Electricity Storage Technology Review



Prepared for

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Office of Fossil Energy

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Contents

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Note about the Review:
The Review is intended to provide a briefing regarding a range of energy storage technologies that includes a detailed listing of primary sources. For that reason, Microsoft® Word, rather than PowerPoint, was used for producing the Review.

Executive Summary

- Objective:
    - The objective is to identify and describe the salient characteristics of a range of energy storage technologies that currently are, or could be, undergoing R&D that could directly or indirectly benefit fossil thermal energy power systems.
    - The uses for this work include:
        - Inform DOE-FE of range of technologies and potential R&D.
        - Perform initial steps for scoping the work required to analyze and model the benefits that could arise from energy storage R&D and deployment.

- Technology Benefits:
    - There are potentially two major categories of benefits from energy storage technologies for fossil thermal energy power systems, direct and indirect.
        - Grid-connected energy storage provides *indirect* benefits through regional load shaping, thereby improving wholesale power pricing, increasing fossil thermal generation and utilization, reducing cycling, and improving plant efficiency.
        - Co-located energy storage has the potential to provide *direct* benefits arising from integrating that technology with one or more aspects of fossil thermal power systems to improve plant economics, reduce cycling, and minimize overall system costs.

- Preliminary Findings:
    - Energy storage technologies with the most potential to provide significant benefits with additional R&D and demonstration include:
        - Liquid Air:
            - This technology utilizes proven technology,
            - Has the ability to integrate with thermal plants through the use of steam-driven compressors and heat integration, and
            - Limits stored media requirements.
            - Of the two most promising technologies, this is the one most ready for immediate deployment.
        - Ammonia Production with Cracking and a Hydrogen Fuel Cell:
            - For thermal integration, this technology is very close to immediate deployment,
            - Eliminates the need for costly cryo-storage of hydrogen, and
            - It offers the opportunity for heat integration and technology adoption as hydrogen electrolysis and fuel cell technology is advanced.

Figure 1. Comparative Matrix with Preliminary Assessment of Energy Storage Technologies

Benefits	Technology Maturity (Experience)	Durability/ Reliability (Degradation)	Duration Capacity (hours)	Dispatch Capacity (MW)	Response Time	Relative Cost	Fossil Themal Integration (Opportunity)
Better (✓✓✓)	High	Limited	High	High	Faster	Low	High
Worse (✓)	Limited	High	Low	Low	Slower	High	Limited
Stationary Battery Energy Storage							
Li-Ion BES	✓✓✓	✓✓	✓	✓✓	✓✓✓	✓✓✓	✓
Redox Flow BES	✓	✓✓	✓✓	✓✓	✓✓✓	✓✓	✓
Mechanical Energy Storage							
Compressed Air	✓✓✓	✓✓✓	✓✓	✓✓	✓✓	✓	niche[1]
Pumped Hydro	✓✓✓	✓✓✓	✓✓	✓✓	✓✓	niche[1]	✓
Thermal Energy Storage							
SC-CCES	✓	✓	✓✓	✓✓	✓✓	✓	✓✓
Molten Salt[2]	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Liquid Air	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓	✓	✓✓✓
Chemical Energy Storage[3]							
Hydrogen (H2)	✓✓[4]	✓✓	✓✓	✓✓[5]	✓✓	✓✓	✓✓✓
Ammonia (NH3)	✓✓[4]	✓✓✓	✓✓✓	✓✓	✓✓	✓✓✓	✓✓✓
Methanol (MeOH)	✓	✓	✓✓✓	✓✓	✓✓✓	✓✓✓	✓✓

Source: OnLocation

Notes:

(1) Compressed Air and Pumped Hydro utilize specific geological formations which are not readily available to all facility locations.

(2) Molten Salt is expanded to include several thermal storage media as the complexity of a high-temperature fluid, as opposed to a stationary/solid media, appears to hold little additional benefit for fossil thermal application.

(3) Chemical Energy Storage consists of several different options, as described in the report.

(4) While conventional hydrogen and ammonia production processes are mature, this report considers newer technologies that are more directly applicable to fossil thermal integration.

(5) Conventional hydrogen storage is relatively mature, however geologic storage is being explored and is similar to Compressed Air storage in technology maturity.

- Other promising technologies include:
  - Super Critical CO_2 Energy Storage (SC-CCES)
  - Methanol with Hydrogen Fuel Cell
- Specific enabling technologies that may benefit from additional R&D include:
  - Electrolysis (generally),
  - Direct Methanol Fuel Cell (DMFC), and
  - High-Temperature Steam Electrolysis (HTSE) that couples 800°C steam with solid-oxide electrolysis to reduce the electricity requirement
- Energy storage technologies that are largely mature but appear to have a niche market, limited application, or R&D upside include:
  - Pumped hydro storage
  - Compressed Air Energy Storage (CAES)

- Energy storage technologies are undergoing advancement due to significant investments in R&D and commercial applications.
- There exist a number of cost comparison sources for energy storage technologies
  - For example, work performed for Pacific Northwest National Laboratory provides cost and performance characteristics for several different battery energy storage (BES) technologies (Mongird et al. 2019).

- Recommendations:
  - Perform analysis of historical fossil thermal powerplant dispatch to identify conditions for lowered dispatch that may benefit from electricity storage.
  - Improve techno-economic modeling tools to better account for the different fossil thermal power plants and their characteristics and expand their storage technology representations to allow for quantitatively evaluating the benefits of energy storage based on grid and integration benefits.
  - Build on this work to develop specific technology parameters that are "benched" to one or more estimates for performance and cost, such as U.S. Energy Information Administration (EIA), Pacific Northwest National Laboratory (PNNL), and other sources of cost estimates, that could be used in modeling and analysis.

Introduction

Project Overview and Methodology

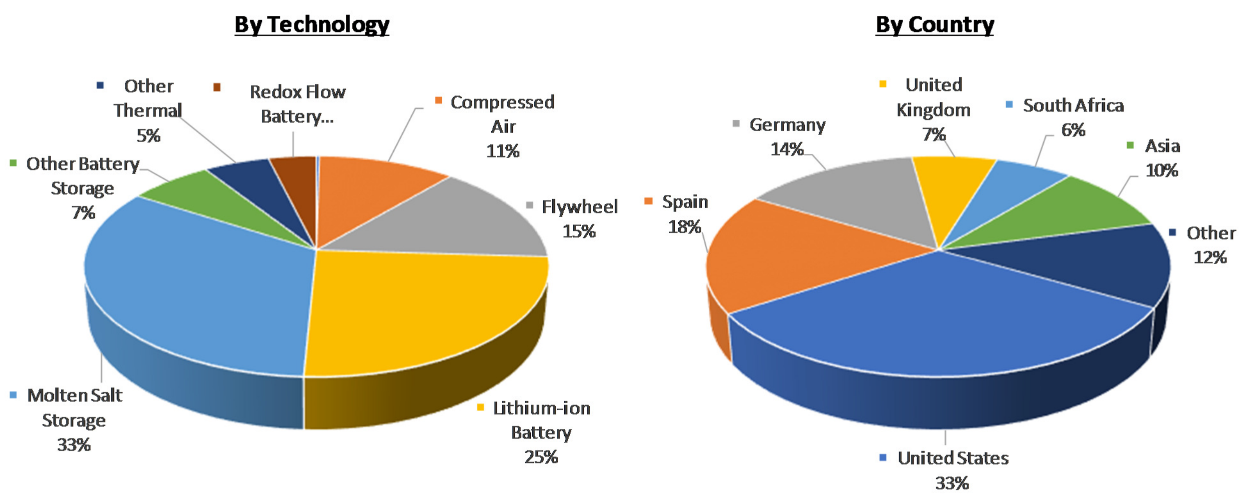
- The **objective** of this work is to identify and describe the salient characteristics of a range of energy storage technologies that currently are, or could be, undergoing research and development that could directly or indirectly benefit fossil thermal energy power systems.
- The **research** involves the review, scoping, and preliminary assessment of energy storage technologies that could complement the operational characteristics and parameters to improve fossil thermal plant economics, reduce cycling, and minimize overall system costs.
- The **report** provides a survey of potential energy storage technologies to form the basis for *evaluating* potential future paths through which energy storage technologies can improve the utilization of fossil fuels and other thermal energy systems.

The work consisted of three major steps:

1) A literature search was conducted for the following technologies, focusing on the most up-to-date information sources available:
    - Stationary battery energy storage (BES)
        - Lithium-ion BES
        - Redox Flow BES
        - Other BES Technologies
    - Mechanical Energy Storage
        - Compressed Air Energy Storage (CAES)
        - Pumped Storage Hydro (PSH)
    - Thermal Energy Storage
        - Super Critical CO_2 Energy Storage (SC-CCES)
        - Molten Salt
        - Liquid Air Storage
    - Chemical Energy Storage
        - Hydrogen
        - Ammonia
        - Methanol
2) Each technology was evaluated, focusing on the following aspects:
    - Key components and operating characteristics
    - Key benefits and limitations of the technology
    - Current research being performed
    - Current and projected cost and performance
    - Research and commercialization status of the technology
3) A comparative assessment was made of the technologies focusing on their potential for fossil thermal powerplant integration in the near term (i.e., commercially available) as well as in the longer term (i.e., opportunities for additional research, demonstration and development).

Worldwide Electricity Storage Installations

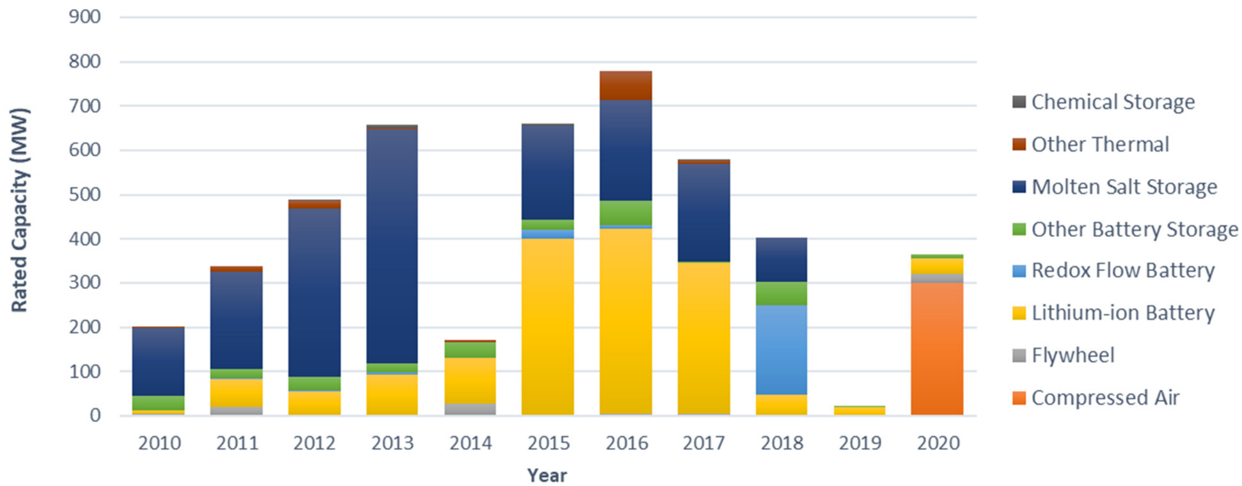
Figure 2. Worldwide Electricity Storage Operating Capacity by Technology and by Country, 2020



Source: DOE Global Energy Storage Database (Sandia 2020), as of February 2020.

- Worldwide electricity storage operating capacity totals 159,000 MW, or about 6,400 MW if pumped hydro storage is excluded. The DOE data is current as of February 2020 (Sandia 2020).
- Pumped hydro makes up 152 GW or 96% of worldwide energy storage capacity operating today.
- Of the remaining 4% of capacity, the largest technology shares are molten salt (33%) and lithium-ion batteries (25%). Flywheels and Compressed Air Energy Storage also make up a large part of the market.
- The largest country share of capacity (excluding pumped hydro) is in the United States (33%), followed by Spain and Germany. The United Kingdom and South Africa round out the top five countries.

Figure 3. Worldwide Storage Capacity Additions, 2010 to 2020



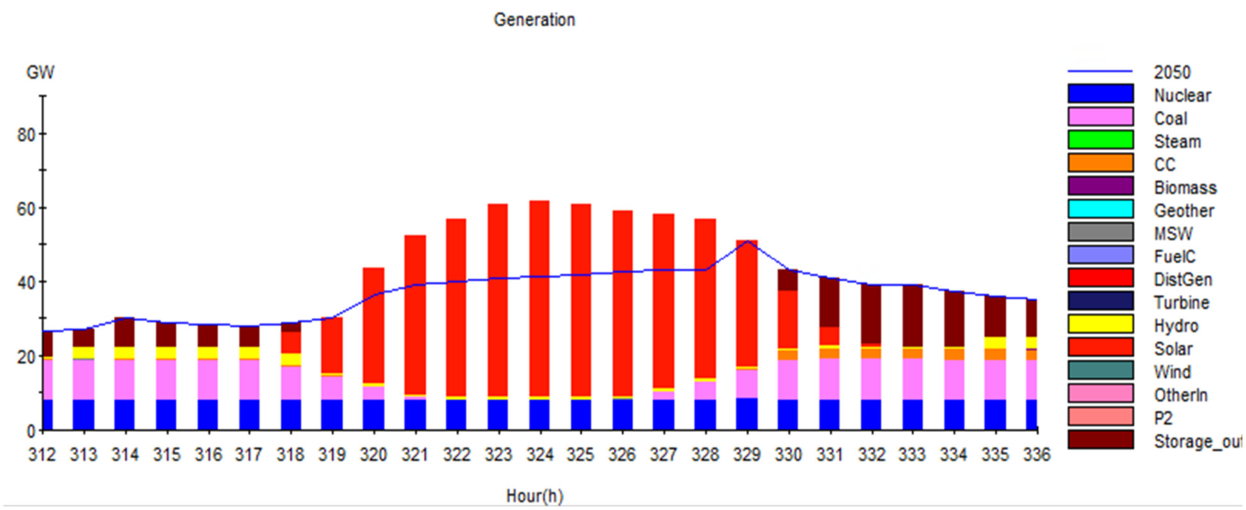
Note: Capacity excludes Pumped Hydro Storage

Source: DOE Global Energy Storage Database (Sandia 2020), as of February 2020.

- Excluding pumped hydro, storage capacity additions in the last ten years have been dominated by molten salt storage (paired with solar thermal power plants) and lithium-ion batteries.
    - About half of the molten salt capacity has been built in Spain, and about half of the Li-ion battery installations are in the United States.
- Redox flow batteries and compressed air storage technologies have gained market share in the last couple of years. The most recent installations and expected additions include:
    - A 200 MW Vanadium Redox Flow Battery came online in 2018 in Dalian, China.
    - A 300 MW compressed air facility is being built by PG&E in California – estimated online date is 2020.

The Issue at Hand: Large Market Penetration of Intermittent Electricity Generation Capacity

Figure 4. Illustrative Example of the Impact of PV Deployment on Generator Dispatch



Source: OnLocation using results from the NEMS REStore Model

- Recent and projected future electricity generating capacity is expected to be increasingly non-dispatchable renewable, especially solar PV, leading to squeezing of other generating sources.
- In addition, most fossil thermal powerplants lack the capability to quickly ramp down generation when the sun rises and ramp up when the sun sets because of thermal cycling limitations.
- The representative 24-hour load profile shown in Figure 4 was created using results of the EIA NEMS REStore model[1]. This profile illustrates some of the challenges facing fossil thermal plant dispatch in regions with large deployment of PV's on the grid.
    - As solar PV generation (shown as the red bars in the chart) ramps up during the mid-day hours, coal generation (pink bars) is squeezed out of the generation mix.
    - Likewise, as PV generation ramps down in the late afternoon hours, coal generation levels are gradually restored to baseload levels.
    - Solar generation that exceeds the system load requirement (blue line) is captured and stored by the system's storage capacity and is then discharged (brown bars) during the shoulder hours when solar generation is not available.
- Fossil thermal plants that have onsite storage capability could store excess generation in the mid-day hours to reduce the need to ramp down during those hours. The stored electricity could then be discharged during hours when solar is no longer available, especially in regions with peak hours that occur later in the day. This would increase the total generation and efficiency of the fossil plant, thereby reducing the need to cycle and its associated costs.

