established technology using standard industrial equipment and may be considered as a potentially low cost energy storage opportunity.

3.6 Electromagnetic

Storing most quantities means finding a protected space to place them until needed. Electricity is notoriously difficult to store as electricity, and most storage technologies seek to store electrical energy by first converting it to another form. However, two technologies store electrical energy as electricity—superconducting electromagnets and capacitors.

3.6.1 Capacitors

Capacitors consist of two electrical conductors separated by a non-conducting material (the dialectric). When a charge is applied across the plates electrical charge builds up on either side. Energy is stored in the electrical field between the two plates.

Electrochemical capacitors (also called double layer, super-capacitors or ultra-capacitors) have a higher energy density than other capacitors. Some double layer capacitors have a voltage rating at or above 600V. This makes them suitable for power quality and intermittent renewables fluctuation suppression applications.

Their disadvantages include interdependence of the cells, sensitivity to cell voltage imbalances and maximum voltage thresholds, and safety issues, including electrical, fire, chemical, and explosion hazards.

3.6.2 Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy Storage (SMES) uses the flow of direct current through a cryogenically cooled superconducting coil to generate a magnetic field that stores energy. Once the superconducting coil is charged, the current will not deteriorate and the magnetic energy can be stored indefinitely. The stored energy is released by discharging the coil. Cryogenic refrigeration is required to keep the device cold enough to maintain superconducting properties.

SMES units offer "permanent" storage, immediate response, life expectancy independent of duty cycle, and high efficiency and reliability. In this case permanent means that the energy is held indefinitely, with no standby losses due to heat dissipation, evaporation, etc. This, coupled with the nearly instantaneous response speeds SMES are capable of, make SMES an excellent choice for uninterrupted power supplies (UPS) and power quality applications. Additionally SMES units boast round trip efficiency above 95% with few mechanical parts, limiting failure points and increasing reliability.

Table 3.7 Summary characteristics of various energy storage technologies[12].

Technology	Maturity	Cost ($/kW)	Cost ($/kWh)	Efficiency	Cycle Limited	Response Time
Pumped Hydro	Mature	1,500 - 2,700	138 - 338	80-82%	No	Seconds to Minutes
Compressed Air (Underground)	Demo to Mature	960 - 1,250	60 - 150	60-70%	No	Seconds to Minutes
Compressed Air (Aboveground)	Demo to Deploy	1,950 - 2,150	390 - 430	60-70%	No	Seconds to Minutes
Flywheels	Deploy to Mature	1,950 - 2,200	7,800 - 8,800	85-87%	>100,000	Instantaneous
Lead Acid Batteries	Demo to Mature	950 - 5,800	350 - 3,800	75-90%	2,200 - >100,000	Milliseconds
Lithium-ion Batteries	Demo to Mature	1,085 - 4,100	900 - 6,200	87-94%	4,500 - >100,000	Milliseconds
Flow Batteries (Vanadium Redox)	Develop to Demo	3,000 - 3,700	620 - 830	65-75%	>10,000	Milliseconds
Flow Batteries (Zinc Bromide)	Demo to Deploy	1,450 - 2,420	290 - 1,350	60-65%	>10,000	Milliseconds
Sodium Sulfur	Demo to Deploy	3,100 - 4,000	445 - 555	75%	4,500	Milliseconds
Power To Gas	Demo	1,370 - 2,740	NA	30-45%	No	10 Minutes
Capacitors	Develop to Demo	-	-	90-94%[13]	No	Milliseconds
SMES	Develop to Demo	-	-	95%[14]	No	Instantaneous

[12] Unless otherwise noted, cost and efficiency data is sourced from: Carnegie, et al, *Utility Scale Energy Storage Systems: Benefits, Applications, and Technologies;* State Utility Forecasting Group, June 2013. Costs are expressed in 2010 dollars.

[13] Fuchs, G., Lunz, B.; Leuthold, M.; Sauer, D. U.; Technology Overview on Electricity Storage; Smart Energy for Europe Platform GmbH (SEFEP), June 2012.

[14] Ibid.

4 Energy Storage Value Streams

Energy storage brings values associated with traditional generation along with some additional services either not provided by traditional generation, or else provided in a more limited way by traditional generation. Energy arbitrage is the clearest example of the former. Realizing the arbitrage value means operating storage such that it consumes energy at times when market prices are low and releases the energy when market prices are higher. Energy storage can provide a host of services that have been identified as being in increasing demand due to the advent of variable renewable energy resources. For example, accommodating variable generation into power systems can require additional fast-ramping generation or load capability to maintain system stability. Energy storage technologies can provide both generation and load to meet those requirements.

Examples of values that are provided both by traditional generation and storage may be ramping capability. In many cases existing power plants were not generally constructed for frequent cycling and rapid ramping, whereas many of the energy storage technologies are designed to provide that capability in a reliable way.

It should be noted that not all energy storage technologies effectively provide all the services described below. For example, very fast-acting flywheel or super-capacitor technologies are not currently cost competitive with other storage technologies for energy arbitrage applications or providing multi-hour peaking capability. Value streams deriving from locational transmission or distribution system constraints are of course site-specific as well as potentially technology specific.

Within such limitations, multiple value streams can be realized in many applications. For example, at the transmission level, energy storage can provide grid-related ancillary services as well as energy arbitrage. Energy storage can simultaneously help meet peak loads and relieve transmission system congestion. More localized (to demand) storage on distribution systems can simultaneously address voltage problems, reduce distribution congestion (deferring capital investments) as well as provide ancillary services to the grid. Energy storage systems located on the customer side of the meter can reduce customers' peak demand and energy charges while improving power quality and reliability.

Solar Thermal Energy Storage

Energy storage addressed in this section is primarily from the point of view of technologies that absorb electric power, store it in some intermediate form, and regenerate electric power on the grid. Thermal storage on solar thermal plants acts somewhat differently.

For example, the capacity value for most storage technologies is generally equal to the generating capability of the associated generator. For solar thermal plants, adding thermal storage capability can enhance the project's reliability in meeting peak demands (i.e., can generate even when the sun isn't shining). Adding storage in this case, adds megawatt-hours of storage without an additional generator, or increased capacity value.

Another unique aspect is that unlike stand-alone storage technologies, the fuel for solar thermal storage is heat from the sun, with no additional air emission considerations.

4.1 Flexible Capacity Value

In most systems, resource additions are driven largely by the need to reliably meet peak demand periods. Peak demands may occur only a few hours per year, making it very expensive to exclusively meet this need through additional generation. Given the relative infrequency with which peaking demand occurs, energy storage is a good candidate for providing such service, especially if the storage resource can provide additional (i.e., non-peak demand related) services. The ability to meet peak demand is not likely a sufficient justification on its own for today's capital-intensive energy storage technologies, but provision of flexible capacity (i.e., generation available on short notice and able to operate efficiently over a range of output levels) is an important value consideration. Fueling flexible capacity from renewable energy sources— storing light load hour renewable energy generation to meet peak demands may be a particularly attractive stacking of energy storage value streams.

Flexible capacity also has value to the customer when installed on the customer side of the meter to reduce exposure to retail peak demand charges. When combined with other potential values such as power quality and backup power, energy storage can be economic at customer sites. Flexible capacity on the customer side of the meter can help utilities to reduce transmission and distribution system congestion, forestall distribution system upgrades, in addition to reducing the need to add peaking resources to the power system.

4.2 Energy Arbitrage

Most power system energy storage today is accomplished with pumped storage units capable of shifting bulk quantities of energy from low price hours to higher price hours. The arbitrage and capacity value aspects of energy storage have been used to justify energy storage investments in the past. Today's relatively low wholesale market prices for power driven by increasing penetration of low variable cost wind, solar generation and relatively low fossil fuel prices have made this a more difficult value proposition on its own. As renewable penetration grows, it is expected that periods of negative market prices may grow—brightening the prospects for energy storage from arbitrage. It will be important to understand the frequency and severity of negative market price events as the penetration of wind and solar resources grow.

The variability of renewable generation could be expected to increase wholesale market price volatility—with prices dropping when renewable energy is being generated at high levels, and prices recovering when renewable energy drops off. Higher volatility opens the door to enhance value of energy storage. Today, this effect is limited by the relative abundance of generating capability and low natural gas prices. A significant carbon emissions cost levied on fossil-fueled resources, or other limits on greenhouse gas emissions could reignite the economics of energy storage based solely on energy arbitrage.

4.3 System Balancing and Ancillary Services

System balancing and ancillary services are needed to ensure the reliable operation of the power system. They are services necessary to support the transmission of energy from resources to loads while maintaining reliable operation of the transmission system in accordance with good utility practice. Individual ancillary services that have been identified that can be provided by energy storage technologies include:

1. System Balancing
    a. Regulation/frequency control
    b. Load Following
    c. Energy Imbalance
2. Contingency Reserve – Spinning
3. Contingency Reserve – Non-Spinning
4. Contingency Reserve – Supplemental
5. Reactive Support
6. Network Stability Services
7. System Black Start Capability

Provision of these services can represent important value streams that should be considered in economic benefit calculations.

A complicating factor is the degree to which services may overlap, may or may not be provided exclusive of one another, the extent to which markets may exist for them, and the extent to which methods have been developed to value them. Of these, four are typically traded in restructured (ISO) markets: Regulation, Contingency (spinning), Contingency (non-spinning) reserves, and Contingency (supplemental) reserves. These services and their relevance to energy storage are explored more fully below.