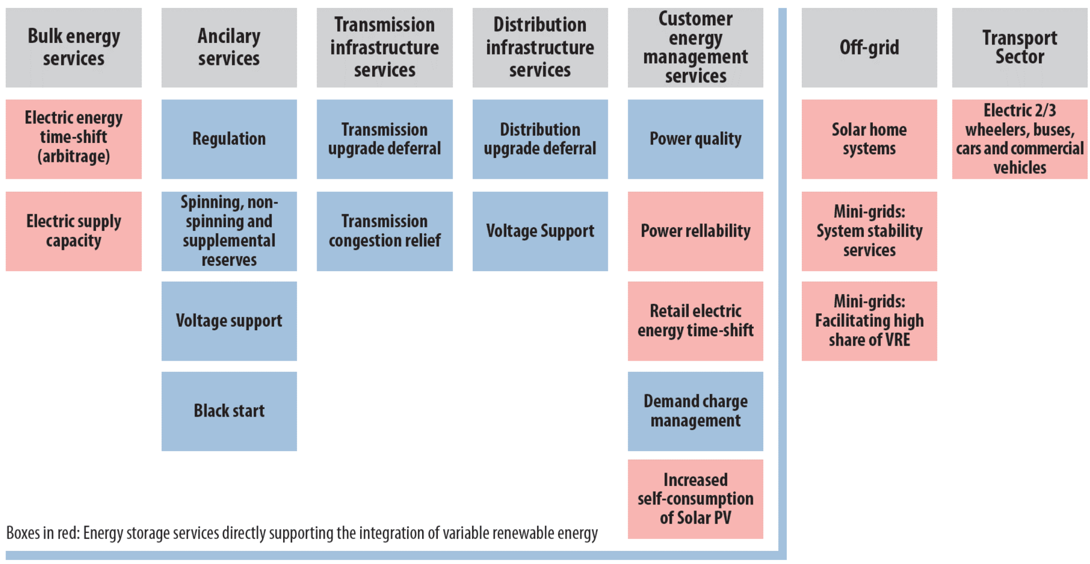
[1] For more information about the EIA NEMS REStore model, see EIA "Assumptions to the Annual Energy Outlook 2020: Electricity Market Module," https://www.eia.gov/outlooks/aeo/assumptions/pdf/electricity.pdf.

Services Provided by Energy Storage Systems

Energy storage systems can provide indirect and direct benefits to fossil thermal powerplants.

Indirect Benefits: Grid-Connected Services Provided by Energy Storage

Figure 5. Overview of Range of Services That Can Be Provided by Energy Storage Systems



Source: (International Renewable Energy Agency 2017)

Electricity storage systems can provide a wide range of services to generators, utilities, and customers when connected to a power grid:

- Generation or bulk energy services
  - **Energy time-shifting/generation arbitrage** involves generating or purchasing electricity at times when electricity rates are low and storing that electricity for sale later when rates are high to reduce costs and/or maximize revenues.
  - **Electric supply capacity and peak demand management** provides support at times of peak demand by storing electricity at off-peak hours and discharging when demand is highest. This allows utilities to defer or eliminate the need for building additional peaking capacity such as combustion turbines.
  - **Capacity firming/smoothing** allows generators to maximize the availability of their generation.
    - For **baseload plants**, storage systems can store electricity during periods of low demand (or high non-dispatchable generation such as solar PV) when baseload plants would normally ramp down their generation, allowing these plants to operate at a higher level. Similarly, during periods of high demand when plants need to ramp up generation, stored electricity can be released to reduce the demand for cycling. Also known as **load following**, energy storage can result is less cycling, which can reduce operating costs, increase plant efficiency, and extend plant lifetime.

    - For **renewable plants**, storage systems can be used to capture solar and wind generation that may exceed demand during certain hours of the day, thus reducing the need to curtail generation. The stored electricity can then be discharged during the "shoulder" hours to smooth out generation, especially for solar generation that ramps up quickly as the sun rises and ramps down quickly as the sun sets, putting a strain on the electric system.
- Grid services
  - **Ancillary Services** provide the necessary support for the transmission of electric power from seller to purchaser to maintain reliable operations of the interconnected transmission system. Examples include frequency regulation, voltage control, black start support, and spinning, non-spinning and supplemental reserves.
  - **Transmission and distribution upgrades** can be deferred to reduce system costs
  - **Transmission congestion** can be relieved by placing storage systems in strategic locations along congested transmission lines. This reduces congestion charges and the potential for supply disruptions.
- Behind the meter
  - Storage systems can be used by customers to provide **backup power** for reliability, **demand shifting** to reduce electricity bills, and **demand charge management** to reduce their average peak load and demand charges (Hewett et al. 2016).

Storage technologies have different attributes that make them more suitable for one type of service over another. Attributes such as storage capacity and duration, response time, round-trip efficiency, cost, and expected lifetime play a role in determining the best application for each technology.

Direct Benefits: Integrating Energy Storage Directly with Generation

- Integrating energy storage directly with generation, also known as "hybrid energy storage," are powerplants with on-site storage.
- Many solar plants have chosen to build on-site storage, including PV plants paired with batteries and solar thermal plants paired with thermal storage such as molten salt.
- NREL estimates that co-locating Li-Ion battery energy storage (BES) with a PV system would save up to 8% in capital costs (Fu, Remo, and Margolis 2018) due to savings arising from:
  - Site acquisition, preparation, and permitting,
  - Shared switchgear, transformer, and control equipment,
  - Installation labor, overhead and profit.

Opportunities for Fossil Thermal Integration with Storage

- Thermal storage technologies are able to store waste heat produced by the fossil powerplant and use it to drive a turbine and supplement the fossil plant's generation during peak hours.
- Chemical storage technologies can use the waste heat for chemical processes such as high-temperature electrolysis and ammonia cracking.
- Battery technologies can store excess electricity produced by the fossil powerplant to maximize generation during peak and off-peak hours.

- Other benefits from fossil/storage integration include:
    - Shared infrastructure such as transformers and transmission lines, thus reducing the investment required for installation.
    - Reduced thermal generator cycling reduces wear and tear on the equipment and improves the plant's heat rate.
    - Storage technologies can provide ancillary services that cannot be met by fossil thermal technologies, providing an additional source of revenue.

Figure 6. Co-Locating Vs. Standalone Energy Storage at Fossil Thermal Powerplants Can Provide Net Benefits Depending on Ancillary Electric Market Structure

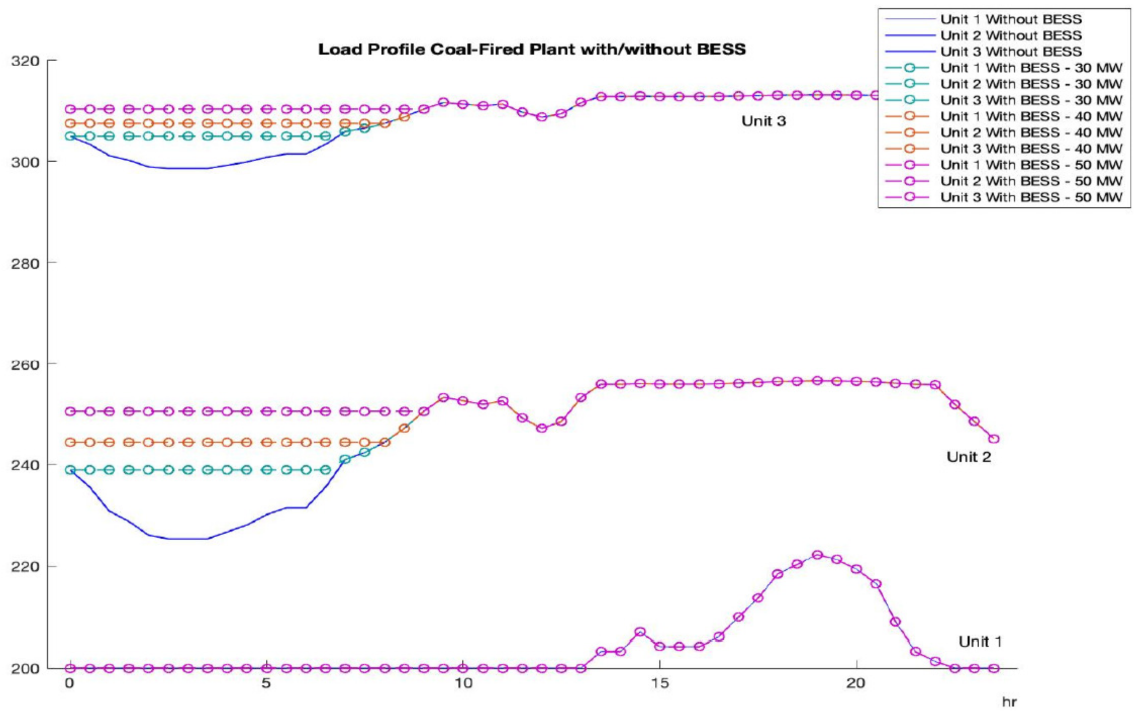


Fig. 7 Load Profile of Coal – Fired Plant with/without BES.

Source: (Sejati et al. 2019)

- Co-locating energy storage with new or existing fossil plants can also save money and increase the value of the fossil plant through the same benefits as described above. In addition, benefits can arise from:
    - Greater utilization of energy that may otherwise be curtailed during periods of low demand and utilize that unit's electricity or steam output to produce an alternative, marketable, product.
    - Reduced wear and tear from thermal generator cycling (Gorman et al. 2020).
    - Improved heat rate due to less cycling, as depicted above.
    - Better returns on installed capacity if electric power markets are not adequately compensating fossil thermal powerplants for their contribution to the electric grid.

Technology Reviews

This section reviews the literature on energy storage technologies and summarizes each as follows:

- Technology Description
- Technology Benefits and Limitations
- Technology Status including research opportunities
- Technology Cost Projections

In performing the work it was found that the technologies can be organized by category, as follows:

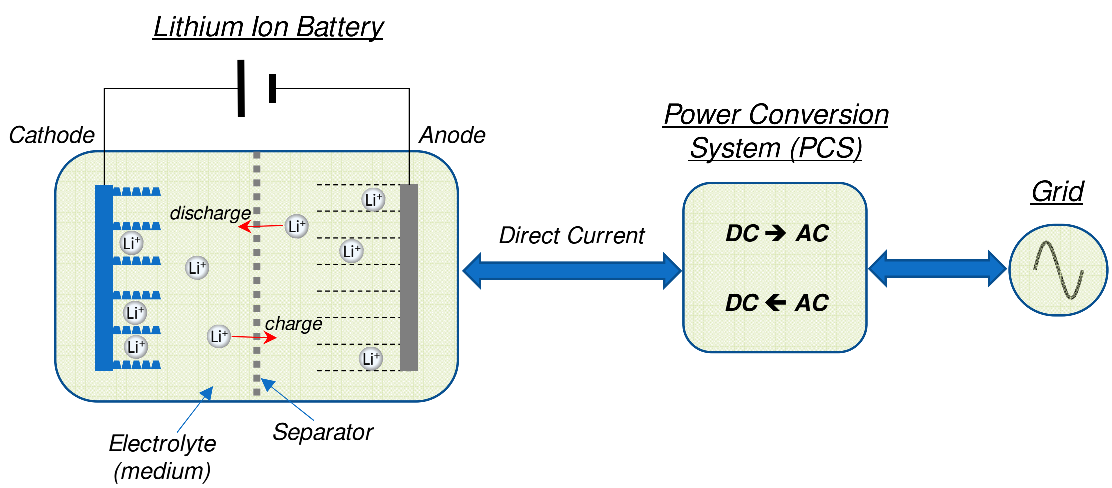
- Stationary Battery Energy Storage
- Mechanical Energy Storage
- Thermal Energy Storage
- Chemical Energy Storage

Stationary Battery Energy Storage

Lithium-Ion BES

Technology Description

Figure 7. Illustrative Configuration of a Stationary Lithium-Ion BES



Source: OnLocation

- A stationary Battery Energy Storage (BES) facility consists of the battery itself, a Power Conversion System (PCS) to convert alternating current (AC) to direct current (DC), as necessary, and the "balance of plant" (BOP, not pictured) necessary to support and operate the system.
- The lithium-ion BES depicted in **Error! Reference source not found.** illustrates the cathode and anode in discharge mode (during charging the electrodes are reversed):
  - Charging: Power is applied to the battery by providing a higher voltage at the positive electrode, which induces lithium ions to be displaced from that electrode that then transport through the electrolyte, through the separator, and are then collected within the negative electrode.
  - Discharging: Power is extracted through reversing the process by applying a load on the battery.
  - The discharge/charge cycle leads to these batteries being referred to as "rocking chair batteries."
- The battery is a self-contained storage device that is sized in a way that considers:
  - Discharge hours (MWh),
  - Maximum required output (MW), and
  - Design life of the battery (number of cycles), which is a function of battery chemistry, expected utilization, and age of the battery.
- The PCS scales with the maximum rated BES output capacity, measured in kW.

- The first batteries were used for consumer electronics such as cellular phones but they have now been scaled for use in electric vehicles and large-scale grid storage applications.
- Li-ion battery cells consist of a graphite anode, metal-oxide cathode, and a lithium salt electrolyte gel. For stationary storage applications, these components are packaged in a pouch or other configuration. Battery cells are integrated into battery modules, which are installed in standard 19-inch-wide racks in a building or specialized container to create an integrated battery system (Aquino et al. 2017).
- The term “lithium-ion” refers to a variety of different chemistries, all of which operate by transferring lithium ions between the electrodes during the charge and discharge reactions. Lithium-ion cells do not contain metallic lithium; instead, the ions are inserted into other materials such as lithiated metal oxides or phosphates in the positive electrode (cathode) and carbon (such as graphite) or lithium titanate in the negative electrode (anode) (Energy Storage Association, n.d.).
- The primary chemistries in use today are:
    - Lithium nickel manganese cobalt oxide (NMC)
    - Lithium manganese oxide (LMO)
    - Lithium iron phosphate (LFP)
    - Lithium titanate (LTO)
- NMC are the most popular chemistries in grid-scale storage systems because they demonstrate balanced performance characteristics in terms of energy, power, cost, and cycle life.
- Li-ion batteries are highly sensitive to temperature. The building or container housing the battery system typically includes an active cooling system to ensure the batteries stay within an optimal temperature range of around 70°F (Aquino et al. 2017).

Technology Benefits and Limitations

Figure 8. Summary Operating Characteristics of Lithium-Ion BES

Table 1.7: Advantages and Disadvantages of Lithium-Ion Batteries

Advantages	Disadvantages
High specific energy and high load capabilities with power cells	Need for protection circuit to prevent thermal runaway if stressed
Long cycle and extended shelf-life; maintenance-free	Degradation at high temperature and when stored at high voltage
High capacity, low internal resistance, good coulombic efficiency	Impossibility of rapid charge at freezing temperatures (<0°C, <32°F)
Simple charge algorithm and reasonably short charge times	Need for transportation regulations when shipping in larger quantities

Source: (Kim et al. 2018)

Benefits:

- **Low Cost**: Lithium-ion battery costs have declined dramatically in recent years, as much as 80% between 2010 and 2017 (Deloitte Center for Energy Solutions 2018). This decline is due in part to synergies with the scale of manufacturing and research in other uses, including in electric vehicles and electronics.
- **Operating characteristics**:
  - Very fast response rates (a fraction of a second) making them good candidates for grid balancing services
  - Flexible sizes and short construction times. For example, "In 2017, Tesla built a 100MW/130 MWh containerized lithium-ion storage system in Australia within just three months." (Kairies, Figgener, and Haberschusz 2019).
  - Highly efficient, generally ranging from 85% to 95% efficiency (Zablocki 2019).
  - Discharge times of 1 second to up to 8 hours
  - Compared to other battery options, lithium-ion batteries have high energy density and are lightweight.
- **Regulatory incentives**:
  - Battery installations are growing rapidly in the many U.S. states that have storage goals, mandates, and incentives. According to the U.S. EIA Annual Energy Outlook 2020, state mandates alone total more than 6,500 MW by 2030.
  - Almost every nation is changing its wholesale market rules to allow batteries to compete for capacity and ancillary services, such as frequency regulation and voltage control (Deloitte Center for Energy Solutions 2018).

Limitations:

- "Due to the temperature sensitivity, fire hazard, and special shipping requirements, many states classify stationary Li-ion systems as hazardous materials." (Aquino et al. 2017)
- Reports of political unrest and human rights abuses, including child labor, related to cobalt mining in the Democratic Republic of Congo which accounts for roughly 60 percent of global production of cobalt (e.g., Barrera 2020).
- Environmental aspects related to very expensive recycling of the many hazardous substances (cobalt, nickel, organic electrolytes) (Noack et al. 2019).
- Poor scalability for high energy (long duration) applications

Not all lithium battery chemistries use cobalt. Tesla announced in February 2020 that they will purchase lower-cost prismatic lithium-iron phosphate (LFP) batteries, the main alternative to cobalt and nickel products, for production of their Model 3 electric car in China (Sanderson 2020). Lithium manganese oxide (LMO) and lithium titanate (LTO) batteries are also cobalt-free. These batteries have lower energy density than the more common NMC batteries but are safer and have a similar cycle life (Deign and Pyper 2018).

Some media outlets have suggested that batteries rely on rare earth elements (REEs) that may become scarce. However, according to the website batterypoweronline.com:

- "Are rare earth elements actually rare themselves? Not exactly. After all, these same rare earth elements—such as yttrium, lanthanum, and terbium—are found in the very items sitting on your desk or in your pocket, including laptops, cell phones, and other personal electronics. Most importantly, there are 17 rare earth elements and none of them are named lithium, cobalt, manganese, or any of the other key components of a lithium-ion battery." (Gorrill 2019)

Technology Status

Research:

- "New innovations, such as replacing graphite with silicon to increase the battery's power capacity, are seeking to make lithium-ion batteries even more competitive for longer-term storage." (Zablocki 2019) Silicon "is appealing because it can hold 10 times the electrical charge per gram compared to graphite. The trouble is, silicon expands greatly when it encounters lithium, and it is too weak to withstand the pressure of electrode manufacturing." Scientists at the U.S. Department of Energy's Pacific Northwest National Laboratory developed "developed a unique nanostructure that limits silicon's expansion while fortifying it with carbon" that could be used to increase the energy capacity of lithium-ion batteries. The next step is "to develop more scalable and economical methods for making the silicon microspheres." (Rickey 2020)

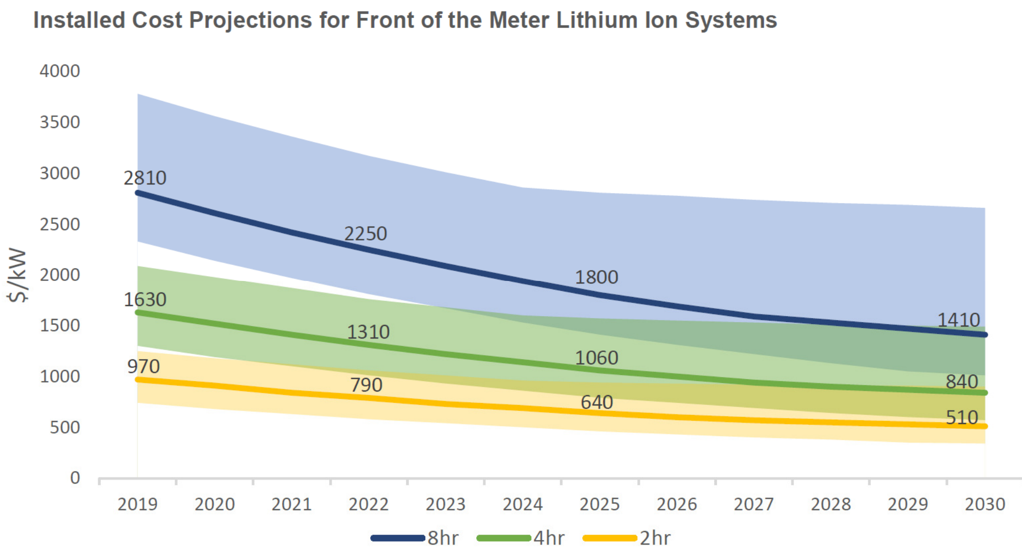
Commercial status:

- Through 2010, there were less than 10 MW of lithium-ion batteries installed world-wide. In 2011, more than 60 MW were installed and the growth of this market continues to accelerate as prices continue to decline. Total world-wide operating capacity exceeds 1.6 GW with about half of the capacity located in the United States (Sandia 2020).
- At the end of 2018, the United States had 862 MW of operating utility-scale battery storage power capacity and 1,236 MWh of battery energy capacity (Linga 2019).

Technology Cost Projections

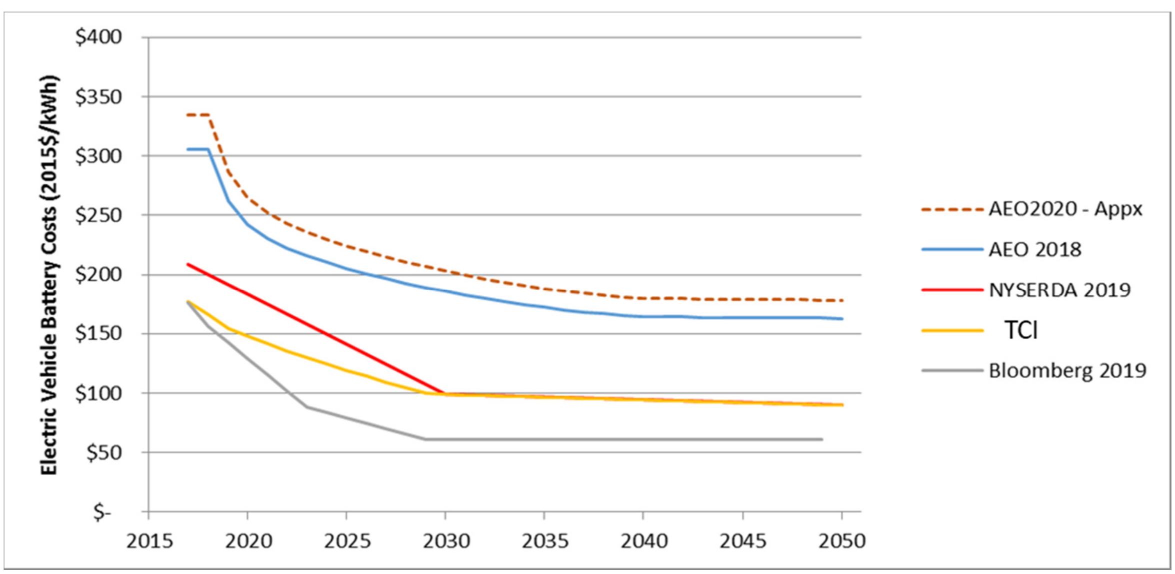
- Costs have declined dramatically in recent years and are expected to continue to decline for both the battery technology and the balance-of-system components such as inverters (Deloitte Center for Energy Solutions 2018).

Figure 9. Example Lithium-Ion BES Cost Projections Illustrating Capacity and Energy Considerations, $/kW



Source: (Electric Power Research Institute 2018)

Figure 10. Evolution of Electric Vehicle BES Cost Projections Illustrate the Effects of Ongoing Technological Change, $/kWh

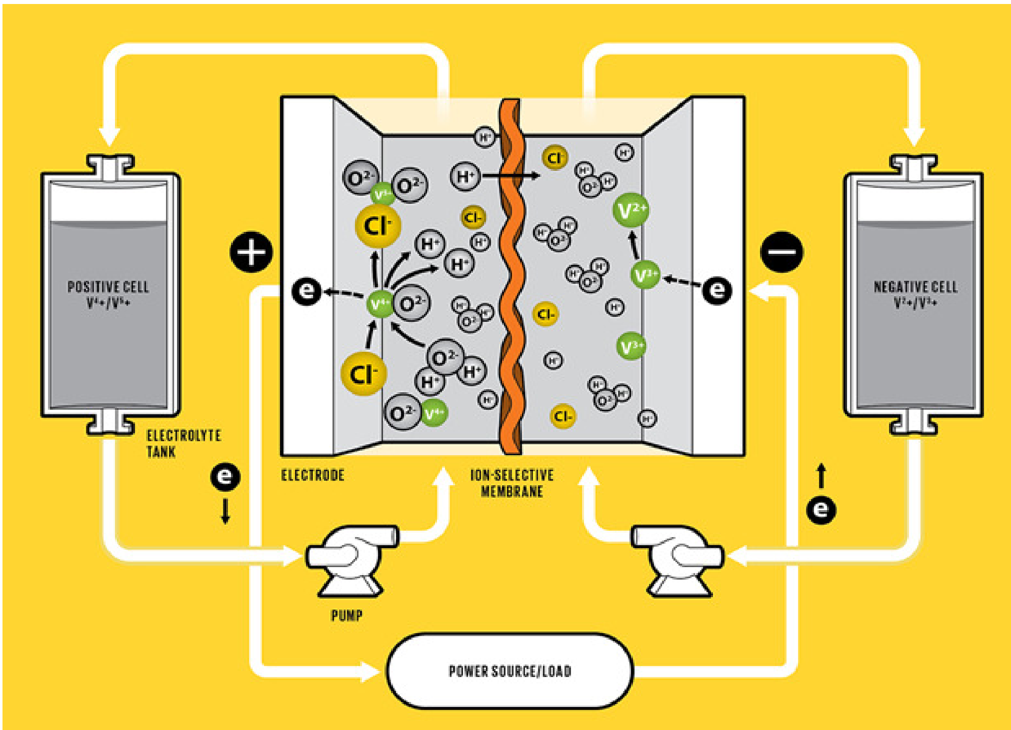


Source: OnLocation, based on work performed for the Transportation & Climate Initiative (TCI)

Redox Flow BES

Technology Description

Figure 11. Example Configuration of a Vanadium Redox-Flow BES



Source: (Yang 2017)

- Flow batteries store energy in liquid electrolyte, which is held in tanks external to the cell stacks that contain the cathode (positive) and anode (negative) sides of the battery. When charging or discharging the battery, electrons are added into or drawn out of the electrolyte as it circulates across membranes inside the stacks. Unlike other types of batteries, vanadium flow batteries use the same electrolyte solution on both the positive and negative side of the battery, yielding a nearly infinitely repeatable electrochemical process.
- Unlike Li-ion and other solid-state batteries which store electricity or charge in electrodes made from active solid materials, Redox Flow Batteries (RFB) work like a reversible fuel cell: to discharge, the battery takes the chemical energy stored in liquid electrolytes and converts it into electrical current, reversing the process to charge.
- "The positive and negative sides of a vanadium redox-flow battery are separated by a membrane that selectively allows protons to go through. During charging, an applied voltage causes vanadium ions to each lose an electron on the positive side. The freed electrons flow through the outside circuit to the negative side, where they are stored. During discharging, the stored electrons are released, flowing back through the outside circuit to the positive side." (Yang 2017)

- Vanadium is a popular electrolyte component because the metal charges and discharges reliably for thousands of cycles. Another research design replaces vanadium with organic compounds that hold and release electrons. Iron is another promising and inexpensive alternative to Vanadium – an all-iron RFB is currently sold by Portland, Oregon, company ESS. Several other chemistries are also being explored (Service 2018).
- Other types of redox batteries include:
  - Polysulfide-bromine battery (PSB): Sodium sulfide (Na_2S_2) and sodium tribromide ($NaBr_3$) are used as electrolytes. The sodium ions (Na+) pass through the membrane during the charging or discharging process.
  - Zinc-bromine (Zn-Br) battery: A hybrid redox flow battery where solutions of zinc and a complex bromine compound are used as electrodes (Kim et al. 2018).

Technology Benefits and Limitations

Figure 12. Summary Operating Characteristics of Flow BES

Table 1.10: Advantages and Disadvantages of Redox Flow Batteries

Advantages	Disadvantages
Long service life: RFBs have a system endurance period of 20 years, with an unlimited number of charge and discharge cycles available without degradation. In addition, the electrolytes can be used semipermanently.	Complexity: RFB systems require pumps, sensors, flow and power management, and secondary containment vessels.
Versatility: With the output and the capacity of a battery capable of being designed independently of each other, RFBs allow flexible design. In addition, the batteries allow a single system to address both short and long periods of output variation, enabling cost-effective power generation.	Low energy density: The energy densities of RFBs are usually low compared with those of other types of batteries.
High safety: RFBs are capable of operating under normal temperatures and are composed of noncombustible or flame-retardant materials. The possibility of a fire with the batteries is extremely low.	

Source: (Kim et al. 2018)

Benefits:

- Vanadium redox-flow batteries have longer lifetimes than Li-ion batteries. They can operate continuously for 20 years or more without degradation.
- RFBs have a flexible design that allows them to be scaled up more easily than Li-ion batteries.
- They also rate high in safety due to being free of combustible materials (Kim et al. 2018).
- RFBs are ideal for energy storage applications with power ratings from tens of kW to tens of MW and long storage durations of up to 10 hours (Energy Storage Association n.d.).

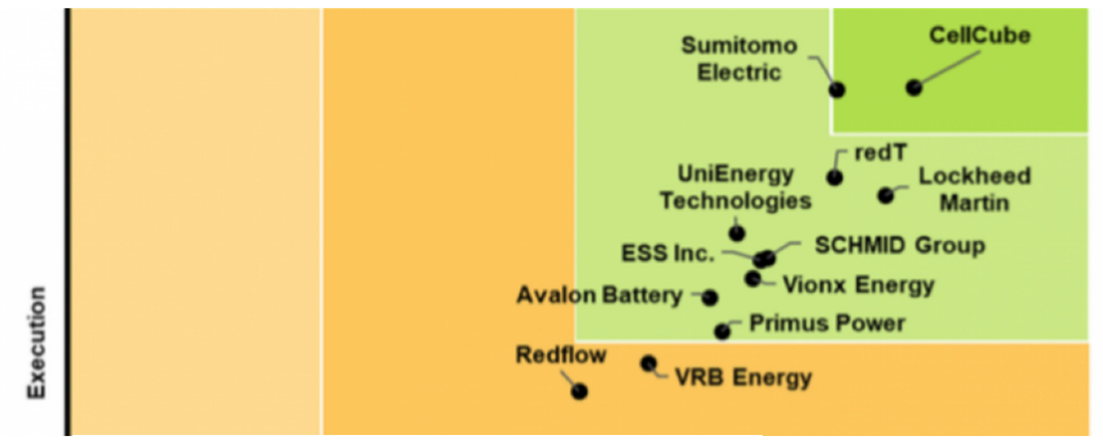
Limitations:

- RFBs have lower volumetric energy densities than other battery designs, especially in applications that require high power and short duration. This is because the volume of electrolyte flow delivery and control components of the system which make the batteries less compact than other systems for a similar output.

- Vanadium is a readily available material, but the market price has been fairly volatile in recent years due to changes in regulations and increased demand in the Chinese vanadium market where roughly half of global production of vanadium occurs. Market forecasts indicate that prices may continue to be volatile in the future (Renner and Wellmer 2019).
- The complexity of RFB systems described as a disadvantage in Figure 12 is not an issue when coupled with thermal powerplants where plant personnel are very familiar with these types of equipment

Technology Status

Figure 13. Companies Active in Flow BES Commercialization Efforts



Source: Navigant Research (Colthorpe 2019)

Research:

- The current vanadium-based redox flow battery technology was developed at the Pacific Northwest National Laboratory in 2011 (Yang 2017).
- The Joint Center for Energy Storage Research (JCESR), a DOE Energy Innovation Hub led by Argonne National Laboratory, is focused on advancing battery science and technology. JCESR works with partner organizations from national laboratories, universities, and industry, with a planned annual funding of $24 million(“Partners - Joint Center for Energy Storage Research” n.d.) through 2024 (Harmon 2018).
- Scientists at the University of Southern California (USC) announced in April 2020 that they have developed a better redox flow battery technology. “The key innovation achieved by the USC scientists involves using different fluids: an iron sulfate solution and a type of acid. Iron sulfate is a waste product of the mining industry; it is plentiful and inexpensive. Anthraquinone disulfonic acid (AQDS) is an organic material already used in some redox flow batteries for its stability, solubility, and energy storage potential. While the two compounds are well known individually,

it's the first time they've been combined to prove potential for large-scale energy storage." According to the research study, "The iron-AQDS flow battery system presents a good prospect for simultaneously meeting the demanding requirements of cost, durability, and scalability for large-scale energy storage." ("USC Scientists Develop a Better Redox Flow Battery | EurekAlert! Science News" 2020)

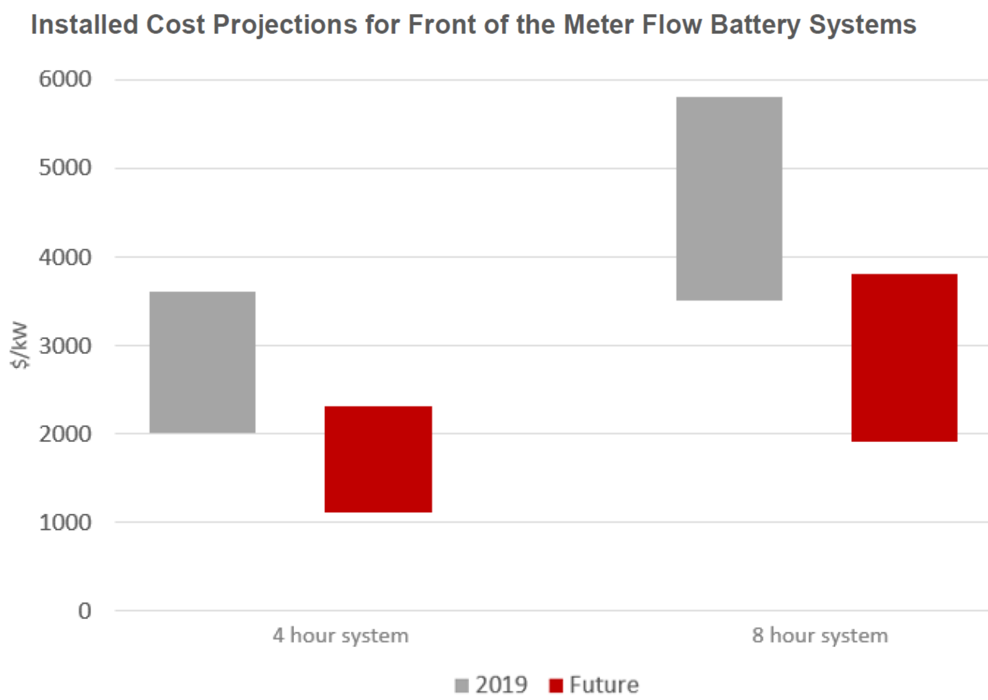
- It appears that an increasing amount of the research and commercialization of this technology is occurring in Asia, principally China. This is due in part to the availability of Vanadium in that country (Colthorpe 2018).