4.3.1 System Balancing

System balancing services are not uniquely defined across the industry, but generally are divided into categories relating to the time scale in which devices need to respond. For the purposes of this paper, balancing reserves include regulation/frequency support, load following and energy imbalance services. Power system balancing refers to the need to hold reserve generation capable of increasing or decreasing generation (or demand) levels on relatively short notice to maintain power system reliability as demand or less-controllable resources unexpectedly shift consumption or generation levels. System balancing includes regulation/frequency control reserves, following reserves, and imbalance reserves.

Balancing services are differentiated according to the response time of the resources. Regulation is the fastest acting of the balancing reserves, capable of responding every few seconds under automated (e.g., automatic generation control) systems. Load following (or just "following") reserves respond within ten minutes. Imbalance reserves are expected to ramp up at their characteristic ramp rate over a 10-30 minute period and run at a fixed output to free up the operating range of the generator on AGC.

How these types of system balancing services are used depends on the organization of the power system. In the ISO and RTO markets with real-time energy dispatch on 5 minute time-frames, the requirement for reserves is reduced to meet imbalances in between the 5 minute dispatch instructions, and the market itself delivers a quantity of operational flexibility. Sub-hourly transactions reduce the need for reserves, although the underlying need for balancing flexibility remains.

System balancing requirements are those that are most directly related to the growth in renewable generation on the system. For example, isolated systems such as Hawaii and Puerto Rico have experienced acute needs for fast-acting regulation services due to high levels of solar PV generation that can fluctuate at very fast rates.

4.3.1.1 Ramping Capability

Ramping capability is the rate at which generation levels can change in time, often expressed in megawatts per minute. Ramping capability is not identified as a separate ancillary service, but is more of an attribute of the generation that comprises the power system, especially generators providing system-balancing services. In organized wholesale markets, the day-ahead market creates hourly schedules where inter-hour ramps are accommodated. Historically, the intra-hourly ramps have been sufficiently covered by on-line units augmented by quick-start resources, such as combustion turbines. The output of renewable resources can shift relatively rapidly and the need for resources that can compensate at similar rates is expected to increase. Power system analysts are beginning to assess the need for ramping capability and its supply. Because these efforts are at an early stage, specific valuation of ramping capability has not been standardized across the industry. FERC order 755 sought in part to require system operators to associate value with the quality of generation providing frequency regulation services—ramp rates presumably being one such quality.

4.3.2 Contingency Reserves

Contingency reserves include spinning, non-spinning and supplemental reserve ancillary services. Contingency reserves are made available to the system to replace generation lost due to the failure of major power system components. They are distinguished by the length of time they may take to achieve full output. Spinning reserves must be operating and synchronized to the system and available within ten minutes. Non-spinning reserves need not be operating and synchronized when called upon, but must also be available within ten minutes and operable for up to two hours. Supplemental reserves are available within an hour or so to replace spinning and non-spinning reserve generation. There are variations in definitions of these quantities among balancing authorities, and specific requirements may vary as well.

4.3.3 Reactive Support Service and Voltage Control

Electric power is derived from the simultaneous product of voltage (electrical "pressure") and current. In the dominant alternating current power systems, voltage and current levels vary in time from positive to negative values. Optimum derivation of power occurs when the voltage and current are perfectly synchronized with each other—e.g., simultaneously reaching maximum and minimum values. System performance degrades when voltage and current fall out of synch with each other. Equipment capable of correcting the phase difference is said to provide reactive support. Voltage problems are often associated with poor reactive support.

Generators, loads, and other devices are capable of providing reactive support. Some energy storage technologies can have an advantage over some other generating technologies in providing reactive support by being available to the grid even when not generating power.

4.3.4 Network Stability Services

The stability of a power system is the ability of a power system to bring itself back to stable operation following a disturbance (e.g., an outage) without incurring additional equipment outages. System stability can be enhanced by automated means. Network stability services generally respond to disturbances in the first 10 to 30 seconds by countering the action of the initial disturbance or any tendency of the power system to propagate the disturbance. Devices used to support network stability generally must respond within about 3 seconds.

Certain energy storage technologies can be a key to supplying energy in the first few seconds to a few minutes until such time as slower moving conventional generation can respond. This can be especially important in isolated systems, or other systems where system inertia is limited (e.g., in systems with very high renewable energy penetration).

4.3.5 Black Start Capability

Black start capability is the ability of a generator to begin generating power without station power. Many generators require station power to start up. Black start capability is important in recovering from system outages.

4.4 Congestion Management

Most power generation is located far from populated areas and is transmitted over high voltage transmission lines to cities where the power is consumed. Transmission lines can become congested, especially through time as demand grows at the destination sties. It can be much more cost effective to relieve congestion by locating generation closer to the population centers than to expand the transmission line capacity.

There are often severe constraints placed on power generation near populated areas such as land availability, noise and air emissions. That, and the fact that congested periods often last for only a few hours or even minutes at a time can result in energy storage technologies being ideal solutions to transmission congestion issues.

Energy storage may also be co-located with variable renewable generation. Doing so raises the possibility of siting more renewable generation in a region served by limited transmission facilities. Energy generated in excess of local transmission capability can be stored for later release when the generation falls and transmission capability is available again.

In addition to congestion that can occur on the major arteries consisting of the high voltage transmission system, congestion can happen more locally on the distribution system. Substation equipment can become overloaded under conditions of high demand, or potentially high levels of distributed generation such as energy from rooftop solar installations. Smaller scale storage on distribution systems, either at load sites or substations may be a cost effective alternative to major component replacements. Distribution system switching gear can experience increased wear and maintenance cost due to fast ramping PV resources that can be ameliorated with smaller scale localized energy storage.

4.5 Emissions

There is a somewhat complex relationship between energy storage and emissions. On the one hand, energy storage is not 100% efficient and, in general, represents an additional load on the system that can result in increased emissions. Some studies have shown that the inclusion of energy storage increases overall carbon emissions by presenting additional load in low load hours to coal plants that might otherwise be reduced for lack of market.

On the other hand, the system is changing and coal is being replaced by a combination of renewable energy and natural gas plants. When the fuel for energy storage comes from renewable power plants, or the more efficient natural gas fired units generally running at night, and displacing less efficient units operating during the day, the carbon emissions can fall. In addition, storage can provide loads for renewable generation that might otherwise be wasted for lack of markets, especially as renewable energy resources account for large fractions of the energy production The same studies that show increased levels of carbon emissions in "base case" analyses, show reductions in emissions in high renewable build-out scenarios[15].

4.6 Power Quality

Power quality refers to the extent to which provision of power:

- Is reliable (i.e., does not suffer outages).
- Maintains nominal voltage levels.
- Maintains unity power factor (voltage and current are in phase with one another).
- Maintains nominal frequency levels (e.g. 60 Hz).
- Maintains a purely sinusoidal waveform (zero harmonics, no transients).

Power quality can be affected by a number of power system conditions. For example, certain types of load can have the effect of reducing the power factor. Equipment malfunctions and switching equipment can cause transient spikes in power. Power quality affects the efficiency of power system components and poor power quality can increase system maintenance costs and cause failures of power system components, including energy consuming equipment such as motors.

Poor power quality can result from rapid variations in generator output that can, for example, occur with some solar energy installations on partly cloudy days. Energy storage can provide system support in ways that improve power quality, providing voltage support and aiding in reliable service. An example of the latter is Portland General Electric's installation of a battery system on a critical substation feeder to

[15] Reference the Argonne study as an example of carbon emission reductions in high renewable case.

maintain local service in the event of outside service interruptions, allowing a cushion until other generation can be brought on line[16].

For some commercial and industrial customers, power quality can be extremely important, justifying energy storage on the customer side of the meter. Partnerships between such loads and the utility systems in which both side realize value may be effective. Conversely, utility customers adding and controlling storage devices, can add to uncertainty in utility loads. Utilities may find benefit in working with certain customers to wring the most benefit out of energy storage on the customer side of the meter.

16 See Salem Smart Power Project, http://www.portlandgeneral.com/our_company/energy_strategy/smart_grid/salem_smart_power_project.aspx.

5 Demand for Energy Storage

5.1 Growth in Variable Energy Resources

The electric power system is undergoing significant changes as more variable energy resources (VER) such as wind and solar are added to the generation mix. These VER are being implemented primarily to satisfy requirements of state renewable-energy mandates. The West Coast states each has a goal for total renewable energy between 15% and 33% of electricity demand. Many neighboring states in the Western Electricity Coordinating Council (WECC) region have similar goals, as can be seen in Figure 5.1.