Commercial status:

- The first operational vanadium redox battery was successfully demonstrated at the University of New South Wales in the late 1980s (Energy Storage Association n.d.). Today, the vanadium redox flow battery is the best investigated and most installed redox flow battery technology (Noack et al. 2019).
- The industry is currently in a phase of continuous improvement, with three generations of technology available (Aquino et al. 2017). Roughly 70 MW of flow batteries are operating worldwide (Mongird et al. 2019).
- Vanadium redox flow batteries are primarily commercialized by a few companies: the U.S.-based UniEnergy Technology (UET) and Vionx Energy, the German-based Gildemeister, and Sumitomo Electric from Japan. To compete with Li-ion, these manufacturers have begun moving toward off-the-shelf systems as opposed to custom ones (Mongird et al. 2019).
- Rongke Power in Dalian, China, is building the world's largest vanadium flow battery, 200MW/800MWh, which will provide peak-load-shifting and should come online in 2020 (Service 2018). Rongke also built a VRFB "gigafactory" in Dalian in 2016 which is designed to produce as much as 3 GWh of batteries a year. The Dalian facility is just one of almost 30 battery installations being built across China by Rongke. Rongke Power is a spin-off from the Dalian Institute of Chemical Physics at the Chinese Academy of Sciences (daSilva 2019),
- Avalon Batteries addressed the cost of materials by renting vanadium from mining companies. By mass-producing turnkey systems in a factory, Avalon has shipped 160 flow batteries. Avalon will soon take over U.K. flow company RedT (Spector 2020).
- There was one effort to site a redox flow battery at a coal-fired powerplant starting in 2010 utilizing American Recovery and Reinvestment Act (ARRA) funding. The site was the City of Painesville 32 MW powerplant in Ohio (McHugh 2015). However, that facility has not been fully built (Cass 2018).

Technology Cost Projections

Figure 14 Illustrative Cost Projections for Flow BES at Different Hour Ratings, $/kW



Source: (Electric Power Research Institute 2018)

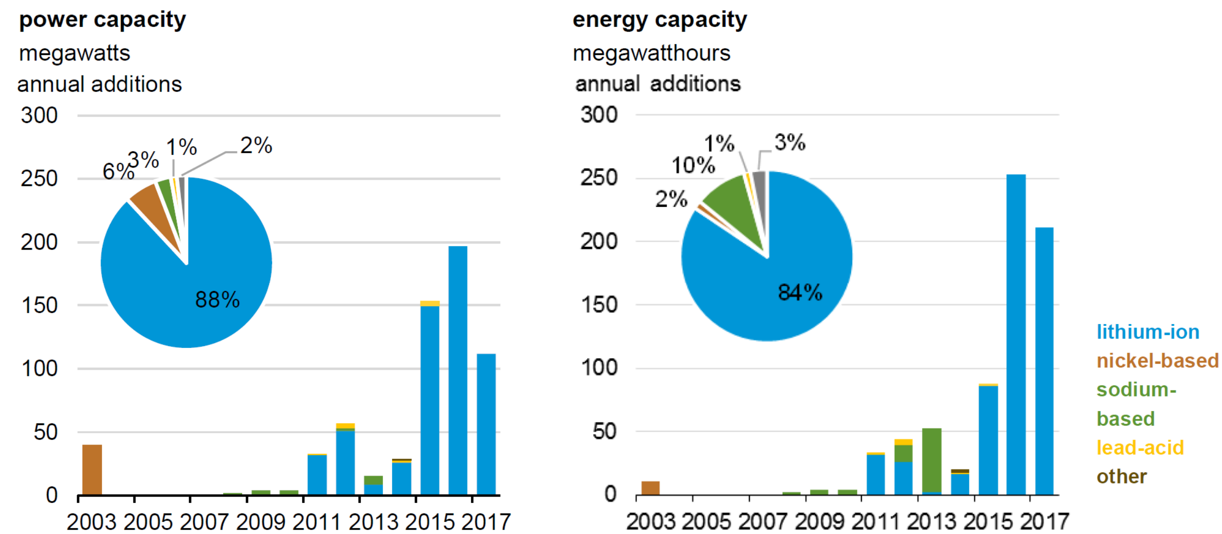
- Installed cost projections shown in Figure 14 are based on vanadium redox flow batteries.
- There is a lot of uncertainty in future raw material costs for flow batteries. As the electrolyte makes up approximately one-third of the technology cost, the viability of all vanadium flow batteries largely depends on vanadium costs which have fluctuated widely in recent years.
- In this EPRI study, future electrolyte costs were based on an assumption of $4-$5/lb. for vanadium pentoxide. In October 2018, however, the vanadium pentoxide price exceeded $20/lb (Electric Power Research Institute 2018).

Other BES

Technology Description

In addition to lithium-ion and flow batteries, several other battery storage technologies exist, many of which are in commercial use today. In the U.S. and world-wide, lithium-ion batteries have by far the highest deployment of all the stationary battery technologies, followed by sodium-based batteries. Figure 15 is a chart produced by the U.S. Department of Energy that illustrates total large-scale battery installations in the U.S. as of 2017 in terms of power capacity (MW) and energy capacity (MWh).

Figure 15. U.S. Large-Scale BES Power Capacity and Energy Capacity by Chemistry, 2003-2017



Source: U.S. Energy Information Administration, Form EIA-861, Annual Electric Power Industry Report

Source: (Cabral 2018)

Here we provide a brief description and some relevant attributes for a few of these most promising battery technologies for large-scale energy storage:

- **Sodium-Sulfur (NaS) Batteries** are a type of molten metal battery constructed from sodium and sulfur. They have a high energy density, high efficiency of charge and discharge (89%–92%), and a long cycle life, and are fabricated from inexpensive materials. However, they have high operating temperatures of 300°C–350°C and the sodium polysulfides they produce are highly corrosive (Kim et al. 2018).
  - NaS batteries were originally developed by Ford Motor Company in the 1960s. The technology was sold to the Japanese company NGK which manufactures the battery systems for stationary applications (Energy Storage Association, n.d.).
  - The active materials in NaS batteries are molten sulfur as the positive electrode and molten sodium as the negative. The electrodes are separated by a solid ceramic, sodium alumina, which also serves as the electrolyte. This ceramic allows only positively charged sodium-ions to pass through (Energy Storage Association, n.d.).
  - Due to the high operating temperatures, these batteries, like lithium-ion batteries, have flammability issues. For example, after a 2-MW system at a plant in Japan caught fire in 2011, NGK recalled its products and temporarily halted production (Yang 2017).

- "NaS battery technology has been demonstrated at over 190 sites in Japan. More than 270 MW of stored energy suitable for 6 hours of daily peak shaving have been installed. In Abu Dhabi, fifteen NaS systems acting in coordination provide 108 MW / 648 MWh to defer fossil generation investment and provide frequency response and voltage control services." (Energy Storage Association, n.d.)
- The largest installation to date is a 34 MW/245 MWh system in Aomari, Japan, which is used for wind stabilization (Mongird et al. 2019).

- **Lead Batteries** have a long history of successful use in vehicles, backup power for commercial buildings, and industrial applications in addition to grid-scale energy storage.
  - Lead Batteries use lead dioxide on the positive plates and finely divided lead on the negative plates. When discharging, these materials react with sulfuric acid to form lead sulfate and water, and the reverse reactions take place on recharge.
  - They are low cost, highly reliable, can be adapted for a wide range of duty cycles, and can achieve energy efficiencies of 90%. They are also designed to be recycled, with more than 90% of their material recovered. They are safer than some other battery chemistries as they have an aqueous electrolyte and active materials that are not flammable (Energy Storage Association, n.d.-a).
  - Lead batteries have seen limited grid-scale deployment because of their relatively low energy density and cycle life (U.S. Energy Information Administration 2018).
  - "The Consortium for Battery Innovation (CBI) is an industry-funded pre-competitive research and market development organization. CBI has been actively supporting new developments for lead batteries for more than 25 years, which has played an important part in improving cycle life under different conditions." (Energy Storage Association, n.d.-a).

- **Electrochemical Capacitors (ECs)** are sometimes referred to as "electric double-layer" capacitors and also appear under trade names like "Supercapacitor" or "Ultracapacitor." The phrase "double-layer" refers to their physically storing electrical charge at a surface-electrolyte interface of high-surface-area carbon electrodes.
  - When the two electrodes of an EC are connected in an external current path, current flows until complete charge balance is achieved. The capacitor can then be returned to its charged state by applying a voltage. Because the charge is stored physically, with no chemical or phase changes taking place, the process is fast and highly reversible, and the discharge-charge cycle can be repeated over and over again, virtually without limit.
  - There are two types of ECs, symmetric and asymmetric, with different properties suitable for different applications.
    - Symmetric designs are where both positive and negative electrodes are made of the same high-surface-area carbon. Symmetric ECs have response times on the order of 1 second and are well-suited for short duration high-power applications related to both grid regulation and frequency regulation.
    - Asymmetric designs use different materials for the two electrodes, one high-surface-area carbon and the other a higher capacity battery-like electrode. Asymmetric ECs are better suited for grid energy storage applications that have a long duration, for instance, charge-at-night/use-during-the-day storage.

- Because of their high power, long cycle life, and good reliability, the market and applications for ECs have been steadily increasing. There are dozens of manufacturers, and more are reportedly entering the market (Energy Storage Association, n.d.).

Technology Cost Projections

Figure 16. Illustrative Comparative Costs for Different BES Technologies by Major Component

Table ES.1. Summary of compiled 2018 findings and 2025 predictions for cost and parameter ranges by technology type – BESS.[(a)]

Parameter	Sodium-Sulfur Battery 2018	Sodium-Sulfur Battery 2025	Li-Ion Battery 2018	Li-Ion Battery 2025	Lead Acid 2018	Lead Acid 2025	Sodium Metal Halide 2018	Sodium Metal Halide 2025	Zinc-Hybrid Cathode 2018	Zinc-Hybrid Cathode 2025	Redox Flow Battery 2018	Redox Flow Battery 2025
Capital Cost – Energy Capacity ($/kWh)	400-1,000 **661**	(300-675) **(465)**	223-323 **271**	(156-203) **(189)**	120-291 **260**	(102-247) **(220)**	520-1,000 **700**	(364-630) **(482)**	265-265 **265**	(179-199) **(192)**	435-952 **555**	(326-643) **(393)**
Power Conversion System (PCS) ($/kW)	230-470 **350**	(184-329) **(211)**	230-470 **288**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**
Balance of Plant (BOP) ($/kW)	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**
Construction and Commissioning ($/kWh)	121-145 **133**	(115-138) **(127)**	92-110 **101**	(87-105) **(96)**	160-192 **176**	(152-182) **(167)**	105-126 **115**	(100-119) **(110)**	157-188 **173**	(149-179) **(164)**	173-207 **190**	(164-197) **(180)**
Total Project Cost ($/kW)	2,394-5,170 **3,626**	(1,919-3,696) **(2,674)**	1,570-2,322 **1,876**	(1,231-1,676) **(1,446)**	1,430-2,522 **2,194**	(1,275-2,160) **(1,854)**	2,810-5,094 **3,710**	(2,115-3,440) **(2,674)**	1,998-2,402 **2,202**	(1,571-1,956) **(1,730)**	2,742-5,226 **3,430**	(2,219-3,804) **(2,598)**
Total Project Cost ($/kWh)	599-1,293 **907**	(480-924) **(669)**	393-581 **469**	(308-419) **(362)**	358-631 **549**	(319-540) **(464)**	703-1,274 **928**	(529-860) **(669)**	500-601 **551**	(393-489) **(433)**	686-1,307 **858**	(555-951) **(650)**
O&M Fixed ($/kW-yr)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)
O&M Variable (cents/kWh)	0.03		0.03		0.03		0.03		0.03		0.03	
System Round-Trip Efficiency (RTE)	0.75		0.86		0.72		0.83		0.72		0.675	(0.7)
Annual RTE Degradation Factor	0.34%		0.50%		5.40%		0.35%		1.50%		0.40%	
Response Time (limited by PCS)	1 sec		1 sec		1 sec		1 sec		1 sec		1 sec	
Cycles at 80% Depth of Discharge	4,000		3,500		900		3,500		3,500		10,000	
Life (Years)	13.5		10		2.6	(3)	12.5		10		15	
MRL	9	(10)	9	(10)	9	(10)	7	(9)	6	(8)	8	(9)
TRL	8	(9)	8	(9)	8	(9)	6	(8)	5	(7)	7	(8)

(a) An E/P ratio of 4 hours was used for battery technologies when calculating total costs.
MRL = manufacturing readiness level; O&M = operations and maintenance; TRL = technology readiness level.

Source: (Mongird et al. 2019)

Figure 16 compares capital cost estimates and other attributes for the major battery technologies as compiled by the Pacific Northwest National Laboratory. Current costs as well as projected costs in 2025 (shown in parentheses) are compared. This table shows the breakout of major component classifications allowing for application of learning-by-doing of individual components.

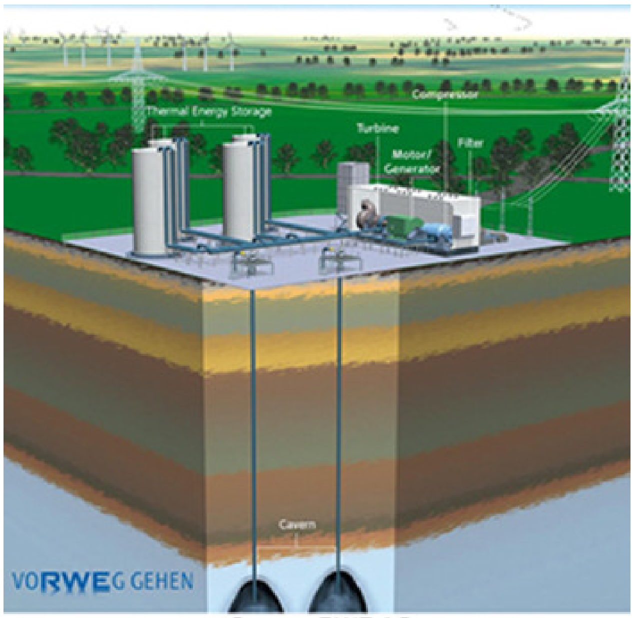
In addition to costs, the table includes operating characteristics such as average round-trip efficiency and response time, along with expected lifetime expressed as the number of cycles (assuming 80% depth of discharge) and in years. Of the BES technologies shown here, Li-ion batteries have the highest efficiency (86% or higher), whereas the Redox Flow Battery has the longest expected lifetime (10,000 cycles or 15 years).

Mechanical Energy Storage

Compressed Air Energy Storage (CAES)

Technology Description

Figure 17. Diagram of A Compressed Air Energy Storage System



Source: (Energy Storage Association, n.d.)