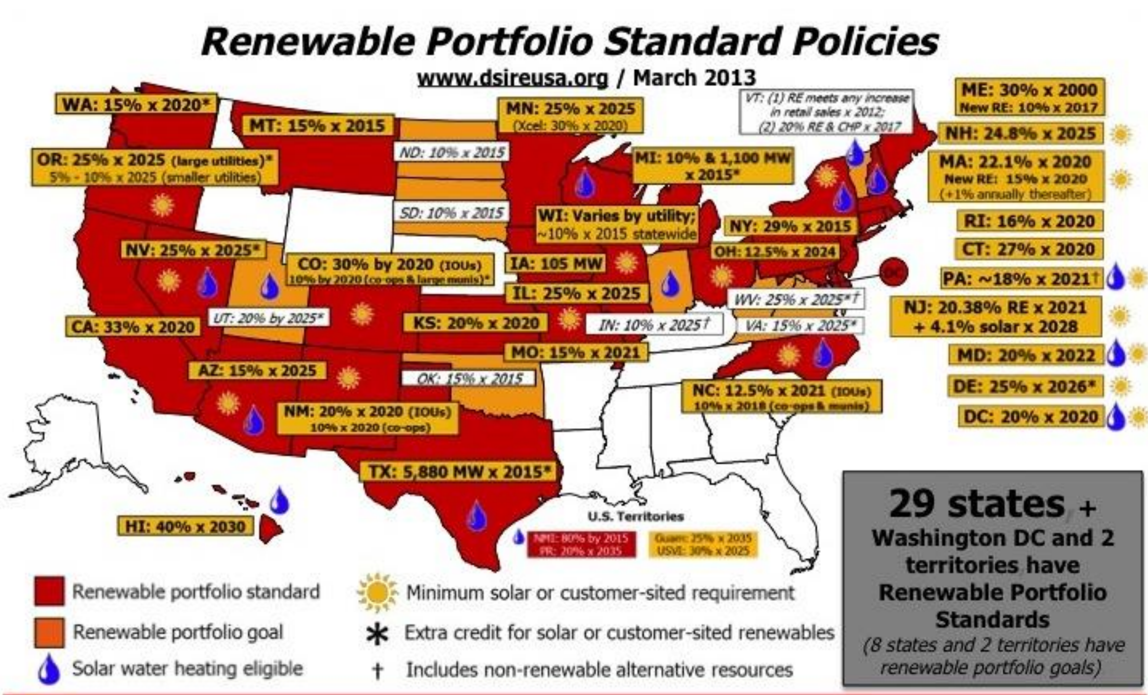


Fig. 5.1 Renewable Portfolio Standards in the US
(Source: DSIRE, Database of State Incentives for Renewables and Efficiency **http://www.dsireusa.org/summarymaps/)**

To give an indication of the magnitude of VER growth, one can look at studies done in California in anticipation of meeting the 33% goal. The total renewable energy expected in the system varies depending on forward-looking assumptions about load growth and assumptions that apply to all generating resources including cost, time to construct and environmental constraints. Nonetheless, several scenarios converge to indicate that the VER in the area served by the California ISO is expected to be about 20 GW by 2020 compared to 11 GW existing in 2012[17].

Oregon has approximately 3.3 GW of renewable energy installed currently, and Washington about 3.0 GW[18]. Both of these Northwest states expect a doubling of renewable energy resources between now and 2020.

5.1.1 Relationship between balancing services and variable energy resources

Growing VER in the electric system necessitates changes in planning and operations. The generation output varies based on the availability of the energy source (e.g., sun or wind) and therefore places different demands on the electric system compared to traditional generation. In general, the operational requirements of greatest concern in a scenario of high VER penetration are:

- Operational ramp
- Load-following capacity and ramp rate
- Regulation capacity and ramp rate
- Additional capacity needed to meet reliability requirements

These requirements must be evaluated for hourly operations as well as intra-hour needs. In the evaluations done by the California ISO for a model year of 2020 there were several important system impacts that show an opportunity for energy storage[19]. First, the load-following balancing needs were estimated at 3.5 GW for load-following up and 4.0 GW for load-following down[20]. The faster-acting regulation balancing requirements are lower, but still in the range of 1.0 GW for regulation up and down. The operating requirements are dependent on error in the estimated load, VER forecast error, the mix of renewable energy resources, and outages.

Differences between gas generation and energy storage flexibility

Natural gas generators are commonly considered a prime source of power system flexibility. This is a reasonable assumption unless the available variable generation begins to approximate the available gas generation.

It should be noted that the availability of gas generation tends to decline on an operational basis as the variable generation increases—economically displaced by low VER generation. Somewhat ironically, the "flexible" natural gas generators tend to be least available when needed most: when the output of variable resources increases to high levels.

Conversely, flexibility from energy storage technologies is available and most economic (in storage mode), during high VER output events.

A shortage in flexible resources to meet reliability requirements was identified in the California study. A shortfall of 1.2 GW in load-following down is expected in 2020. This condition occurs for a limited number of hours per year, and a possible solution put forward to the California PUC was curtailment of VER. This

17 CAISO (2011) Summary of Preliminary Results of 33% Integration Study – 2010. CPUC LTPP Docket No. R.10-05-006. Folsom, CA: CAISO.

18 Renewable Northwest Project, State Energy Project Fact Sheets, 2013. www.rnp.org

19 CAISO (2011) Summary of Preliminary Results of 33% Integration Study – 2010. CPUC LTPP Docket No. R.10-05-006. Folsom, CA: CAISO.

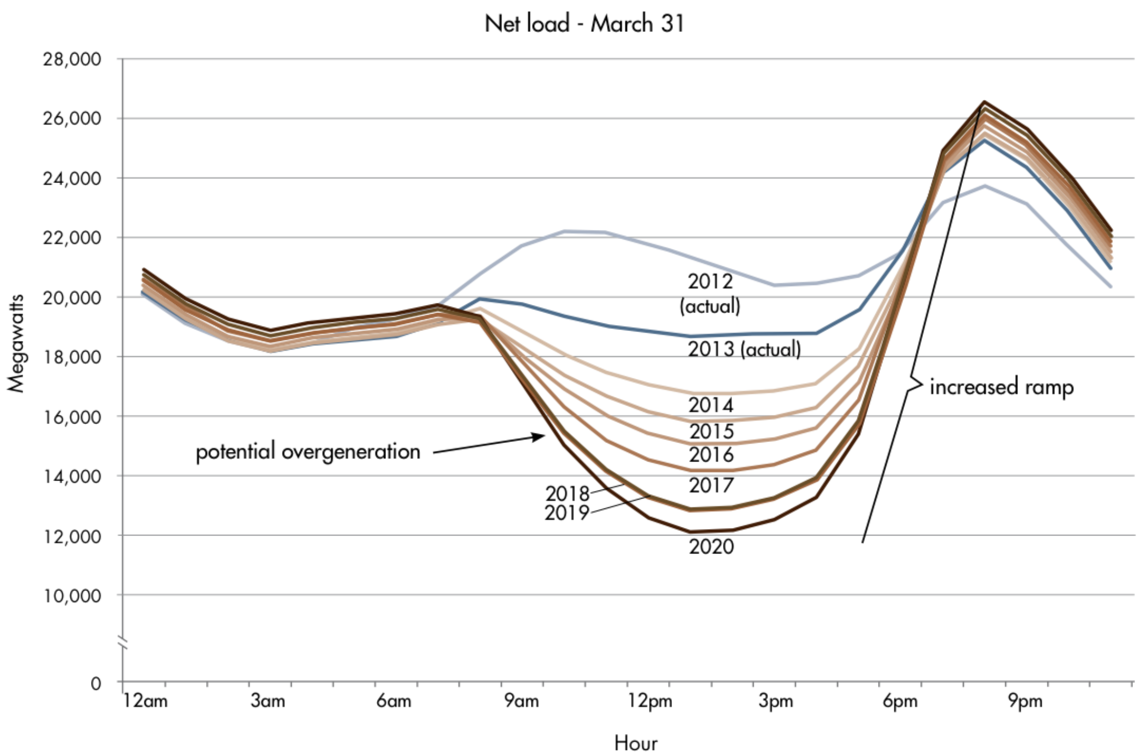
20 Balancing needs are divided into up- and down-categories in which reserve generators either increase output levels ("up"), decrease output levels ("down"). The up requirements may be also be provided by loads that can decrease demand levels, and down needs can be provided by increases in demand.

need for a reduction in VER generation, which corresponds to a need for a place to "put" energy, represents a clear opportunity for energy storage.

The current conventional resources of choice for providing balancing needs are natural gas turbines, both combined cycle and simple cycle. There is also growing interest in reciprocating engines that can ramp quickly and efficiently, can be built in multiple small units, are relatively cheap, and reliable. Notwithstanding the capabilities of these generating technologies, there is a significant increase in operating cost for units used frequently to provide balancing services[21]. In the CAISO study for 2020, there were 80 to 90 starts of gas turbines per year. Reducing the number of turbine starts results in savings both in fuel, incremental operating costs and emissions.

The "duck curve" most famously illustrates the changing profile of generation expected in California and potential opportunity for energy storage on the West Coast. The California Independent System Operator created this graph from the 33% state renewable portfolio standard data. It shows predicted net load (electricity demand net of renewable generation) through 2020[22] when California expects to reach its full 33% renewable portfolio standard.

THE DUCK CURVE
(Net load chart)



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21 Intertek APTECH. (April 2012). "**Power Plant Cycling Costs**." EAS 12047831-2-1.

22 CAISO "Demand Response and Energy Efficiency Roadmap: Maximizing Preferred Resources", California ISO, Dec. 2013

Figure 5.2 Predicted Net Load in CAISO in 2020 (Source: CAISO *Demand Response and Energy Efficiency Roadmap: Maximizing Preferred Resources*, California ISO, Dec. 2013)

The graph depicts an increasing late-afternoon/evening ramp, which is forecasted to be a 14,000 MW swing in net load by 2020. The largest ramps on the system currently are less than half that size. In the later years, renewable generation plus baseload (e.g. nuclear) generation may exceed demand during the day. Energy storage can absorb that energy and return it later in the day as the sun goes down.