- CAES plants are largely equivalent to pumped-hydro power plants in terms of their applications. Instead of pumping water from a lower reservoir to an upper reservoir during periods of excess power, a CAES plant uses excess energy to power an electrically driven compressor which compresses ambient air to 1000 psi and stores the pressurized air in an underground cavern or container. When electricity is needed, the pressurized air is heated and expanded in an expansion turbine and used to drive a generator (Energy Storage Association, n.d.).
- Existing plants use single-shaft machines where the compressor-motor/ generator-gas turbine are both located on the same shaft and are coupled by a gearbox.
- The ability to use exhaust heat energy from a conventional gas turbine (or other fossil technology) to heat the high-pressure air before expansion in an air bottoming cycle allows CAES plants to be built in variable sizes based on cavern storage volume and pressure.
- Preferred locations for these plants are in artificially constructed salt caverns in deep salt formations. If no suitable salt formations are available, it is also possible to use natural aquifers (Energy Storage Association, n.d.).
- "Canadian company Hydrostor took a different approach: pumping compressed air into purpose-built caves or existing ones, such as abandoned mine shafts, and using water to maintain pressure. The water keeps things at constant pressure and allows for the use of smaller cavities than typically used in traditional techniques." (Spector 2020).

Technology Benefits and Limitations

Benefits:

- CAES offers the potential for small-scale, on-site energy storage solutions as well as larger grid-scale installations that can provide sizable energy reserves for use in load shifting (Energy Storage Association, n.d.).

Limitations:

- Very large volume storage sites are required because of the low storage density (Energy Storage Association, n.d.). These sites are geologically constrained.

Technology Status

Research:

- As of 2018, diabatic CAES systems are the only CAES systems that have been deployed for commercial purpose. Diabatic CAES is the conventional type of system where the excessive heat generated during the compression process is released to the atmosphere. During power generation, the required heat is generated generally using natural gas. The more efficient adiabatic and isothermal CAES systems are currently in the research phase (PRNewswire 2019).
- Researchers are working on other CAES plant designs where the motor-compressor unit and the turbine-generator unit will be mechanically decoupled, making it possible to expand the plant modularly to provide more flexibility in the amount of power input and output.

Commercial Status:

- The world's two first CAES projects -- the 290-megawatt plant in Huntorf, Germany, built in 1978, and the 110-megawatt McIntosh, Alabama plant, built in 1991 -- have been able to provide very cheap, long-duration energy over decades of operation, by boosting the output of natural gas-fired power plants at the sites.
- In the United States, there are three operating CAES systems with a combined capacity of 113.5 MW. In addition to the Alabama plant, General Compression built a 2 MW, 300 MWh project in Gaines, Texas, and SustainX built a 1.5 MW, 1 MWh project at its Seabrook, N.H. headquarters.
- North America is the largest market and is likely to dominate in the near future. "Some of the major upcoming CAES projects include Pacific Gas and Electric Company underground CAES project in California, and Bethel Energy Center CAES Project in Texas." Europe is the second-largest market, with several new CAES projects lined up to be commissioned between 2020 – 2024 (PRNewswire 2019).
- Some of the key players operating in the market are Siemens, Hydrostor, Apex CAES, and Ridge Energy Storage and Grid Services (PRNewswire 2019). Hydrostor has a commercial system operating in Canada and is building a demonstration site in Australia. The company is also in the process of creating a pipeline of increasingly ambitious plants (Spector 2020).

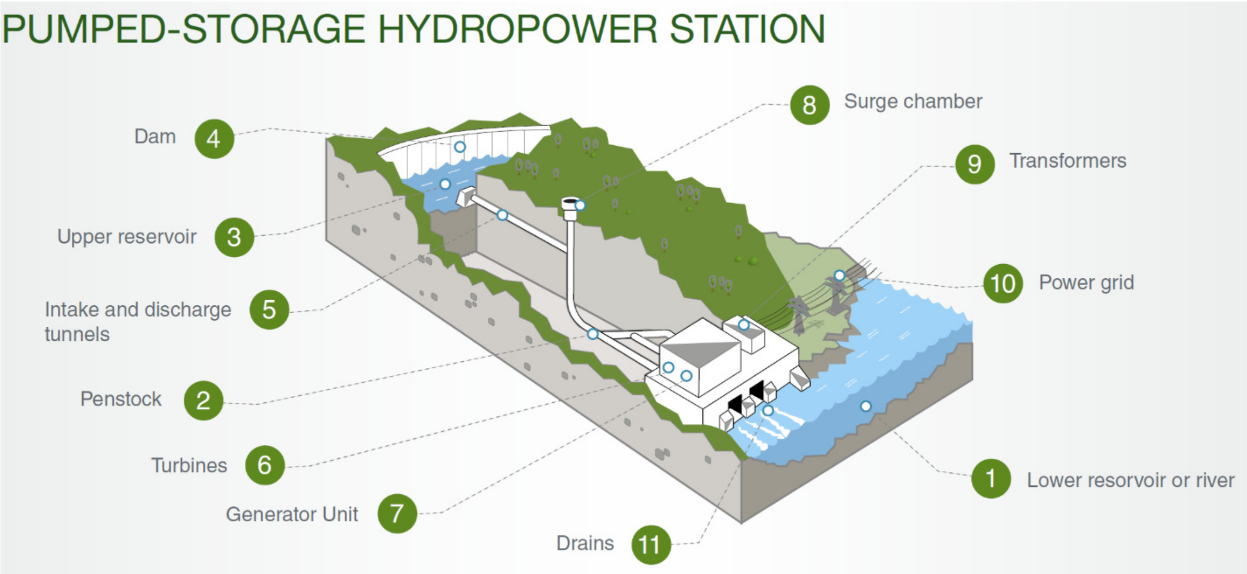
Technology Cost Projections

- CAES is considered a mature technology. While technology innovation has the potential to further reduce costs, CAES involves a long-range development timeline and, therefore, a substantial reduction in costs is unlikely to be experienced in a relatively short number of years (Mongird et al. 2019).

Pumped Storage Hydropower (PSH)

Technology Description

Figure 18. Diagram of A Pumped Storage Hydropower Station



Source: (Iberdrola n.d.)

- Pumped storage hydroelectric (PSH) facilities store energy in the form of water in an upper reservoir, pumped from another reservoir at a lower elevation (Energy Storage Association n.d.).
- During periods of high electricity demand, power is generated by releasing the stored water through turbines in the same manner as a conventional hydropower station. During periods of low demand, the upper reservoir is recharged by using lower-cost electricity from the grid to pump the water back to the upper reservoir (Energy Storage Association n.d.).
- Reversible pump-turbine/motor-generator assemblies can act as both pumps and turbines (Energy Storage Association n.d.).
- PSH capabilities can be characterized as open loop—where there is an ongoing hydrologic connection to a natural body of water—or closed loop, where the reservoirs are not connected to an outside body of water.
- While all PSH projects in the United States are built with fixed-speed units, one or two projects have been modified to adjustable speed. Most new U.S. projects under development are using variable-speed units (>60 to 70 percent), while <5 percent have ternary units. For new projects globally, the split is close to a 50-50 split, with a very small percentage for ternary systems (Mongird et al. 2019).

Technology Benefits and Limitations

Benefits:

- Once built, these systems have a very low cost of storage, and they hold massive amounts of energy compared to the world's biggest battery (Spector 2020).
- Pumped storage hydropower can provide energy-balancing, stability, storage capacity, and ancillary grid services such as network frequency control and reserves. This is due to the ability of pumped storage plants, like other hydroelectric plants, to respond to potentially large electrical load changes within seconds (Energy Storage Association n.d.).
- These plants are typically highly efficient (round-trip efficiencies reaching greater than 80%), and can prove very beneficial in terms of balancing load within the overall power system (Energy Storage Association n.d.).

Limitations:

- It is extremely difficult to build new pumped-hydro storage plants due to the permitting implications of large water-based infrastructure and of executing massive construction projects in general. Recent projects focus on isolated reservoirs that do not disrupt river ecosystems; this simplifies permitting, but projects still face a decade-long development timeline and billion-dollar price tags (Spector 2020).

Technology Status

Research:

- New water turbine designs are directed at improved watershed and fishery protection, in addition to developing designs that can better harness the potential for water power for retrofit or new projects (Tsanova 2020).
- Research and commercialization of new hydro turbine designs are being funded by a mix of private sector (Tsanova 2020) and government sources (U.S. Department of Energy 2020).
    - A few of the private sector organizations funding research and development of water turbine technologies include Schneider Electric Ventures, Breakthrough Energy Ventures (a company affiliated with Bill Gates), and EPRI.
    - The DOE Water Technology Office has awarded significant funding to several organizations with innovative technologies that can demonstrate the potential to lower capital costs and deployment timelines (and environmental footprint) for pumped-storage technologies and non-powered dams (U.S. Department of Energy 2020).
- Technologies currently being studied include:
    - A reversible pump-turbine with submersible permanent magnet motor generators installed in vertical shafts'
    - A ternary pumped-storage hydropower system, a system that allows nearly instantaneous switching between generation and pumping;
    - A modular 5MW closed-loop PSH facility, the Hydro Battery. The Hydro Battery consists of a corrugated steel tank as the upper reservoir, a floating membrane as the lower reservoir, and a floating powerhouse;
    - Different techniques for improved fish identification and protection; and
    - Tools to better understand the potential additional revenues that can be achieved from pumped storage assets.

Commercial status:

- Pumped storage hydroelectric projects have been providing energy storage capacity and transmission grid ancillary benefits in the United States and Europe since the 1920s (Energy Storage Association n.d.).
- The 43 pumped-storage projects operating in the United States provide almost 23 GW or about 2 percent of the capacity of the electrical system (U.S. Energy Information Administration 2020).
- Plants under development: the 400-megawatt Gordon Butte project in Montana has permits and financial backing; the 1,300-megawatt Eagle Mountain in California has a federal license to construct and backing from NextEra Energy, and utility Dominion Energy is working on an 800-megawatt, 10-hour duration system in southwestern Virginia (Spector 2020).
- Current commercial technology vendors are incorporating watershed and fishery protection into their designs, much of which is directed at the retrofit market. In addition, pumped storage offers potentially other benefits to the electric power grid, but with the potential environmental consequences as discussed above.

Technology Cost Projections

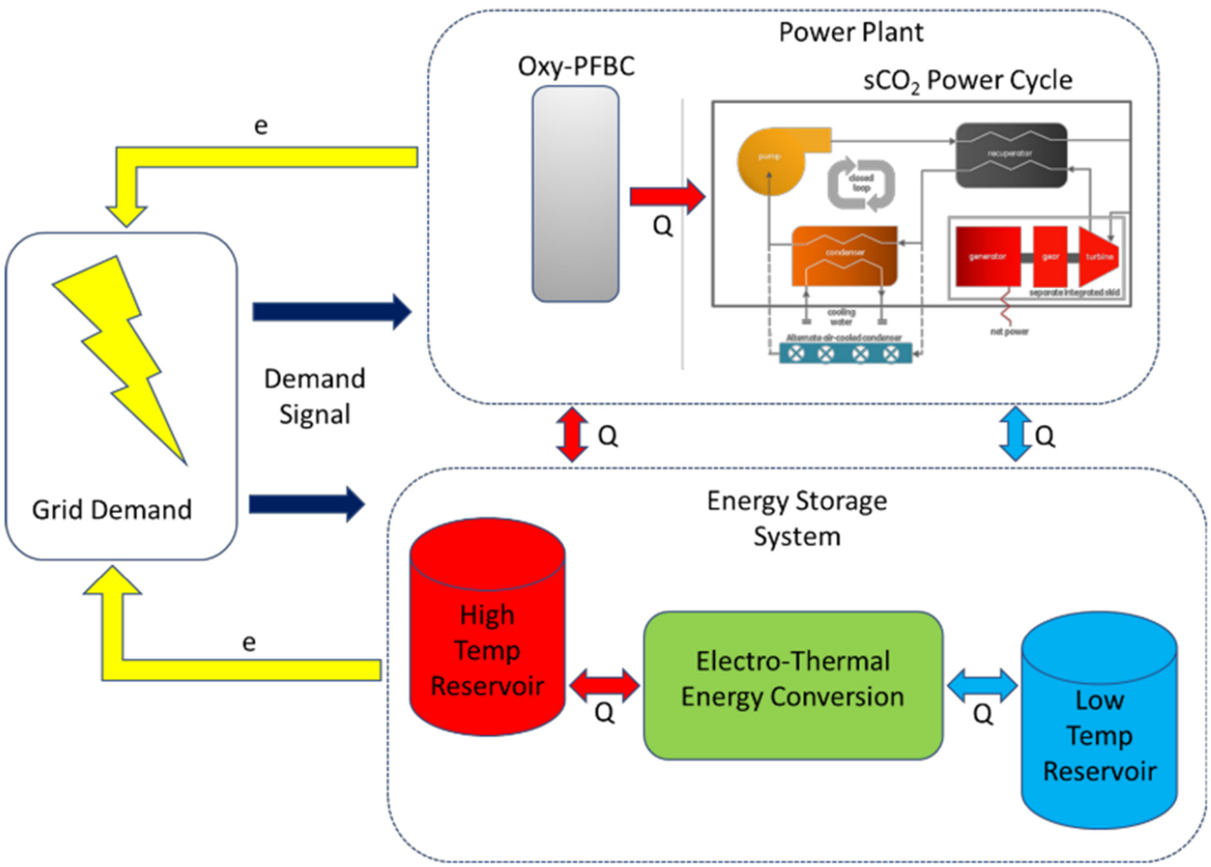
- PSH systems have a wide cost range of $1,500/kW–$5,100/kW. The lower component of this range originates from the projected cost for a PSH project at Eagle Mountain in Southern California. Costs vary primarily due to equipment (fixed, variable-speed, or some hybrid approach), project size/capacity, and availability of existing infrastructure (transmission, dams, reservoirs, etc.) (Mongird et al. 2019).
- Pumped-storage hydro is considered a mature technology. While technology innovation has the potential to further reduce costs, PSH involves a long-range development timeline and, therefore, a substantial reduction in costs is unlikely to be experienced in a relatively short number of years (Mongird et al. 2019).

Thermal Energy Storage

Super Critical CO_2 Energy Storage (SC-CCES)

Technology Description

Figure 19. Diagram of Super Critical CO2 Energy Storage System



Source: (Miller 2019)

- This process combines three technologies to minimize CO_2 generation and store power to reduce cycling on the plant.
    1. A pressurized fluidized bed oxy-combustion system (Oxy-PFBC) where pure oxygen is pumped into a fluidized bed of pulverized coal for combustion. This process creates a pure CO_2 stream that can then have contaminants removed and the purified product sold for downstream chemical processes, such as methanol production.
    2. The heat generated in the Oxy-PFBC heats supercritical CO_2 (sCO_2) with drives a power turbine to generate electricity.
    3. Excess heat from the Oxy-PFBC and sCO_c and cold generated from expansion over the turbine is stored in reservoirs to generate electricity when demand requires.

- An indirect-fired supercritical CO_2 (sCO_2) power cycle is integrated with a pressurized fluidized bed oxy-combustion system (Oxy-PFBC) at a nominal 100 MWe net size.
- This technology is well designed for thermal energy storage, which can be readily integrated using a system based on a concept already being studied under a separate ARPA-E grant.
- Energy storage could allow the coal unit to operate near continuously, putting power on the grid when needed, and storing energy when not. This allows the unit to run more often at its design conditions, avoiding ramping and turndown, which have negative impacts on efficiency, emissions output on a per MWh basis, and unit lifetime. Moreover, if this unit captures CO_2 for utilization (e.g., EOR), it may be required to operate near continuously, either to deliver an agreed-to amount of CO_2 or to improve the overall economics. With energy storage, the plant can provide CO_2 continuously while allowing the power to be provided to the grid when needed. In short, energy storage can have a significant impact on the unit's competitiveness.
- Advancements Required of Proposed Technology
    1. Advancement of the technologies and components that are at lower technology readiness levels must be achieved, including in particular the fluidized-bed heater that joins the pressurized oxy-combustion system with the sCO_2 power cycle.
    2. Assessment of the most beneficial duration and size of storage for the overall system.
    3. Development of an optimal plant layout and integration that balances efficiency with cost aimed at producing an economically viable solution for the marketplace.
    4. Evaluation of how the air separation unit (ASU), which provides the O_2 for oxy-combustion, can operate flexibly, which may require **liquid air storage** (Miller 2019)**.**

Technology Benefits and Limitations

Benefits:

- Integrates low-emission technology with thermal energy storage, including some expansion cooling capture.
- Indirect sCO_2 can be added to some current facilities.
- Competitive in areas where natural gas is expensive or limited.
- Thermal storage technology can be one of various options (molten salt or sand, for instance).

Limitations:

- High cost to build or retrofit.
- Limited experience for both Oxy-PFBC and sCO_2 technologies.