On Oct. 17, 2013, the California Public Utilities Commission approved a policy requiring California's three largest investor-owned utilities to procure a combined 1,325 MW of energy storage capacity by 2020. the first procurement request for offers is scheduled to take place December 2014 for a combined 200 MW of energy storage aggregated over the three investor-owned California utilities. The mandate developed from a 2010 California bill, AB 2514, which enabled an investigation into the appropriate procurement targets for energy storage.

The energy storage bill does not prohibit specific energy storage technologies or methods, but does limit the size of pumped storage hydro to no more than 50 MW so that this technology doesn't monopolize the quota. The mandate also prescribes that the utilities may own no more than half of the storage assets procured, opening up a market for distributed storage providers. Interestingly, the mandate prescribes maximum charging and discharging rate (MW), but not energy itself (MWh).

The applications for integrating renewable energy using energy storage include both short- and long-duration technologies[23]. Services such as time-shifting of renewable energy output and forecast hedging, mitigating financial impacts of forecast error, can be provided with long-duration energy storage. These services may be needed frequently (defined as >20 events per year) if the time-shifts are within a single day, or infrequently (<20 events per year) if the time-shifts are over several days or weeks. Balancing services and grid operational support can be provided by short-duration energy storage. These services are typically called upon frequently.

The Pacific Northwest National Laboratory (PNNL) is undertaking a geographically wider study of energy storage. Their ultimate charge is a nationwide assessment, but their phase I study of the WECC: *National Assessment of Energy Storage for Grid Balancing and Arbitrage: Phase 1, WECC Assessment of Storage*[24] was released in 2012.

The PNNL study recognized that balancing service requirements could be met by a combination of electrical energy storage, demand response, and limits on VER generation ("wind spillage" in the study).

- 20% RPS for WECC in 2020
- Total intra-hour balancing requirement was calculated to be approximately 6.3GW, which is an increase of ~ 1.5GW
- If the total balancing requirements were provided by energy storage, this could be supplied by energy storage capacity of 2.0 GWh. The storage would be needed to operate at rated power for periods up to 20 minutes.
- Balancing requirements are 3% to 5% of peak load estimates.
- Study assumes a single balancing area for each of the four WECC sub-regions. This likely represents an *under-estimate* of the balancing and energy storage needs by 2020 given the limited progress on balancing area consolidation in the region today.

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23 Carnegie, R.; Gotham, D.; Nderitu, D.; Preckel, P.; (June 2013). Utility Scale Energy Storage Systems: Benefits, Applications and Technologies. State Utility Forecasting Group.

24 Kintner-Meyer, et. Al., (June 2012). National Assessment of Energy Storage for Grid Balancing and Arbitrage: Phase 1, WECC. Pacific Northwest National Laboratory.

5.2 Energy Storage Alternatives

5.2.1 Variable Generator Control

The cost to curtail VER is not insignificant. In the Northwest, Bonneville Power Administration experienced a series of events in the spring of 2012 involving high flows in the Federal Columbia River Power System combined with high output from wind generation. BPA implemented an Oversupply Management Protocol (OMP) that curtailed wind generators and provided partial financial compensation. In 2012, the OMP displaced approximately 47,000 MWh of generation with energy from the hydro system at a cost of $2.7 million[25]. Although significant, they are not yet large compared with energy storage alternatives capable of eliminating the curtailments.

Balancing requirements created by VER generation cover relatively extreme events— for example, very extreme system-wide generation ramps when the sun comes up, or regional-scale weather fronts that affect wind generation en masse. Such events are often represented in regional wind forecasts, and limits place on generation to reduce the severity of the event on the power system. Solar plants morning ramps can be controlled. Lowering maximum generating rates slowly prior to sunsets can reduce evening solar ramps. Similarly, wind generator ramp up rate limits may be selectively imposed in advance of forecasted weather fronts, and maximum allowed generating rates reduced ahead of the tail ends of weather fronts. These more sophisticated controls on VER generation have implementation costs, institutional challenges to implementation, and costs in the form of reduced VER generation. These types of controls can reduce system-balancing requirements and may compete with energy storage technologies.

5.2.2 Demand Management

Demand management can provide similar services to the electric system as energy storage technologies. Demand management programs take advantage of new capabilities in communication and control, enabling two-way communication with loads as small as 5 kW. Demand management not only provides similar services to energy storage, but also in many cases is actually a kind of energy storage. For example, selective timing of the cooling of buildings, or heating of water, make use of the inherent thermal storage in buildings or insulated water tanks.

Some loads can be controlled on very short time scales, and verification of their performance is nearly instantaneous. Loads in the residential sector, including air conditioning and water heating, as well as industrial loads such as cold storage warehouses and district energy systems are examples of demand response solutions that also incorporate a thermal energy storage component[26]. Municipal water systems can sometimes provide the direct small scale equivalent to pumped storage hydro by timing the reservoir refill to the needs of the power grid. Irrigation systems may have similar capabilities.

Although demand management in some cases provides the equivalent to energy storage, it has its own challenges. Accessing and aggregating meaningful quantities of distributed kilowatt-level loads can be very labor intensive, may have relatively high initial costs, and can take substantial resources to maintain. Coordinating utility interests and consumer interests can be a challenging paradigm shift as well. Nevertheless, demand management has the capability to directly compete with electrical energy storage technologies.

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[25] Bonneville Power Administration (2013) BPA revises policy for managing seasonal power oversupply. Portland, OR.

[26] Bonneville Power Administration (2013) Technology Innovation Project 220: Smart End-Use Energy Storage and Integration of Renewable Energy. Portland, OR.

5.2.3 Market Mechanisms

Implementation of real-time markets for balancing services across wider portions of the Western states would reduce the cost of the services and potentially reduce the total amount of necessary reserves. Many western markets have traditionally traded across multiple utility boundaries through bilateral agreements in one-hour increments. This effectively places the burden of all intra-hour variability on individual utilities. Larger, faster (i.e., trading more frequently than hourly) markets allow wider access to flexible resources across the region.

Current efforts to enable regional or WECC-wide Energy Imbalance Markets must be monitored, as the outcome will certainly affect the opportunities for energy storage to provide renewable energy integration benefits[27]. Wider implementation of markets will substantially reduce the demand for new flexible resources. It should be noted however, that the PNNL study of WECC cited in section 5.1 assumed a great deal of market aggregation. In other words, the need for balancing services, and opportunities for storage may be significantly higher than projected in that study if market consolidation does not move forward.

5.3 Longer Term Outlook

The Duck Curve shows how different a system will need to operate with a substantial fraction of power coming from variable energy resources. Very high levels of VER penetration will be needed to power a grid that no longer relies on fossil fuels as a significant contributor to meeting demand. The economics for bulk energy storage may change dramatically in such a system. Whereas today, bulk energy storage and arbitrage may provide a minority of the value derived from energy storage, which may significantly change in systems where 30% or more of the energy comes from VER. With larger contributions from VER come more frequent times of oversupply. In turn, more frequent oversupply periods results in increased energy arbitrage opportunities.

The focus of this paper is primarily on the next decade or so. Today, renewable resources are being pursued mainly in response to state renewable portfolio standards. The state standards are in place for a number of reasons that include:

1. Desire to localize production of energy and reduce dependence on imported energy
2. Stimulate local employment—especially in economically disadvantaged rural areas
3. Reduce air emissions associated with fossil generators
4. Stimulate a production pipeline for renewable resources, helping to reduce costs through economies of scale
5. Address threat of climate change.

Although climate change is just one of many purposes served by the state standards, it is a clear subtext for them. Very ambitious targets have been set in Europe for reductions in carbon emissions to address climate change[28] and California has imposed a cap and trade system for reducing carbon emissions. It is possible that the status quo will remain. However, as the concerns over climate change are materialize, the US may end up undertaking a much more aggressive stance over carbon emission reductions.

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[27] Federal Energy Regulatory Commission (Feb. 2013) Staff Paper: Qualitative Assessment of Potential Reliability Benefits from a Western Energy Imbalance Market. Accessed at http://www.westgov.org/PUCeim/meetings/2013sprg/briefing/03-08-13FERC-EIMrbqa.pdf

[28] "European Council reconfirmed in February 2011 the EU objective of reducing greenhouse gas emissions by 80-95% by 2050 compared to 1990," *A Roadmap for Moving to a Competitive Low Carbon Economy in 2050*, The European Commission, March 2011.

Much of today's opportunity for energy storage services can be tied to the provision of short-duration (less than one hour) energy services. That will likely change for systems largely dependent on renewable resources. Storage may be needed over periods of days to months. Electrification of transportation is expected to be needed to reach ambitious carbon reduction targets[29]. In short, if the US joins efforts to substantially curtail carbon emissions the opportunity for energy storage may be expected to change in quality and quantity.

5.4 Summary

The rapid development of variable renewable generation is opening a significant opportunity for energy storage in the west. That opportunity is expected to grow with the growth of VER, and its character may change over time as the system experiences higher fractions of energy coming from VER. The incremental need for energy storage or energy storage alternatives has been estimated as 1.5 GW for the WECC in 2020—assuming substantial balancing area consolidation and market development.

Alternatives to electrical energy storage exist in the form of more sophisticated control of variable energy resources; managing demand where there may be inherent storage capabilities; and developing larger, faster markets. These opportunities face their own challenges and costs, but must be considered viable alternatives to electrical energy storage technologies.