Technology Status

- A **Oxy-PFBC** pilot unit located at CnmetENERGY in Ottawa, Canada, and co-funded by NETL and Natural Resources Canada (NRCan) has begun testing at a pilot-scale (Stevenson and Follett 2020) specifically, to prove the reduction in the cost of capturing concentrated CO_2 (Patel 2016).
- **sCO_2:** A 25 MW Natural Gas Direct-sCO_2 in LaPorte Texas was started up in May 2018, and is reported to be continuing its testing program (Flin 2019). The developer for that project has discussed plans to build a 300 MW commercial plant as early as 2022 (Patel 2019).

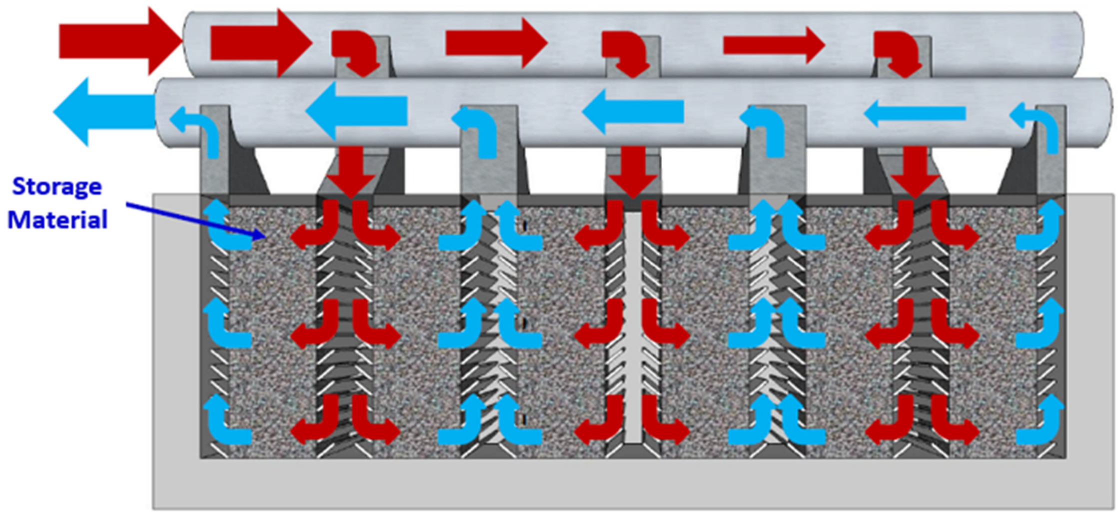
Technology Cost Projections

The technology is very new, and significant performance and cost advances are possible with future study.

Molten Salt

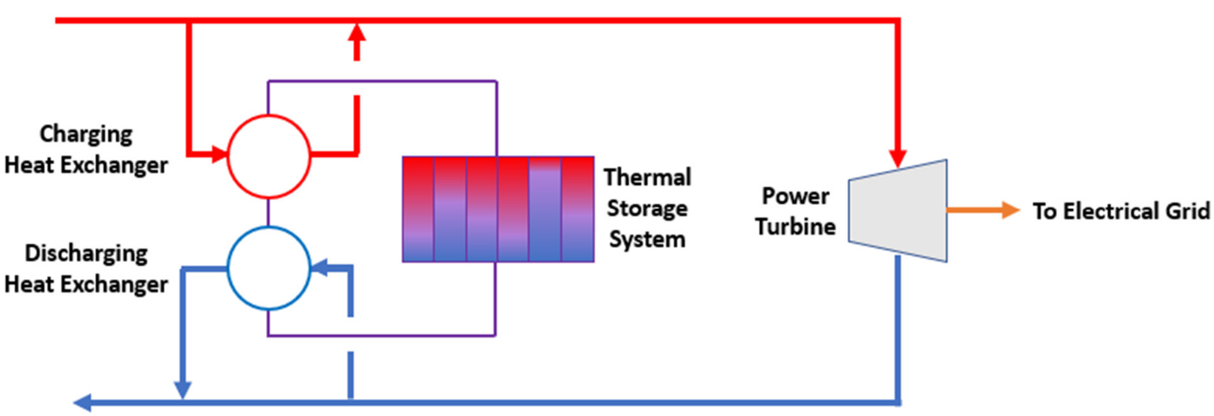
Technology Description

Figure 20. Molten Salt Energy Storage Principle of Operation



Source: (STORASOL 2019)

Figure 21. Illustrative Integration of Thermal Energy Storage into Powerplant



Source: OnLocation

High Temperature Thermal Storage Systems store heat in a variety of media using heat exchangers and a transfer media (either air or a specialized fluid) to facilitate the exchange.

Molten Salt technology is a subset of High Temperature Thermal Energy Storage Systems (HTTESS), which include sand, paraffins, and eutectics. There are three main HTTESS categories:

- **Sensible Heat Thermal Energy Storage** (SHTES) is the more common application, where a media is stores energy through temperature change. The media properties are important, with molten salts being used in solar tower applications and rock/sand being used for thermal plant balancing.
- **Latent Heat Thermal Energy Storage** (LHTES) stores energy in the phase shift from solid to liquid, resulting in high energy storage with limited temperature change. Salts, eutetucs, and paraffins are being researched for media in this application (Sharma and Sagara 2005).
- **Thermo-Chemical Heat Storage** (TCHS) stores and discharges energy by breaking and reforming molecular bonds. This technology is very much in the research stage (Rao, Niyas, and Muthukumar 2018).

Technology Benefits and Limitations

Benefits:

- HTTESS can be integrated into Thermal Plants to storage energy directly from the steam or sCO_2 being circulated through the power turbines.
- HTTESS pricing vs other technology often includes the cost of the power plant equipment such as boilers and turbines, but as thermal plants already have this equipment, the cost drops significantly.

Limits:

- SHTES is limited by the maximum operating temperatures of the materials of the equipment, which limits the temperature differential and creates the need for large units to store significant energy.
- LHTES is limited by thermal conductivity of the solid phase of the medium.
- TCHS is not well researched for commercial applications.

Technology Status

Commercial status:

- SHTES: Storasol has operated a pilot plant at the University of Bayreuth since 2015 for thermal plants. Several molten salt applications have been used in solar concentration plants, with relative success.

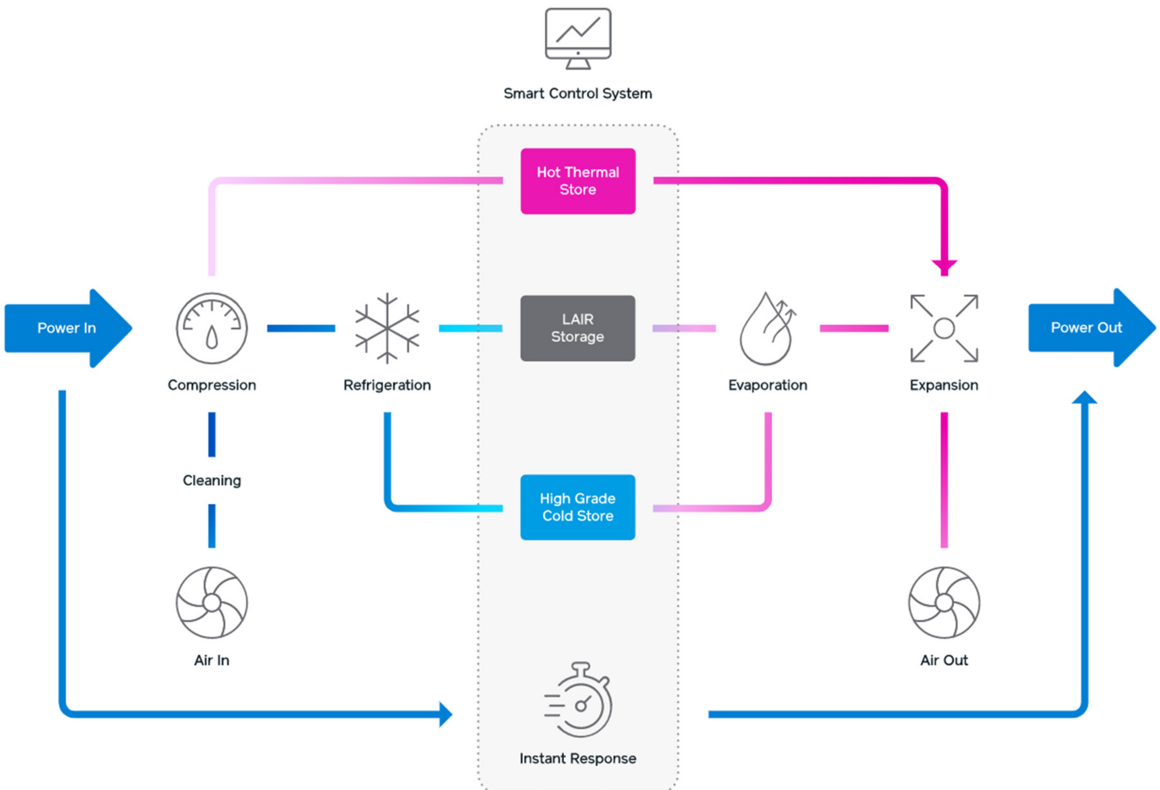
Technology Cost Projections

- SHTES is through pilot testing and ready for commercial deployment.

Liquid Air

Technology Description

Figure 22. Liquid Air Power Cycle



Source: *("Technology: Highview Power" 2020)*

- Liquid Air Energy Storage (LAES), also known as cryogenic energy storage, uses excess power to compress and liquefy dried/CO_2-free air. When power is needed, the air is heated to its boiling point and expanded through a generator.
- Efficiency is increased by capturing and storing heat from compression and cold from expansion, which aids the ability to cycle on a daily basis.
- The compression equipment and power generators come from established supply chains in mature industries. The technological innovation here is using them for grid storage (Spector 2020).

Technology Benefits and Limitations

Benefits:

- Technology used is commonplace in the industry today.
- Abundant storage medium limits storage costs.
- Not limited by surrounding geography.
- Efficiency improvements may be possible by using steam-driven compressors (Park, Lee, and Heo 2019), or by using waste heat to assist in air expansion (Fitch 2019).
- This study raises what should be a straightforward application not currently discussed in the literature that was reviewed. Namely, that this technology might be adaptable to separating different components of air, such as CO_2, for sequestration or for marketing.

Limitations:

- Equipment is expensive.

Technology Status

Research:

- Integration into thermal plants, maybe similar to research to integrate into nuclear plants (Park, Lee, and Heo 2019).
- Some discussion of ongoing research on a similar process using CO_2.

Commercial status:

- Pilot Plant (2.5MWh) in Slough, UK was commissioned in 2014, followed by a 15MWh unit in Bury, Greater Manchester, UK. Another 50MW/250MWh project is located in the north of England at a decommissioned thermal plant site (Tsanova 2019).
- Highview's leaders raised $46 million from Sumitomo Heavy Industries in February 2020 to self-finance early projects to show the market that they work (Spector 2020).
- Highview Power borrows equipment from the power and oil and gas industries to liquefy air and release it to turn a turbine. Highview recently secured the first cryogenic storage deal in the U.S., in partnership with Encore Renewable Energy. The project will serve the Vermont grid with at least 50 megawatts/400 megawatt-hours. The developers are targeting an online date at the end of 2022, and will provide an array of services including renewables integration, grid inertia, frequency regulation, transmission constraint relief and more (Spector 2019).

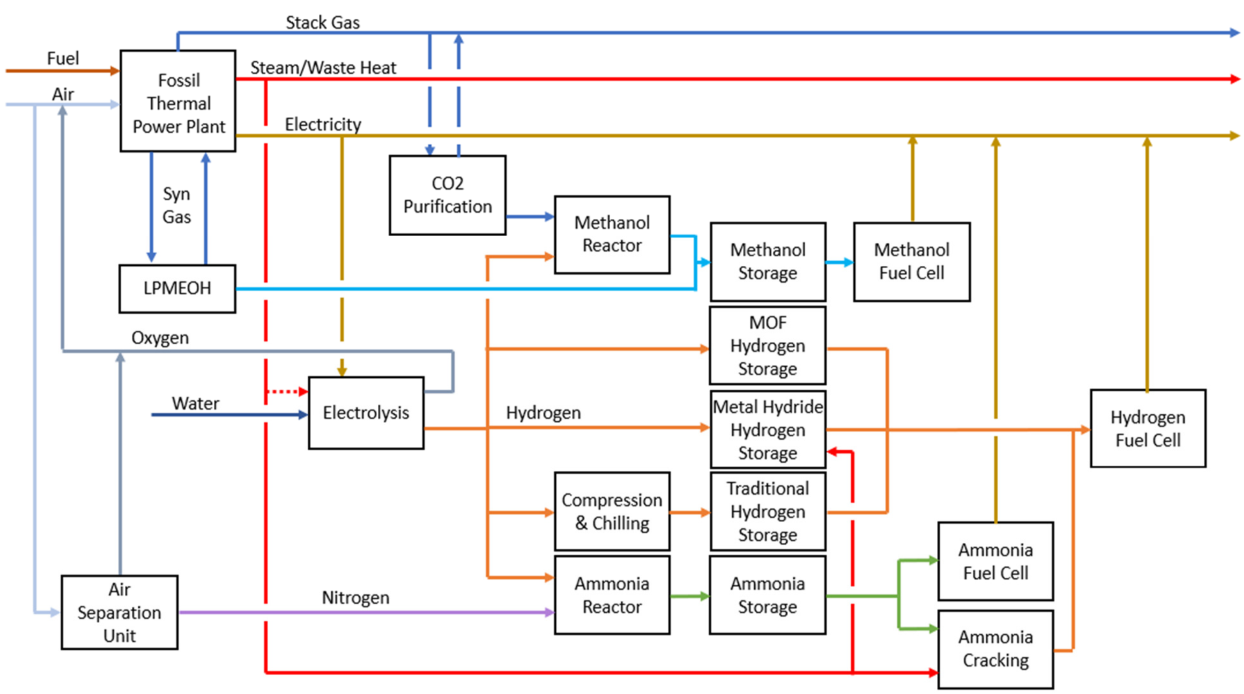
Technology Cost Projections

- Limited efficiency improvement expected on mechanical pieces due to extensive use in petrochemical processes.
- Potential increase in efficiency in controls and thermal storage integration.
- Opportunities to integrate into thermal plants by saving the cost of heat storage and using excess cold to increase thermal plant efficiency during peak power operation (increasing condenser efficiency).

Chemical Energy Storage

- This section reviews chemical energy storage as it relates to hydrogen, methanol, and ammonia as the energy storage medium.
- Methanol and ammonia constitute a sub-set of hydrogen energy storage in that hydrogen remains the basic energy carrier where the different molecular forms offer certain advantages and challenges, as discussed below.
  - For example, methanol and ammonia-based energy storage systems require electrolysis for hydrogen (except in the cases where SynGas is produced) and utilize hydrogen fuel cells in cases where the hydrogen is disassociated from methanol or ammonia.
- Figure 23 represents a "universal flow block diagram" that identifies the many different technology blocks that may be included in a Chemical Energy Storage technology as they may be integrated into the operation of a fossil thermal power plant.

Figure 23. "Universal" Block Flow Diagram Illustrating a Multitude of Opportunities for Fossil Thermal Powerplant Systems to be Integrated with Chemical Energy Storage



Source: OnLocation

Hydrogen

This hydrogen review is separated into three sections: Hydrogen Production, Hydrogen Storage, and Electricity Generation from Hydrogen.

Technology Description

In this process, excess electricity is used to produce hydrogen by the electrolysis of water. The hydrogen is stored in one of several methods and released through a fuel cell to produce electricity when needed.

Hydrogen Production

Currently, over 90% of hydrogen produced today is from fossil fuels, with the remaining minority produced by electrolysis (U.S. Energy Information Administration 2008). There are three technologies for water electrolysis: alkaline water electrolysis (AEL), proton exchange (or electrolyte) membrane (PEM), and solid oxide electrolysis (SOEL) (Brauns and Turek 2020).

- **Alkaline Water Electrolysis** (AEL) is the oldest of the technologies and one of the original methods of hydrogen production. The three main components (Diaphragm, Electrodes, and Electrolyte) have the opportunity to research. This technology is particularly suited to integrate with a thermal fossil plant due by using heat for High Temperature Water Electrolysis. The electrical requirement to produce hydrogen via AEL decreases significantly with the rise of temperature, as well as pressure (Rashid et al. 2015).
- **Proton Exchange Membrane** (PEM) is moderately developed technology using a solid membrane and electricity to separate hydrogen from water. Heat is produced in this process and hinders the efficiency if not removed. The technology is suited to highly variable needs, such as wind and solar.
- **Solid Oxide Electrolysis** (SOEL) is the least developed technology, using low costs materials and steam to produce hydrogen, making it an ideal option to pair with a thermal fossil power plant. However, the high manufacturing cost has limited its application. Additionally, SOEL units can theoretically be reversed to convert hydrogen to electricity (Liu 2019),

Hydrogen Storage

There are several forms in which hydrogen can be stored, ranging from gas, liquid, chemical, or within a solid-state framework (U.S. Energy Information Administration 2008). A technical consideration with hydrogen storage is that hydrogen gas has a low density and that hydrogen liquefaction requires 12 KWh/kg H2 to compress and chill the material to -240 °C.