Meeting nearer term (2020) renewable energy targets suggests opportunities for energy storage technologies that can store over periods of minutes to hours. Longer term, if the US develops plans to reduce carbon levels consistent with European targets, the market for energy storage could become much larger and require storage over periods of hours to weeks or perhaps months.

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[29] See: *The Energy Report: 100% Renewable Energy by 2050*, WWF, January 2011.

6 Valuation Techniques

6.1 Overview

Energy storage presents a challenge to regulators and policy makers. Power generating resources have tended to be added to systems in order to reliably meet demand at times of system peaks or to ensure sufficient energy is available (chiefly hydro systems) to meet load through the year. Energy storage provides both generation and load—it can add generation to aid in meeting peak demand, while also presenting additional energy requirements to take greater advantage of generation during low load periods. Energy storage resources may find economic application for other reasons altogether, such as postponing or eliminating transmission or distribution system upgrades. Historically, bulk energy storage has been justified on the basis of diurnal price variations, but recent studies have shown as much value coming from provision of ancillary services.

Approaches to valuing energy storage fall into two main categories: Market price methods, and power system dispatch models. Market price approaches tend to be easier to implement and can form the basis for determining that more sophisticated methods are warranted.

Power system dispatch models are a mainstay of power planning studies. However, determining the ancillary service value usually requires models capable of operating in time steps of 1-5 minutes. Models capable of doing that are relatively limited at this time, data on those time scales can also be difficult to find, and resulting model runs may have unacceptably long run times. Most studies have been done using hourly models, with reserve requirements as inputs calculated outside the models. The approach can work well when the ancillary services are defined as reserve requirements (e.g., in traditional vertically integrated utilities without ancillary service markets or sub-hourly trading).

Many of the published energy storage value studies focus on the generic economics— comparing the cost of an energy storage facility to the benefits of adding storage to an existing system. That type of approach is the type of valuation that might be undertaken by an independent developer. From the utility perspective, analyses are more commonly made in comparison to one or more alternative investments needed to meet certain power system requirements. For example, an energy storage project might be compared against the cost of increasing transmission capacity, or adding a peaking generator. That type of analysis is often necessary to capture the unique benefits in a particular application where the alternative is not the existing system, but some other investment necessary to maintain system reliability.

Important questions to address in undertaking or understanding any valuation study are:

- What value streams are analyzed, which are not?
- Does the analysis seek to address a specific power system need against an alternative?
- Is the analysis based on a market-price valuation, and if so, does it account for the market price effects of the added unit?
- Are environmental costs and benefits addressed?
- Does the evaluation look at a range of futures (e.g., load growth, fuel prices, renewable penetration, etc.), and if not, is there some evaluation of the sensitivity of the results to the assumed parameters?

6.1.1 Energy Storage Operational Optimization

Another significant challenge for modeling energy storage is that the optimum operation of storage under stochastic uncertainties around price and load, combined with the time dependent nature of storage, make it an open area for research[30]. The main complicating factor for energy storage is that a decision to store or generate power at one time affects future operability. For example, filling the storage at one point in time precludes additional storage at a later time until energy is withdrawn. In other words, actions now affect the resource available at later times. This property, together with uncertainties about the future, makes optimization a mathematically challenging problem. Inclusion of storage in dispatch models usually entails assumptions around expected operations.

6.2 Market Price Method

The opening of transparent electric power markets in the late 1990s, and the development of ancillary services as components of those markets, provides an opportunity to establish a face value for some energy storage services. For example, historical diurnal price spreads can be used to estimate the value of providing bulk energy storage service—moving energy from low price hours to higher price hours. History is of course not a predictor of future value, but this is a place to start.

Similarly, where market prices for ancillary services exist, the value of providing those services can also be assessed. There can be interplay between and among various potential services that may need to be considered. For example, choices may need to be made between providing balancing services and contingency reserves. At some point it may be more cost effective to provide one or the other of the services, opening up the opportunity to optimize the operation among various services that may be provided. The California ISO has an optimization algorithm to maximize the value of the available resources, but that level of sophistication may be missing from many market price analyses.

Locational or zonal energy market prices can also provide insight into the value of relieving transmission congestion. The value of a specific proposed project in one location could be significantly different than in a different location.

Market price methods can help inform decisions, but should probably be a first step in a valuation process. Prices can evolve over time, but there is potentially an even bigger vulnerability of the method. The market price method assumes that a new market entrant could have received the historical market price had it been present at that time. However, market prices are roughly based on the marginal cost of providing a service with the available resources at that time. If the quantity of services traded on the

[30] See for example:

- P. Brown, J. Peas Lopes, and M. Matos, "Optimization of pumped storage capacity in an isolated power system with large renewable penetration," Power Systems, IEEE Transactions on, vol. 23, no. 2, pp. 523–531, 2008.
- C. Abbey and G. Joos, "A stochastic optimization approach to rating of energy storage systems in wind-diesel isolated grids," Power Systems, IEEE Transactions on, vol. 24, no. 1, pp. 418–426, 2009.
- S. Boyd, N. Parikh, E. Chu, B. Peleato, and J. Eckstein, "Distributed optimization and statistical learning via the alternating direction method of multipliers," Foundations and Trends in Machine Learning, vol. 3, no. 1, pp. 1–122, 2010.

market is small compared with the added resource, the new resource can have a major effect in depressing prices.

In addition, the marginal cost of ancillary services for conventional generation is based on opportunity costs. Opportunity costs are determined from the value that could be received by the resource from providing a different service to the market. For example, a resource bidding into the contingency reserve market could alternatively be operated to provide energy to the market. In the ancillary service auctions, it will be paid that opportunity cost to make it indifferent between providing energy and providing reserves. For some energy storage technologies, there may be no other alternative. If a project is built to provide frequency control, it could become a price taker and potentially collapse the market price for that service. There are also techniques that can estimate the effect of new resources on price[31].

Another modeling difficulty revolves around making assumptions about the level of foreknowledge of pricing. It is simple to assume that the storage device takes the highest price in a given day, but that is not likely known in real time. For example, a storage device with three hours of storage must choose which hours are the most beneficial for purchasing, and which for selling. In actual operations, this may not be known with precision. Similarly, the optimal tradeoff among various services may also not be clear in operations. Techniques for taking account of the limited availability of information have also been employed to address this vulnerability[32]. In structured (ISO) markets, the system operator has information that may be close to perfect foreknowledge for at least the next few hours, and can dispatch units close to their optimal value.

6.3 Power System Dispatch Model Method

Power system dispatch models use grid simulation tools that model the operation of the entire power system, including generation, load, and transmission facilities. These models calculate production costs associated with meeting demand under given constraints (e.g., transmission, emissions, energy availability). Production costs include the cost of fuel and operation and maintenance (O&M) that result from providing both energy and ancillary services in a manner that minimizes overall production cost. Costs associated with emissions can be computed as well, and often may optionally be included in the optimization logic. The investment costs are generally handled outside the models, or at least separately from the operations logic since they do not affect how the system is operated.

The value of a new power system component is estimated by comparing the difference in production cost between two simulations. The two simulations can be either: with and without the added storage facility, or a comparison between a study with the storage facility and one with an alternative device (e.g., peaking generator or transmission line). Studies are done in the context of many assumptions about loads, emission requirements and costs, and generator fuel prices. These may be varied and the production cost differences recomputed under a range of scenarios to give an idea of the range of costs that might ensue given uncertainties about the future.

An important difference between market price-based methods and dispatch model methods is how they capture the capacity value of new resources. Historical market prices may or may not include scarcity pricing -- very high prices that occur when the system demand approaches the total supply of generation. Dispatch models capture only the operational value of a new storage device. The value of

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31 Sioshansi, R.; Denholm, P.; Jenkin, T.; Weiss, J. (2009). Estimating the Value of Electricity Storage in PJM: Arbitrage and Some Welfare Effects. Energy Economics (31); pp. 269–277.

32 Ibid.

resource adequacy needs to be calculated separately and combined with the operational value to produce a more complete value of a storage device. Again, this may be addressed by comparison studies of energy storage against an alternative generator that provides the needed service (e.g., meeting peak load).

Most commercial system dispatch models are time-sequential, stepping through time in increments. Time increments can theoretically be any size, with most models choosing hourly time increments as a good trade-off between level of detail and modeling costs. Modeling costs include data collection and validation, and model run times. Going to one-minute time steps from hourly time steps can cause a sixty-fold increase in both data requirements and run time.

The importance of sub-hourly modeling has increased in recent years with the advent of re-regulated markets that clear on time-frames as short as five minutes. To the extent it is desired to capture the need and value of certain fast-acting ancillary services such as frequency control, modeling on a one-minute basis may be necessary. Some studies have shown that the value of providing ancillary services from energy storage may equal or even exceed the arbitrage value potentially available to bulk energy storage (moving energy from high price hours to low price hours). This highlights the importance of accurately assessing production cost effects on sub-hourly bases.

6.3.1 Ancillary Service Representation

Historically, ancillary services have been represented in hourly models as reserve requirements—generation needed on the system, but not available to meeting hourly energy demands. Three ancillary services are most commonly represented in dispatch models are: contingency, regulation, and flexibility reserves. The quantity of needed reserves are sometimes calculated outside the model and input as a reserve requirement. Models have generally become more sophisticated in their treatment of reserves, with some calculating reserve requirements based on contemporaneous system parameters (e.g., as a function of current demand level, wind generation, etc.). The most detailed models simulate the operation of reserve generation.

6.3.2 Energy Storage Representation

Most commercial production cost models have algorithms specific to representing energy storage. Important parameters include the maximum rates at which energy can be stored or generated, the energy storage capability, ramp rates, operational range, minimum up and down times, and conversion efficiency (may be a function of state of charge and ramp rate).

An important component of the energy storage logic is how the energy storage is managed. Receiving the maximum possible value from energy storage would necessitate perfect knowledge of future prices and operations. These are not available in practice and logic needs to be imposed to reasonably simulate how the facilities would actually operate. In older algorithms, storage was assumed to store energy at night for release during daytime heavy load (and high price) hours. This type of algorithm may be insufficient to capture the value of storage in high renewable resource penetration scenarios where the optimal operation may be very different from the assumed diurnal pattern. For example, the highest value in a solar-heavy system may be to rapidly store energy over the morning sunrise, and discharge as the sun sets in the evening—the timing of which is different over the seasons.

Without perfect foreknowledge of market prices through time, algorithms must look ahead over some time horizon—possibly a day or a week—and establish a target storage content level for the end of that period. Target end-of-period storage levels can be fixed values or be based on situational awareness. There can be a range of sophistication in energy storage control algorithms.

The most common representation of energy storage in system dispatch models is pumped hydro. It may be necessary to manage input assumptions or work directly with programmers to implement other technologies.

6.4 Survey of Valuation Results

Comparing results from studies with different assumptions, of different technologies, situated in different regions, using different methods, and valuing different services is fraught with difficulty. Nevertheless, some results of recent studies are provided here with the caveat that the numbers are nearly meaningless out of context, and readers are urged to review the details in the cited references. Table 6.1 shows results from a range of market price based studies. Table 6.2 contains a listing of recent studies performed with the aid of power system dispatch models.

Table 6.1 Survey of energy storage valuation analyses based on market price studies in restructured markets (Source: The Value of Energy Storage for Grid Applications, Denholm; P., et al; NREL, May 2013)

Market Evaluated	Location	Years Evaluated	Annual Value ($/kW)	Assumptions
Energy Arbitrage	PJM[a]	2002-2007	$60-$115	12 hour, 80% efficient device. Range of efficiencies and sizes evaluated. Also considers price difference suppression effect in a market setting using price/load relationships.
	NYISO[b]	2001– 2005	$87–$240 (NYC) $29-$84 (rest)	10 hour, 83% efficient device. Range of efficiencies and sizes evaluated.
	USA[c]	1997-2001	$37–$45	80% efficient device. Evaluates ISO-NE, CAISO, PJM
	CA[d]	2003	$49	10 hour, 90% efficient device.
	CA[f]	2010-2011	$25-$41	4 hour, 90% efficient device.
	CA[h]	2011	$46	16 hour, 75% efficient pumped storage device.
Regulation Reserves	NYISO[b]	2001-2005	$163-$248	
	USA[e]	2003-2006	$236-$429	PJM, NYISO, ERCOT, ISO-NE.
	CA[f]	2010-2011	$117-$161	Co-optimized arbitrage and regulation, most value is derived from regulation.
Contingency Rerserves	USA[e]	2004-2005	$66-$149	PJM, NYISO, ERCOT, ISO-NE.
Combined Services	CA[f]	2010-2011	$117-$161	Arbitrage and regulation, most value is derived from regulation.
	CA[h]	2011	$62-$75	Arbitrage, regulation, and contingency. Included operational constraints of pumped storage.
	USA[g]	2002-2010	$38-$180	Arbitrage and contingency. CAISO, PJM, NYISO, MISO.

[a]Sioshansi, R.; Denholm, P.; Jenkin, T.; Weiss, J. (2009). "Estimating the Value of Electricity Storage in PJM: Arbitrage and Some Welfare Effects." *Energy Economics* (31); pp. 269–277.
[b]Walawalkar, R.; Apt, J.; Mancini, R. (2007). "Economics of Electric Energy Storage for Energy Arbitrage and Regulation in New York." Energy Policy (35:2007); pp. 2558–2568.

[c]Figueiredo, F.C.; Flynn, P.C.; Cabral, E.A. (2006). "The Economics of Energy Storage in 14 Deregulated Power Markets." Energy Studies Review (14); pp. 131–152.
[d]Eyer, J.; Iannucci, J.; Corey, G.; "Energy Storage Benefits and Market Analysis Handbook: A Study for the DOE Energy Storage Systems Program," SAND2012-9422. Albuquerque, NM: Sandia National Laboratories, SAND2004-6177 (2004).
[e]Denholm, P.; Letendre, S.E. (2007). "Grid Services From Plug-in Hybrid Electric Vehicles: A Key to Economic Viability?" Electrical Energy Storage – Applications and Technology Conference,; September 25, 2007.
[f]Byrne, R.H.; Silva-Monroy, C.A. (2012). Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation. SAND2012-3863. Albuquerque, NM: Sandia National Laboratories.
[g]Drury, E.; Denholm, P.; Sioshansi, R. (2011). "The Value of Compressed Air Energy Storage in Energy and Reserve Markets." Energy (36); pp. 4959-4973.
[h]Kirby, B. (July 2012). Co- Optimizing Energy and Ancillary Services from Energy Limited Hydro and Pumped Storage Plants. Palo Alto, CA: EPRI, HydroVision.

Table 6.2 Listing of recent dispatch model valuation studies (Source: Denholm; Jorgenson; Hummon; Jenkin; Palchak; The Value of Energy Storage for Grid Applications; National Renewable Energy Laboratory, 2013).

Location	Model	Notes
Western Interconnection[a]	PROMOD	Evaluates arbitrage and renewable energy balancing services for a variety of devices in various locations throughout the Western Interconnection
Maui[b]	PLEXOS	Evaluates several storage technologies providing operating reserves and arbitrage/time-shifting. Considers changes in fuel use and renewable curtailment.
MISO[c]	PLEXOS	Preliminary analysis of storage, identified challenges in simulating both day-ahead and real-time markets in a large system.
MISO[d]	PROSYM	Evaluated a proposed compressed air energy storage project in Iowa.
Idaho[e]	AURORA	IRP simulated using light load hour wind generation as the fuel source for pumped storage used to provide heavy load hour generation.
Western Interconnection[f]	PLEXOS	Simulated adjustable-speed pumped storage hydro-generators in base (14% in WI) and high renewable generation (33% in WI) scenarios.

[a] Kintner-Meyer, M, et al; National Assessment of Energy Storage for Grid Balancing and Arbitrage: Phase 1, WECC; PNNL, June 2012.
[b] Ellison, J.; Bhatnagar, D.; Karlson, B. (2012). "Maui Energy Storage Study." SAND2012-10314. Albuquerque, NM: Sandia National Laboratories.
[c] Rastler, D. (November 2011). "MISO Energy Storage Study Phase 1 Report." Palo Alto, CA: Electric Power Research Institute.
[d] Black & Veatch Corporation. (March 2005). "Iowa Stored Energy Plant Economic Feasibility Analysis, Final Report." Centennial, CO: Black & Veatch.
[e] Idaho Power Integrated Resource Plan, 2013.
[f] Guo, T.; Liu, G.; Yu, L.; Energy Exemplar; Koritarov, V.; Argonne National Laboratory; "Adjustable Speed Pumped-Storage Hydro-Generator (PSH) Evaluation by PLEXOS" (October 2013)

7 Policy Considerations

7.1 Overview

Energy storage development has lagged far behind the development of variable renewable energy resources. Significant flexibility existing in today's power systems is being tapped more extensively to accommodate the new variability. More emphasis is being placed on market efficiencies and demand side management to find sources of flexibility needed to accommodate the new variable energy resources. The resilience and flexibility of the existing system (both resources and institutional/market structures) are rightly being developed to the fullest extent before embarking on highly capital-intensive new resources. Nevertheless, with the expansion of variable generation expected to continue, power systems must be prepared to add flexibility beyond what may be available today, and to do so in an economic, reliable, and environmentally benign manner.

A basic regulatory challenge for energy storage is the regulatory concern that resources need to either be regulated, paid through the regulated tariff billed to all rate payers, or they need to be competitive and paid through market prices. Allowing regulated assets to compete in competitive markets can cause market distortions. However, keeping regulated storage out of markets risks losing some of the system benefits because the same device can be useful for both transmission and distribution system capital deferrals and for generation services (e.g., arbitrage & ancillary services).

Developers reasonably face competition on price and efficiency, but it is also important to examine policies that unproductively hinder development of energy storage, and new policies needed to overcome unnecessary barriers to the cost-effective implementation of energy storage. There are three general areas[33] in which changes in policy may need to be considered:

1. Valuation and Markets
2. Regulatory Treatment
3. Development Risk

There are significant efforts underway[34] to address some of the barriers faced by energy storage. Most notably the recent FERC orders (755 and 784) have the effect of opening ancillary service markets to energy storage. Policies are being implemented at the state level as well, both for implementing the FERC orders and to encourage or outright mandate energy storage development. For example, California's legislation[35] directing the California Public Utilities Commission to develop methodology for calculating levels of economic energy storage for state utilities to target. These policies and proposals represent recognition that the playing field needs to be adjusted to ensure fair and appropriate development of energy storage.