- **Large-Scale Gaseous Storage**: Large quantities of hydrogen are stored as a compressed gas in salt caverns or other geological formations. Salt dome formations are of particular interest since the compression and release of the stored hydrogen can occur at a much faster rate than, say, a depleted oil or natural gas field. There exists substantial industry experience with this type of storage, primarily in petroleum refining operations, such as in desulfurizing fuels. For example, a large hydrogen storage facility was commissioned in the Texas Gulf Coast area in 2016 (*Hydrocarbon Processing* 2019), while Chevron's Phillips Clemens Terminal, also in Texas has been used for hydrogen storage in the 1980s; with a capacity of 1,066 million cubic feet. Connecting this underground storage to end-users such as refineries is accomplished through pipelines, with over 1,500 miles of hydrogen pipelines in service (PHMSA 2020). Large-scale salt dome storage is also now being developed to allow coupling hydrogen storage to electricity generation (Magnum Development 2020).

- **Compressed Tank Gas Storage**: Generally requires high-pressure tanks operating in the range of 5,000 to 10,000 psi (350 to 700 bar). These storage tanks are generally suited for small-scale and mobile storage systems, storing five to ten kilograms of hydrogen each.
- **Liquid Hydrogen Storage Tanks**: Storing hydrogen in liquid form has the benefit of providing a high energy density, but also requires a storage container appropriate to the application and requires an energy-intensive liquefaction process.
- **Chemical Storage**: Hydrogen can be combined with CO_2 to make methanol or nitrogen to make ammonia. Both chemicals are significantly cheaper to store and can be used for power when required. See the appropriate sections for additional information.
- **Solid-State Hydrogen Storage Materials**: These materials absorb and hold hydrogen under certain conditions and release hydrogen under a different set of conditions. There are two main classes: Metal Hydrides (which hold hydrogen via chemical formation and require heat to release) and Metal Organic Frameworks (MOFs, which are porous absorbents but are limited in storage capacity).

Electricity Generation from Hydrogen:

Hydrogen, generally high purity, is used as a fuel to generate electricity. Polymer Exchange Membranes (PEM) are the most commonly used fuel cells in these applications but suffer from low efficiency when used with atmospheric oxygen. Alkaline Fuel Cells (AFC) are an older technology, with the main limitation being CO_2 poisoning. Solid Oxide Fuel Cells (SOFC) remains a promising technology and is thought to offer flexibility, durability, and a low cost.

Figure 24. Efficiencies of Fuel Cells at Different Chemistries and Temperatures

Fuel Cell Type	Electrolyte	Anode Gas	Cathode Gas	Temperature	Efficiency
Proton Exchange Membrane (PEM)	Solid Polymer Membrane	Hydrogen	Pure or Atmospheric Oxygen	75°C (180°F)	35-60%
Alkaline (AFC)	Potassium Hydroxide	Hydrogen	Pure Oxygen	80°C (175°F) or lower	50-70%
Direct Methanol (DMFC)	Solid Polymer Membrane	Methanol Solution in Water	Atmospheric Oxygen	75°C (170°F)	35-40%
Phosphoric Acid (PAFC)	Phosphorous	Hydrogen	Atmospheric Oxygen	210°C (400°F)	35-50%
Molten Carbonate (MCFC)	Alkali-Carbonates	Hydrogen, Methane	Atmospheric Oxygen	650°C (1200°F)	40-55%
Solid Oxide (SOFC)	Ceramic Oxide	Hydrogen, Methane	Atmospheric Oxygen	800-1000°C (1500-1800°F)	45-60%

Source: (Pollet 2011)

Technology Benefits and Limitations

Hydrogen Production

Benefits:

- AEL and SOEL can utilize steam and heat from a thermal plant to increase the efficiency of hydrogen production from the electrolysis of water.
- Hydrogen can be used in multiple downstream applications, including as a feedstock for ammonia or methanol, direct burn, or through a fuel cell.

Limitations:

- AEL has low hydrogen gas purity.
- Hydrogen is difficult to store.
- High-Temperature AEL and SOEL both require additional research (Membranes used in AEL cannot exceed 150 deg C and ceramics in SOEL are not sufficiently conductive).

Hydrogen Storage

Benefits:

- Solid State Hydrogen Storage Materials can save significant energy versus existing technology.
- Metal Hydrides require heat to release hydrogen, so can utilize waste heat from a thermal plant.

Limitations:

- MOF technology is limited in storage capacity.

Electricity Generation from Hydrogen:

Benefits:

- Several technologies benefit from higher temperatures and can be integrated with thermal plants.
- Hydrogen can be blended with natural gas to feed a gas-fired power turbine,
- Some technologies are readily available.

Limitations:

- The technologies available today are high in cost and have poor or moderate durability.

Technology Status

Installations of hydrogen-based technologies include the following:

Hydrogen Production:

Alkaline Water Electrolysis:

- The Djewels project located in the Netherlands is underway, intending to demonstrate a 20 MW pressurized alkaline electrolyzer (CORDIS 2020a). The demonstration project is expected to continue through 2025, and the developer has announced plans to build a 100 MW electrolyzer in Germany (Franke 2020).

- The Asahi Kasei Hydrogen Energy Research Field 10 MW, located in Fukushima, Japan, reportedly began operations during March 2020 (Bailey 2020).

Proton Exchange Membrane:

- A 6 MW electrolyzer located in Linz, Austria, began operations during November of 2019 using a Siemens Silyzer 300 PEM electrolyzer, and is intended to be operated to provide load-following, spinning reserve, and other grid services (Collins 2019).
- Refhyne by Royal Dutch Shell is a $22.5MM, 10MW electrolyzer, unders construction at Shell's Rheinland refinery in Wesseling Germany is scheduled to be online during the second half of 2020 (Brightmore 2020).

Solid Oxide Electrolysis:

- Research is underway at the U.S. Department of Energy's Integrated Energy Systems (IES) program within the Office of Nuclear Energy to develop High-Temperature Steam Electrolysis (HTSE) technology that will use a solid oxide electrolysis unit operating at around 800°C that would reduce the electricity needed to split water into hydrogen and oxygen (Patel 2020).
    - This technology would appear to provide a benefit to fossil thermal power systems.
- The GAMER Project seeks to demonstrate a 10 kW high temperature steam electrolyzer technology based on a Proton Ceramic Electolyzer (PCE) stack operating at temperatures between 500°C to 700°C. The project is located in located Trondheim, Norway (CORDIS 2020b).

Technology Cost Projections

- Current electrolysis methods are 70% efficient but solving high-temperature limitations will increase the efficiency to 80%.
- Proton Ceramic Electrochemical Cells (PCECs) are a promising technology to replace SOEL but still very early. The technology is reversible to produce and consume hydrogen to balance the electrical load (Ghezel-ayagh, Sullivan, and Hayre 2019) and (Pedersen and Science 2019).

Ammonia

Technology Description

This technology addresses the complications associated with storing hydrogen by converting the hydrogen to ammonia. The hydrogen, once produced by electrolysis of water, is combined with nitrogen from an air separation unit through a conventional ammonia reactor. The ammonia, which is relatively easy to store at ambient temperature and pressure, can be combusted in the thermal plant or a standalone generator or can produce electricity directly through an ammonia fuel cell or by cracking the ammonia and passing the resulting hydrogen across a hydrogen fuel cell.

Ammonia Production:

The majority of ammonia production today uses (1) high-pressure, hot natural gas and steam that is reacted over a catalyst (CO2 and H2), which is then (2) mixed with air (CO2, H2, N2, H2O), (3) cleaned to remove CO2 and H2O (H2 and N2), and (4) reacted over a second catalyst at 850F and 4500 psi in the Haber-Bosch (HB) process to create ammonia (the process is not 100% efficient so that unreacted products are recycled to the front of the reactor).

The technology for produce ammonia intermittently from a thermal plant would involve using excess electricity to produce hydrogen through electrolysis and nitrogen through an air separation unit, like a simple pressure-swing absorption (PSA) system. The resulting hydrogen and nitrogen would be converted to ammonia through a conventional HB reactor (Nayak-Luke and Wilkinson 2018).

Ammonia Storage:

Ammonia storage is commonplace and requires minimal investigation.

Electricity Generation from Ammonia:

Thermal Use: Ammonia can be used in a thermal power plant or standalone generators directly as a fuel.

Fuel Cell:

- **Proton exchange membrane systems (PEM):** Ammonia PEMs produce less power than hydrogen PEMs as ammonia is more difficult to oxizide and are susceptible to ammonia crossover and catalyst poisoning. Research is underway using higher temperatures to address oxidation barriers and membranes that limit crossover (Zhao et al. 2019).
- **Solid Oxide Fuel Cells (SOFC)** are gaining traction as research continues to improve performance (Nayak-Luke and Wilkinson 2018) and (Kishimoto et al. 2020).
- **Ammonia Cracking:** Ammonia can be cracked into hydrogen and nitrogen to use more developed hydrogen fuel cells. A higher temperature is generally required to minimize ammonia slip, which can damage the hydrogen fuel cell (Nayak-Luke, Bañares-Alcántara, and Wilkinson 2018).

Technology Benefits and Limitations

Benefits:

- Ammonia handling is an established technology
- Ammonia cracking can use waste heat from thermal plant.

Limitations:

- Same limitations on hydrogen production
- HB process requires heat and pressure which may hinder ability to quickly start up.
- Fuel cells still require development.

Technology Status

Ammonia Production:

- Yara Pilbara is integrating hydrogen production by solar PV into existing process to produce ammonia.

Electricity Generation from Ammonia:

- GENCELL: According to the company's website, "Recognizing that the limitations of today's hydrogen infrastructure keep the cost of hydrogen prohibitively expensive as a fuel for primary power, we have developed a revolutionary process that allows us to create hydrogen-on-demand from anhydrous ammonia (NH3) at 10 times the efficiency of other solutions and without any outside electrical power. This breakthrough enables GenCell to provide the first viable green primary power solution for off-grid and poor-grid telecom as well as rural electrification—at a cost less than diesel solutions." https://www.gencellenergy.com/
- RENCAT: "RenCat's innovative core technology is the invention of a mixed metal oxide catalyst which can remove trace ammonia impurity in hydrogen to the level of 0.1 ppm. The competitor technology is Palladium-based membrane which is very expensive and has stability problems. Because of the use of very inexpensive metal oxides and metal alloys as catalyst, the price of H_2 generator will be at least an order of magnitude lower compared to the Pd-membrane based system." https://rencat.net/Technology/

Technology Cost Projections

Ammonia Production:

- Improvements for Ammonia Production will correlate to improvements in Hydrogen production from electricity, such as PEM and SOEL.

Electricity Generation from Ammonia:

- Improvements in electricity generation will need to focus on direct ammonia fuel cells and hydrogen fuel cells.

Methanol

Technology Description

This technology addresses the complications associated with storing hydrogen by converting the hydrogen to methanol. One method uses hydrogen from electrolysis of water by combining with CO_2 extracted from flue gas through a reactor. A second method adjusts combustion to create syn gas, which is passed through a slurry tower with catalyst to produce methanol. The methanol can produce electricity through a methanol fuel cell, can be power a conventional gas generator, or be used directly as a transportation fuel.

Methanol Production:

The majority of methanol produced today uses natural gas and steam in a reformer to produce syngas which is then passed across a catalyst to produce crude methanol (methanol and byproducts) and water, as well as heat. This stream to subsequently distilled to high-purity methanol.

There are two alternative production options which can be incorporated into a thermal plant energy storage system:

- **Direct Carbon Dioxide Hydrogenation:** High Purity Hydrogen (produced via electrolysis from excess electricity) and high-purity CO_2 (extracted from flue gas) pass over a catalyst in a single reactor to produce a methanol-water mix (with limited byproducts), (Samimi, Rahimpour, and Shariati 2017) and (Marlin, Sarron, and Sigurbjörnsson 2018).
- **Liquid Phase Methanol (LPMEOH):** This process diverts a portion of syngas produced from Integrated Gasification Combined Cycle (IGCC) plants through a slurry bubble column reactor containing catalyst powder which partially converts the syngas to Methanol, with the remaining unconverted syngas continuing to the gas turbine for power production (Heydorn et al., n.d.).

Electricity Generation from Methanol:

- **Thermal Power:** Methanol can be used as a fuel for power generation, either through a separate peaking unit or in the main power generating unit (Heydorn et al., n.d.).
- **Direct Methanol Fuel Cell (DMFC):** Pure methanol fuel cells have longevity concerns, however (1) studies with graphene and other membrane materials are extending the lifetime, and (2) an aqueous solution increases the reliability of methanol fuel cells significantly (Yan et al. 2016). In both methanol production methods, a methanol solution is produced naturally, and energy can be saved by avoiding the splitter tower.
- Methanol can also be converted to **Dimethyl Ether (DME)** as a diesel substitute or **Formic Acid** (as a hydrogen carrier)
- **Transportation Fuel,** as a drop-in fuel to gasoline similar to ethanol.

Technology Benefits and Limitations

Methanol Production:

Benefits:

- **Conventional:** Common process, can use excess CO_2 to increase reaction efficiency.
- **Direct carbon dioxide hydrogenation:** Small footprint facility and the product can be directly used by DMFC units and can be paired with any hydrogen generation technology.
- **Liquid Phase Methanol (LPMEOH):** Simple process and no need for hydrogen generation.

Limitations:

- **Conventional:** Requires gasifier or IGCC unit, of which there are only two in the US. CO2 efficiency increase requires high-purity CO2 separated from flue or exhaust gas, unless the facility is using supercritical CO2.
- **Direct carbon dioxide hydrogenation:** Requires high purity CO2, which needs to be separated from flue or exhaust gas, unless the process is using supercritical CO2.
- **Liquid Phase Methanol (LPMEOH):** Only works with IGCC plants, of which there are only two in the US.

Electricity Generation from Methanol:

Benefits:

- **Thermal Power:** Straightforward process.
- **Direct Methanol Fuel Cell (DMFC):** Methanol-water mix, while not ideal for transportation applications due to the lower energy density, in this application would simply require more storage tanks and will benefit the life of the fuel cell (Dalena et al. 2018).
- **Methanol to DME or Formic Acid:** Offers other options for monetization.
- **Transportation Fuel:** Flexible Fuel Vehicles are available for up to 85% methanol (Joghee et al. 2015).

Limitations:

- **Thermal Power:** Best efficiency would require methanol separation from water.
- **Direct Methanol Fuel Cell (DMFC):** Pure methanol fuel cells suffer reduced efficiency due to methanol crossover (Dalena et al. 2018).
- **Methanol to DME or Formic Acid**: Additional capital cost will not be supported on intermittent production vs. dedicated facilities.
- **Transportation Fuel:** Limited market, and would require infrastructure and consumer education.

Technology Status

Methanol Production:

- **Direct carbon dioxide hydrogenation:** Carbon Recycling International (CRI) operating George Olah Plant, Reykjanes, Iceland since 2012.
- **Liquid Phase Methanol (LPMEOH):** Pilot plant in Kingsport, Tennessee, operational as of 1997 (Heydorn et al., n.d.).

Electricity Generation from Methanol:

- **Direct Methanol Fuel Cell (DMFC):** Several low-volume producers, including:
    - Element 1: Commercializing onsite methanol-to-hydrogen production for vehicle and stationary hydrogen use (Schluter 2019). Element 1 claims that hydrogen can be produced at $3/kg H2 at $408/ton for methanol.
    - Siqens: This German company is commercializing methanol-to-hydrogen to be used in an integrated fuel cell (Siqens 2019). The company is seeking to penetrate the off-grid diesel generator market in developing economies (Esser 2018).