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[33] Adapted from *Market Policy Barriers to Deployment of Energy Storage*, Sioshansi, Denholm, Jenkin, Economics of Energy and Environmental Policy, 2012.

[34] For a listing of proposed policies, see: http://www.energystorageexchange.org/policies.

[35] *California Pub. Util. Code § 2835(a)(3),* see http://www.leginfo.ca.gov/cgi-bin/displaycode?section=puc&group=02001-03000&file=2835-2839.

7.2 Valuation and Markets

The value of energy storage has historically been based on the difference between light load hour prices and the higher prices during heavy load hours in the wholesale electric market. This represents the expectation that the main value of energy storage derives from purchasing low price electric power at night for storage, and generating during the day when prices are higher. The reality is more complex than that.

Storage brings all the values associated with other generation including: the provision of ancillary services such as contingency reserves; regulation and load following reserve; and transmission and/or distribution system support. Storage can also bring special advantages associated with speed of response, bi-directionality of reserve capability, and low or zero emissions.

Policies enter into valuation in several ways. In the bi-lateral markets of much of the west, standard utility valuation methods may focus primarily, or even exclusively on the relative cost of energy and peaking capability. Such methods may miss some of the other values brought by energy storage. Regulatory commissions have a role in the assessment methodology. In Oregon for example, the state PUC has asked utilities to calculate the availability of, and demand for, flexible resources.

In the organized markets such as the California Independent System Operator (CAISO), ancillary service markets have been in operation for over a decade, and historically were largely irrelevant to total market value (e.g., in the range of 1-2% of total financial settlements in CAISO), but have gotten more attention due to the focus on improving the quality of frequency regulation and response. FERC orders 890, 755 and 784[36] mandated organized markets to specifically recognize the quality (e.g., ramp rate and response time) of generation bidding into the markets while also requiring more standardization of payments for these services outside the organized markets.

Ancillary service markets have already begun opening the door to energy storage technologies where they have been implemented (e.g., a 20 MW flywheel project in the New York ISO and a 1 MW battery in PJM). These investments were made possible, in large part, by Order 890, which was issued by the Federal Energy Regulatory Commission (FERC) in 2007 and requires wholesale markets to consider non-generation resources (including storage and DR) for grid services.

System-wide benefits include reduced ramping and cycling on power generators that may incur significant degradation responding to variable generation on the system. Costs show up as increased operations and maintenance and higher outage rates. Most new energy storage technologies are designed for rapid ramping without incurring degradation. However, the cost savings are not reflected in the market prices seen by the energy storage market participants.

Whether market prices provide enough economic incentive for any generation expansion is an open question. Low natural gas prices and the advent of low variable cost resources such as wind and solar have depressed market prices generally. It may be that market prices would not reflect the value of resource additions until major shortages were to occur such as happened in 2000 in west coast markets. Restructured markets are considering actively engaging in “capacity payments” designed to provide sufficient incentive to resource developers.

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[36] FERC order 755 mandates compensation for frequency regulation resources, including a capacity payment and a payment for performance that reflects the quantity of frequency regulation service provided by a resource. FERC Order 784 (2013) mandates transmission providers to take into account the speed and accuracy of regulation resources in its determination of reserve requirements for Regulation and Frequency Response service.

Another important concern over recovering costs through market prices for ancillary-service-specific storage is that ancillary service market prices are dominated by the real-time opportunity cost for the supplying generators. A service-specific device has no other opportunities and therefore no opportunity cost. If enough such storage devices enter the market, this can result in a price collapse under current market structures. Unless such new technologies are guaranteed long-term contract payments (as is being considered in California) they could face significant cost recovery risk.

The market's inability to support new market entrants has meant that most resources are being added as part of utility or ISO adequacy studies or in response to state renewable energy standards. Adequacy studies are mostly performed in integrated resource planning (IRP) processes. However, few IRPs take full account of all the values attributable to energy storage[37]. Many may not seriously consider energy storage in any detail given the relatively high price per kilowatt compared with traditional generating resources. An important policy consideration is whether utilities and regulatory bodies need to devise analytical requirements for addressing energy storage valuation, or require energy storage consideration along with generating resources that takes account of the full value potential of storage resources.

7.3 Regulatory Treatment

The regulatory treatment of storage faces significant, but different challenge in both the traditional vertically integrated utility structures and the new restructured markets. In a traditional regulated market, utilities are allowed to rate base "prudent" generation, transmission, and distribution investments in meeting targeted levels of system adequacy and reliability. Storage investments are recovered similarly as part of a least-cost plan. This can be difficult to do using standard capacity expansion tools due to the limitations of models in capturing the full value of storage. It is not common for expansion models to take account of ancillary service needs and value, nor distinguish values among resources that bring different qualities (e.g., ramp rates). Valuation techniques are becoming available, but are still not common and the need for ancillary services may not be well defined or recognized fully by regulators.

In addition to ancillary services is treatment of emissions in the regulatory environment. Historically, utilities and regulators focused on environmental compliance. Environmental regulation of carbon dioxide emissions is still at an early stage. In some jurisdictions utilities have adopted, or allowed to adopt, carbon pricing in considering competing resource expansion options. California's cap and trade system, and British Columbia's carbon tax are explicit expressions of carbon cost that may be taken into account. The Environmental Protection Agency is beginning to regulate carbon emissions as well. The direction for reduced carbon emissions seems clear and some utilities are becoming more concerned over the risk of future, potentially much more stringent, carbon emission regulation.

A reduction in the reliance on fossil fuels, combined with existing and rising state-level requirements for renewable energy, and dramatic reductions in the cost of variable renewable energy resources will almost certainly entail higher penetrations of variable renewable energy resources and some level of energy storage to accommodate them.

One of the most compelling value propositions for energy storage can be as an alternative to transmission line expansions for addressing congestion. The legacy of cultural separation between utility transmission and generation planning functions, underscored for a time by FERC's requirement for

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[37] For example, Avista's 2013 Integrated Resource Plan states that valuing the benefits of storage "…requires new system modeling tools. Presently there are no adequate tools available in the marketplace. Avista is developing a tool it believes will enable detailed valuations of storage (and other) technologies within our existing mix of flexible hydro and thermal system. The results of these studies are not available for this plan, but should be available in the next IRP."

functional separation between transmission and merchant functions has resulted in weak coordination between generation and transmission planning in many IRP processes. FERC's Order 1000 in 2011 recognized the need for better coordination among transmission and generation planning, forming regional transmission planning entities. However, those efforts remain at a nascent stage. More communication between generation expansion and transmission planning functions may be needed or possibly further mandated by regulatory bodies.

7.4 Development Risk

Uncertainty and lack of the ability to rely on markets and regulatory structures to reflect the value of energy storage increases development risk, and discourages potential new market entrants and technologies. Relatively more complex valuation techniques needed to reflect energy storage prudency to regulators might discourage utility planners and management from pursuing prudence declarations with their regulators. Reliance on market prices in nascent markets for new services adds uncertainty in cost recovery for capital-intensive resources as well.

Arbitrage values for energy shaping and ancillary service prices represent highly variable markets that add significant uncertainty to capital recovery. This can be true for other generating resources, but traditional resources can be justified on the basis of capacity or energy alone. Much of the value of energy storage may be based on more efficient provision of ancillary services, energy arbitrage and emissions reduction. The dependence on these other sources of revenue adds risk to projects.

These uncertainties contribute to development risk, discourage third party development, and can dampen interest in utility personnel from pursuing energy storage from the regulatory commissions. To be sure, the risks are real and the risks must be shouldered if the resources are to be developed. It is important to address who bears the risks, and how will the risks be shared by power system participants.

The danger in not acting on prudent risk sharing mechanisms is to potentially forego a resource that may be crucial to developing a cost effective, environmentally responsible power system. It is reasonable to strive to spread the risks among the potential beneficiaries, and to minimize risks where possible. Policies can be adopted to manage risks to encourage responsible development.

Policies that seek to remove barriers or even encourage energy storage can be mechanisms for managing risk. Developing energy storage at a relatively small but significant level tests the waters and provides a market over which project proposals and technologies may compete. Without some level of development, the risks may be left open, technologies undeveloped and opportunities lost. The converse of that is the potential for over-development of energy storage at the expense of potentially cost effective alternatives such as demand management and more sophisticated controls on renewable generation. Care must be taken to strike a balance, especially with respect to technology-specific incentives, so as not to forestall developments of competing alternatives.

California's mandate to develop cost effective energy storage is one such policy. Another is the Puerto Rico Energy Authority's announcement[38] that all new photovoltaic resource development be accompanied by minimum energy storage to maintain system reliability and frequency control. Mandates such as these have the effect of minimizing development risk for an identified level of energy storage. In both cases, care was taken to assess the need for energy storage. In the California case, the need will be based on

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[38] December 12, 2013 Puerto Rican Power Authority press release: http://www.prepa.com/spanish.asp?url=http://www.aeepr.com/noticias.ASP

economic analysis; in the Puerto Rico system case, the need was based on studies of power system reliability and power quality.

7.5 Industry Acceptance and Standardization

7.5.1 Industry Acceptance of New Technologies

A key challenge to the wider adoption of energy storage is utility industry acceptance. Industry acceptance has several important facets. First, regulatory body requirements for prudence tend to foster a high degree of caution among utilities in adopting any new technologies. Utilities also wear the risk of failure under used and useful regulatory standards that add to the cautious approach to any technologies that, though may be mature from a development standpoint, may be new to the utility company.

7.5.2 Lack of Standardized Controls and Interfaces

Another barrier to industry acceptance has to do with the lack of standardized interfaces and controls for energy storage with respect to existing utility energy management systems. While familiar to many hydro-based utilities, energy-limited generators can present unfamiliar challenges to power system operators. A key component of the operational challenge is the recognition that an action at one time, affects the capability of the resource at a later time. This is not the case with most kinds of generators where the fuel is effectively unlimited. Lack of standardized controls and interfaces is a technical challenge, but one that may have policy implications. For example, policies to work across technologies and utility companies to develop standardized interfaces may be contemplated.

Work on standardization is taking place at the National Institute of Standards and Technology (NIST).[39] The issue is also being addressed by the International Electrotechnical Commission (IEC), which recommends[40]:

> *The IEC recommends industry to develop storage management systems which will allow use of a single storage system for not just one but many of the applications described in the IEC study. Controllers and management systems are required which function independently of the types of the batteries being controlled. Also, the control technology should function even when the applications belong to different actors (grid operator, end-use supplier, consumer).*
>
> *For mature EES[41] systems such as PHS, LA, NiCd, NiMH and Li-ion various IEC standards exist. The standards cover technical features, testing and system integration. For the other technologies there are only a few standards, covering special topics. Up to now no general, technology-independent standard for EES integration into a utility or a stand-alone grid has been developed. A standard is planned for rechargeable batteries of any chemistry.*
>
> *Standardization topics for EES include:*
> - *terminology*
> - *basic characteristics of EES components and systems, especially definitions and measuring methods for comparison and technical evaluation*
>   - *capacity, power, discharge time, lifetime, standard EES unit sizes*

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39 See NIST Smart Grid Collaboration Wiki for Smart Grid Interoperability Standards website:http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP07Storage.

40 IEC, Electrical Storage White Paper, December 2011.

41 Electrical Energy Storage.

- *communication between components*
  - *protocols, security*
- *interconnection requirements*
  - *power quality, voltage tolerances, frequency, synchronization, metering*
- *safety: electrical, mechanical, etc.*
- *testing*
- *guides for implementation.*

Given the wide variety of storage technologies competing in the marketplace, with widely varying characteristics and unique control considerations, utility-scale control standards would likely end up addressing control standards at a relatively high level. Given the relative lack of maturity of the energy storage marketplace, standardization is an area that remains open for study and further discussion.

Standardizing communication protocols merits the combined efforts of the various parties involved including; manufacturers, utilities, grid operators, and regulatory agencies. However, it is unclear whether the optimum solution is a single communication standard for energy storage that cuts across all of the actors involved; or whether a more nuanced approach is necessary given the diversity of utility scale systems existing today, and the potentially far different systems in play for behind-the-meter storage solutions.

7.5.3 Cross-Functional Operability

Other barriers may exist due to the unique nature of energy storage compared with other power system components. For example transmission provider may need to develop procedures to allow for energy storage device interactions with the grid to be evaluated more realistically. Requests for an energy storage interconnection project would normally be evaluated as though the device is simultaneously consuming at peak levels as a storage device and generating at maximum levels during system peaks. Standardized guidelines are needed that recognize more realistic operating regimes-- that the storage device would only be generating when other sources are limited, and storing energy when demand is generally low.

7.6 Summary of Policy Considerations

In addition to the legitimate technical and economic challenges energy storage developers face, there also exist policy and market challenges that form less productive development barriers. Market and policy barriers include incomplete valuation of the full benefits storage can provide, regulatory treatment, and financial risks associated with storage project development.

Regulatory treatment tends to require energy storage to focus on the need for energy or peaking capability in order to meet cost recovery standards. Commissions are beginning to consider flexibility as a power system requirement, but lack of clear definitions and requirements present challenges.

Alternatively, costs might be recovered through market transactions—buying and selling services sufficient to recover construction and operating costs. However, recovering costs through current market structures overlooks significant value and may be insufficient to justify investment. Markets are not fully developed for all ancillary services, and market depth can present an additional uncertainty. Markets may not reflect system-wide values such as reduced cycling costs on distant, or variously owned thermal units. In addition, markets have not fully developed around the emissions and emission savings that may be realized from energy storage projects—both conventional pollutants and carbon emissions.

The difficulty of electric power markets to reflect the full system benefit of energy storage, and the relatively high risks associated with the investments suggests a need for policy intervention. There are several reasons inaction on the policy front can have costly implications:

- Cost effective energy storage resources may not be developed and power system costs may be greater than they would otherwise be.
- Progress in improving the cost and efficiency of energy storage technologies may be delayed.
- Higher air emissions may occur by relying on less benign sources of peaking capability and flexibility.

A number of policies have been implemented to support other power generation technologies for various purposes. These include investment and production tax credits, target procurement levels, feed-in tariffs, regulatory requirements revolving around analytical techniques, and others. These policy approaches have various strengths and weaknesses that can be debated.

FERC's directives to balancing authorities to create more formal markets for ancillary services and recognize the relative value associated with response times help realize the value of energy storage technologies. These are needed steps in the right direction, but don't encompass the entirety of valuation, particularly values associated with system-wide benefits. Additional policies being contemplated may be necessary to realize the full economic and environmental benefits available through energy storage.

8 Conclusion

Interest in energy storage has exploded in the last few years, largely fueled by the rapid development of variable renewable energy resources. Energy storage technologies span a range of approaches, capabilities, and development maturity. Relatively high capital costs of currently mature technologies compared with traditional generating resources has hampered their development. Other barriers to development exist that suggest the importance of policies designed to facilitate energy storage development. Some such policies have been implemented at state and federal levels, while others continue to be considered.

Demand for services that energy storage can provide is expected to increase with the growth of renewable energy resources. Energy storage is not the only way to provide the needed services. Example alternatives include restructured markets (e.g., balancing area consolidation and energy imbalance markets), demand management and more sophisticated controls on variable renewable resources (at the expense of energy generation). An emphasis on energy storage is merited as power systems continue to move toward higher levels of renewable-sourced generation, and reduced reliance on fossil fuels.

Interest in energy storage is spurring improvement in many of the technologies that are at relatively early stages of maturity. Competition among technologies is fostered by policies that reduce barriers and provide incentives for developing energy storage. Prudent policies attract investment crucial to continued technology development without overshadowing alternatives to energy storage (demand management, market development, and controls on renewable resources).

After examining much of the literature available on energy storage, the following may be concluded:

- Complexities in calculating and realizing the value of energy storage results in a failure to recognize that the full system benefits of storage, at least partly because of the complexity involved.
- Energy storage includes both mature technologies and technologies that appear to have much development potential.
- Energy storage deserves to be evaluated on par with other resources in utility resource plans.
- Barriers (e.g. regulatory recovery and utility planning) to energy storage development suggest policy intervention is merited to promote competition among projects and technologies.
- Standardized integration with utility system energy management systems may be lagging and merits development.

Today, generation rises and falls to meet demand by tapping existing energy storage available in hydro reservoirs, natural gas production and storage fields, gas pipelines, and coal piles. As reliance on variable generation grows, so will the need for balancing services and opportunities for storage during times of oversupply. Policies supportive of energy storage are providing support for the rapid development of a wide range of promising storage technologies in the development phase.

Longer term, if policies are adopted to reach very high levels of renewable penetration, storage over longer periods may become economic. Chemical and thermal technologies appear promising to meet that challenge should it arise.

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Appendix B: About Ecofys

Ecofys is a sustainability consulting company doing business in the US and headquartered in Utrecht, The Netherlands. Ecofys combines deep technical knowledge, real-world experience and skills related to renewable resources, emissions, and sustainability analysis. Ecofys has completed projects for energy companies, independent power producers, state authorities and energy consumers around the U.S. and internationally.

With offices in five countries around the world, the US office primarily focuses on Power Systems and Markets, and challenges related to integration of renewable energy in electric power systems. Our interdisciplinary expert team consists of power system engineers and market specialists. Projects typically combine expertise in technical, regulatory and commercial issues related to electricity supply in a changing environment. The Ecofys team commonly employs interdisciplinary approaches to identify and analyze linkages between technical, regulatory and economic systems. Our services cover:

- Conceptual designs, modeling, engineering and optimization of components and electrical infrastructure.
- Advice on technical guidelines and standards as well as grid code requirements.
- Modeling and evaluation of complete power systems and power markets.
- Design and implementation of commercial concepts and products for electricity traders (e.g. wind power prediction).
- Analysis and design of regulations and legal frameworks for the power industry with special attention to specific challenges associated with renewable energy sources.

Ecofys has sister offices in The Netherlands, Germany and the UK (**www.ecofys.com**). Ecofys is a leading knowledge company that creates sustainable energy solutions that impact people's everyday environment. The company has a track record spanning more than 25 years in energy-efficiency, sustainable energy and climate change consultancy, with over 250 staff working internationally in five countries (Netherlands, USA, China, UK, Germany).

Our mission is **sustainable energy for everyone**. Ecofys and the World Wildlife Fund launched The Energy Report, showing the route to a 100% sustainable energy system[42]. The Energy Report concludes that through taking action now, the global energy system can be sustainable, secure, affordable and fully based on renewable sources by 2050. Ecofys is committed to working toward a cleaner, healthier, sustainable energy future.

[42] Download the executive summary or the full report from the Ecofys website: www.ecofys.com/com/publications

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sustainable energy for everyone