Technology Cost Projections

- Fuel Cell Performance with membrane technology improvements
- All hydrogen electrolysis improvements

Conclusions and Recommendations

Figure 25. Comparative Assessment of Energy Storage Technologies

Benefits	Technology Maturity (Experience)	Durability/ Reliability (Degradation)	Duration Capacity (hours)	Dispatch Capacity (MW)	Response Time	Relative Cost	Fossil Themal Integration (Opportunity)
Better (✓✓✓)	High	Limited	High	High	Faster	Low	High
Worse (✓)	Limited	High	Low	Low	Slower	High	Limited
Stationary Battery Energy Storage							
Li-Ion BES	✓✓✓	✓✓	✓	✓✓	✓✓✓	✓✓✓	✓
Redox Flow BES	✓	✓✓	✓✓	✓✓	✓✓✓	✓✓	✓
Mechanical Energy Storage							
Compressed Air	✓✓✓	✓✓✓	✓✓	✓✓	✓✓	✓	niche
Pumped Hydro	✓✓✓	✓✓✓	✓✓	✓✓	✓✓	niche	✓
Thermal Energy Storage							
SC-CCES	✓	✓	✓✓	✓✓	✓✓	✓	✓✓
Molten Salt	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Liquid Air	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓	✓	✓✓✓
Chemical Energy Storage							
H2-AEL	✓✓✓	✓✓	N/A	N/A	✓✓✓	✓✓	✓
H2-PEM	✓✓	✓	N/A	N/A	✓✓✓	✓	✓
H2-SOEL	✓✓	✓	N/A	N/A	✓✓	✓	✓✓✓
H2-MOFs	✓✓	✓✓	✓	✓	✓✓	✓✓	✓
H2-Hydrides	✓	✓✓	✓✓	✓	✓	✓✓	✓✓✓
NH3-Prod	✓✓✓	✓✓✓	N/A	N/A	N/A	✓✓	✓✓
NH3-Cracking	✓✓	✓✓✓	✓✓✓	✓✓	✓✓	✓✓✓	✓✓✓
NH3-FC	✓	✓	✓✓✓	✓✓	✓✓✓	✓✓✓	✓
MeOH-Prod Conv	✓✓✓	✓✓✓	N/A	N/A	N/A	✓	✓
MeOH-Prod CO2	✓✓	✓✓✓	N/A	N/A	N/A	✓	✓
MeOH-LPMEOH	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓✓	✓	✓✓
MeOH-FC	✓	✓	✓✓✓	✓✓	✓✓✓	✓✓✓	✓✓

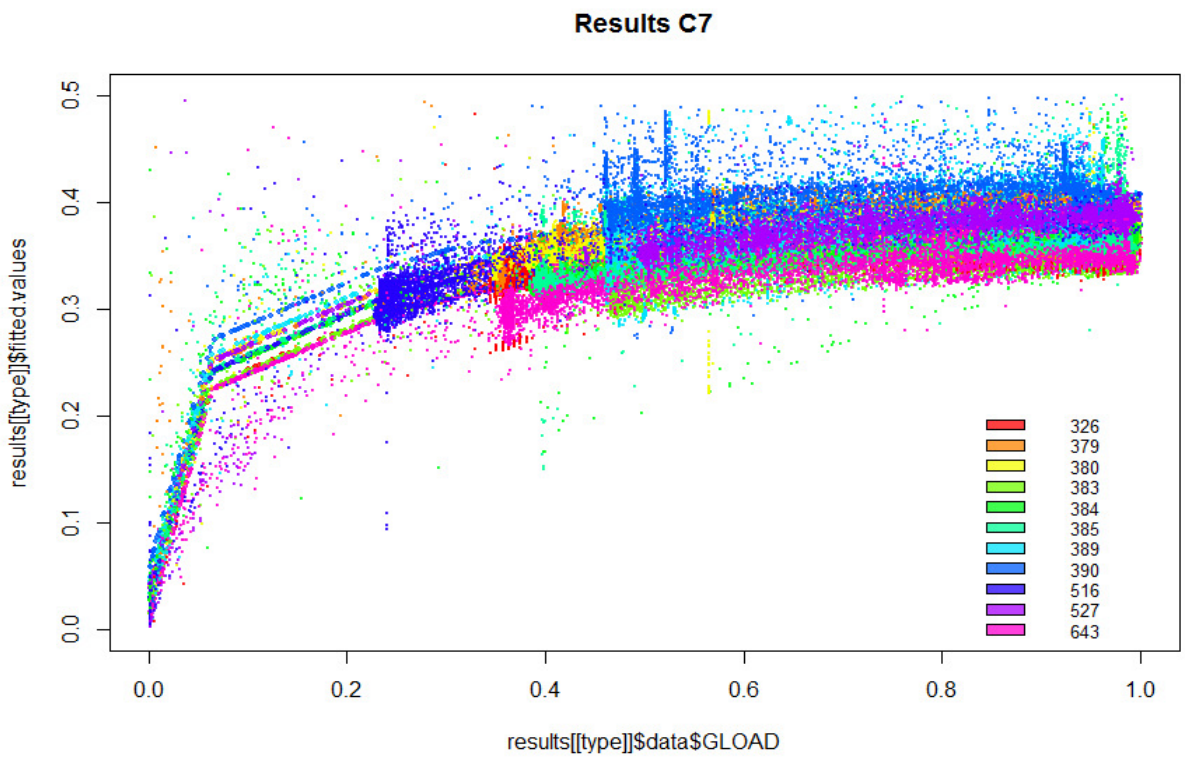
Source: OnLocation

- The technologies were ranked in seven (7) categories:
    1. **Technology Stage (Experience):** The level of experience (high level or limited level) with the technology in commercial application.
    2. **Durability/Reliability (Degradation):** The amount of expected performance degradation of the technology with usage/cycles.
    3. **Duration**: The capacity for storage and discharge of the technology within reasonable cost and footprint.
    4. **Dispatch Capacity**: The amount of electricity which the technology can generate.
    5. **Response Time**: The time required for a technology to produce electricity when needed.
    6. **Relative Cost:** The cost to build and operate the technology.
    7. **Fossil Thermal Integration (Opportunity):** The potential for the technology to be integrated and synergize with a thermal plant.

- Energy storage technologies with the most potential to provide significant benefits with additional R&D and demonstration include:
  - Liquid Air:
    - This technology utilizes proven technology,
    - Has the ability to integrate with thermal plants through the use of steam-driven compressors and heat integration, and
    - Limits stored media requirements.
    - Of the two most promising technologies, this is the one most ready for immediate deployment.
  - Ammonia Production with Cracking and a Hydrogen Fuel Cell:
    - This technology is very close to immediate deployment,
    - Eliminates the need for costly cryo-storage of hydrogen, and
    - It offers the opportunity for heat integration and technology adoption as hydrogen electrolysis, and fuel cell technology is advanced.
  - Other promising technologies include:
    - Super Critical CO_2 Energy Storage (SC-CCES)
    - Methanol with Hydrogen Fuel Cell
  - Specific enabling technologies that may benefit from additional R&D include:
    - Electrolysis (generally),
    - Direct Methanol Fuel Cell (DMFC), and
    - High-Temperature Steam Electrolysis (HTSE) that couples 800°C steam with solid-oxide electrolysis to reduce the electricity requirement.
- Energy storage technologies that are largely mature but appear to have limited extended application or R&D upside include:
  - Pumped hydro storage
  - Compressed Air Energy Storage (CAES)
- Energy storage technologies are undergoing advancement due to significant investments in R&D and commercial applications.
- There exist a number of cost comparison sources for energy storage technologies
  - For example, work performed for Pacific Northwest National Laboratory provides cost and performance characteristics for several different battery energy storage (BES) technologies (Mongird et al. 2019).

Recommendations for Future Analysis

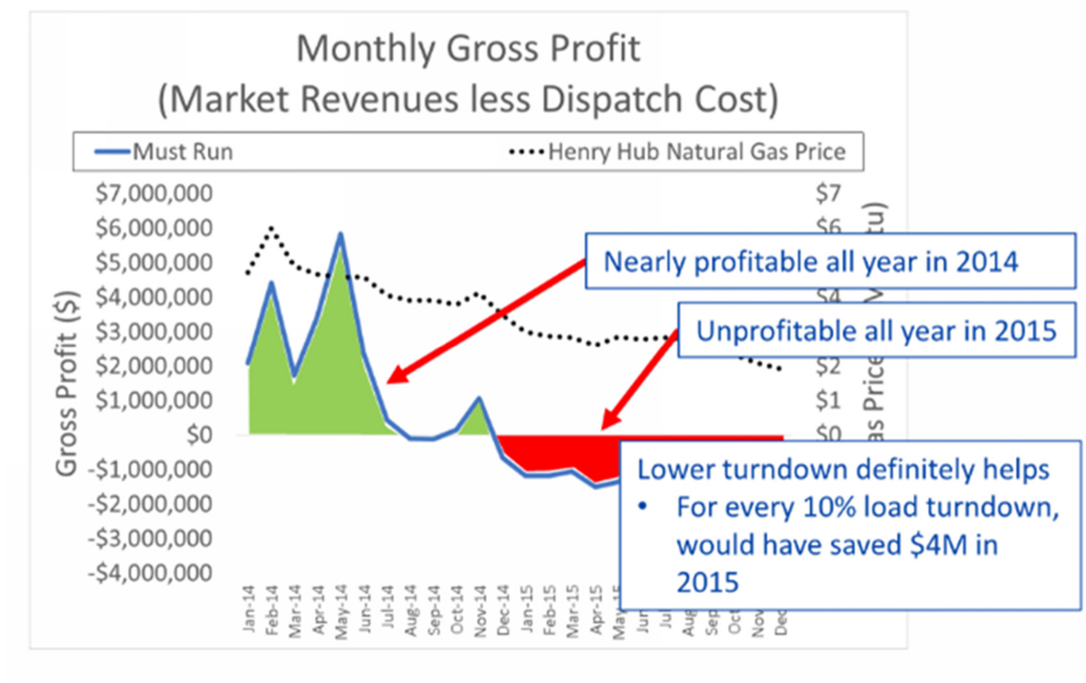
Figure 26. Hourly Coal Powerplant Efficiency by Load Level for a Representative Region in 2013 - 2015



Source: OnLocation

- Perform analysis of **historical fossil thermal powerplant dispatch** to identify conditions for lowered dispatch – how has the deployment/utilization of coal and other fossil-fueled generating technologies been impacted by market, capacity mix and renewable polices.
- For example,
    - Use the recently developed powerplant tool to extract CEMS data and characterize operations of units/plants in a region (hourly or subhourly)
    - Use Power Market data to provide economic context
    - Use Power Market data to provide generating load requirement (hourly or subhourly)
    - Use regional data of aggregate or aggregate by type (wind vs. PV) renewable output (hourly or subhourly)
    - Assess patterns of use such as minimum load, ramp requirements, spinning reserves, etc.
    - Study two study years, early in the penetration of renewables and later after substantial penetration, to establish changes in system behavior
    - Track emission profiles and changes caused by changed fossil fuel dispatch
    - Account for alternative use of CT/GTs in the generating mix

Figure 27. Fossil Thermal Powerplant Characteristics



Source: https://www.eapc.net/is/program-offerings/low-load-operation-optimization-2/

  - Characteristics relevant to the economics of dispatch include:
    - Turndown ratio: Lowest load necessary to maintain plant systems
    - Ramp rate/thermal cycling:
    - changes in load induce stress on boiler tubes and other components, which, in turn, increases outage frequency and reduces utilization.
    - Short and long-term shutdown and startup times and costs

- Improve **techno-economic modeling tools** to better account for the different fossil thermal power plants and their characteristics to allow for quantitatively evaluating the benefits of various thermal power gen/energy storage technology combinations (grid and co-located)

  - Develop key measures of economic performance
    - Cost of electricity
    - Ancilliary market
    - Transactional support (market operations or bi-party)
    - Emissions/other environmental impacts
  - Develop economic frameworks to evaluate these factors/measures through simulation, optimization, and potentially other types of modeling. One potential option being:
    - RESTore Model: Improve techno-economic modeling tools, such as EIA's REStore module within the NEMS model, to better account for the different fossil thermal power plants and their characteristics and expand the model's

storage technology representations to allow for quantitatively evaluating the benefits of energy storage integrated with fossil plants

- Build on this work to **develop specific technology parameters** that are "benched" to one or more estimates for performance and cost, such as EIA, PNNL, etc. that would be used in modeling and analysis.

Figure 28. "Getting It Right" in Economic Unit Commitment and Dispatch is Key

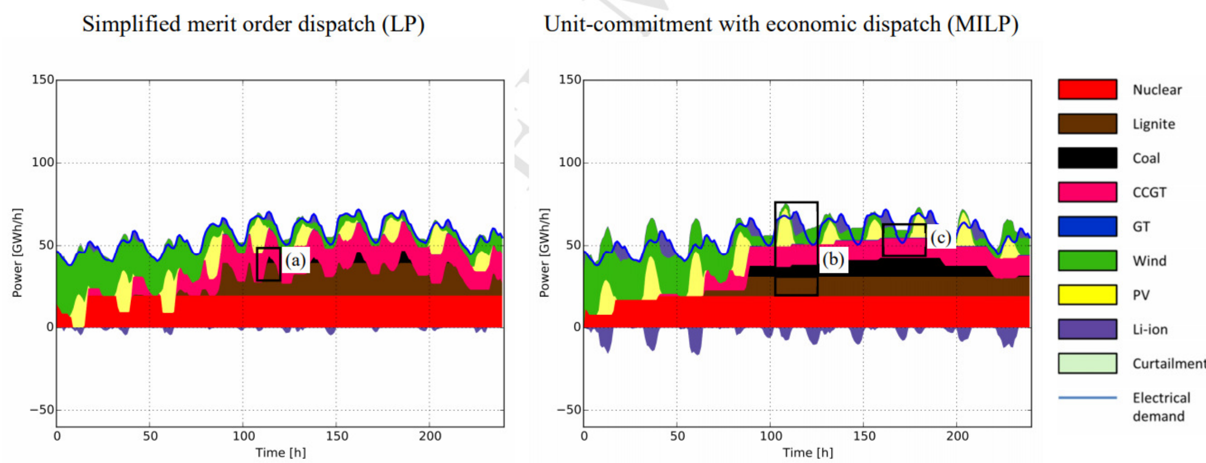
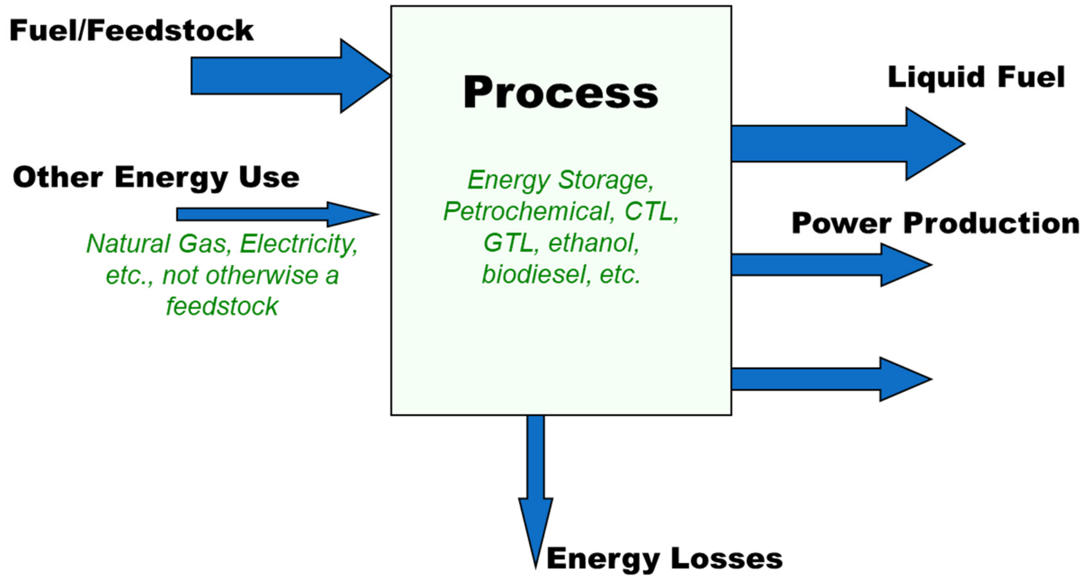


Fig. 7: Comparison of the hourly electricity generation of the simplified merit order dispatch (LP) and unit-commitment with economic dispatch (MILP) power plant modeling approach for the hours 0 – 240 for the scenario with a VRE share of 0.33 and a PV share β of 0.4. The latter's in brackets refer to the observations described in the text above.

Source: (Cebulla and Fichter 2016)

- "Grid-Connected" Energy Storage:
  - Not accounting for operating constraints of thermal powerplant results in over-optimization of dispatch and a lower value of storage
- "Co-Located" Energy Storage:
  - Integrating energy storage within the thermal powerplant allows for grid optimization
- The objective of the modeling and analysis being to determing whether the benefits of "Co-Location" outweigh that "Grid-Connected" energy storage.

Figure 29. Modeling Issues



Source: OnLocation

- Dispatch modeling
  - Evaluating the benefits of different dispatch options.
- Co-product issues
  - Evaluating the co-product production potential.
  - Evaluate whether there is a CO_2 co-benefit of increased ammonia production in increasing the fertility of marginal lands.

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