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AN OVERVIEW OF MACHINERY IN ENERGY STORAGE AND HYDROGEN APPLICATIONS

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ABSTRACT

Decarbonization of electric power infrastructure requires the development of cost-effective, sustainable, and reliable energy storage technologies that are capable of many Megawatts or Gigawatts of output and long storage durations potentially spanning days, weeks, and months. These technologies would absorb power from the grid during periods of excess renewable generation, and release the stored energy to generate power when renewable sources are unavailable. The first part of this tutorial introduces the history of energy storage technologies, general requirements for energy storage applications, and challenges with grid-scale electrochemical batteries that drive the development of machinery-based systems for energy storage.

There are many existing or developing machinery-based energy storage systems to fulfill this need. These systems include various pumped hydro technologies, flywheels, compressed air, gravitational, liquid air, thermal energy storage including pumped thermal, and various thermochemical technologies such as hydrogen, ammonia, synthetic natural gas, or sulfur. A comprehensive overview of all of these technologies is provided including basic working principles, role/requirements of turbomachinery, hybridization with existing power generators, current state of development including pilot/demo activities, capabilities relative to other technologies, and research & development needs for system improvements and commercialization. In particular, the authors will discuss hydrogen machinery including an overview of hydrogen impacts on compression and combustion in machinery for pure hydrogen and blended hydrogen applications.

INTRODUCTION

Significant global integration of renewable energy sources with high variability into the power generation mix requires the development of cost-effective, efficient, and reliable grid-scale energy storage technologies. Many energy storage technologies are being developed that can store energy when excess renewable power is available and discharge the stored energy to meet power demand when renewable generation drops off, assisting or even displacing conventional fossil- or nuclear-fueled power plants. The development and commercialization of these technologies is a critical step for enabling a high penetration of renewable energy sources.

Many mature and emerging energy storage technologies utilize combinations of thermal, mechanical, and chemical energy to meet storage demands over a variety of conditions. These systems offer the potential for better scalability than electrochemical batteries. Energy storage demands are complex and the resulting solutions may vary significantly with required storage duration, charge/discharge duty cycle, geography, daily/annual ambient conditions, and integration with other power or heat producers and consumers. This tutorial explains the energy trends that motivate development efforts for new thermal, mechanical, and chemical energy storage technologies, discusses a wide variety of existing and developing machinery-based technologies for energy storage, and describes the opportunities and challenges for successful development and commercialization of these technologies.

A strong focus on decarbonization is resulting in significant changes to the power generation mix is on global and local scales. In 2018, the world consumed approximately 26,641 TWh of electric power. Based on data in [1] fossil-based sources accounted for 64.2% of generation, supplemented by 10.2% nuclear power. The remaining ~25% was produced by renewable sources including hydroelectric (15.8%), wind (4.8%), solar (2.2%), and geothermal/biomass (2.4% combined). Notably, although wind and solar sources are still a relatively low percentage of the overall energy mix, they are the fastest-growing categories globally and particularly for OECD (Organisation for Economic Cooperation and Development) member countries. From 2017 to 2018, the IEA [2] reports overall declines in electricity production in OECD countries from combustible fuels (particularly coal and oil) that are substantially offset by 19.8% and 7.0% growth in solar and wind production, respectively. In local regions, more dramatic changes can be seen. California's electricity production profile shows that coal-based electricity in that location has declined to negligible amounts. Natural gas power plants constitute the largest source of electrical power at about 46%, but renewables have grown rapidly in the past decade, combining for 21% growth from 2017 to 2018. In 2018, renewable sources including solar, wind, hydro, geothermal, and biofuels were a close second to natural gas, providing 44% of California's electricity production [3].

Two significant challenges result from the rapid introduction of renewable resources into the energy mix. First, much of the capacity growth will be provided from solar and wind generators that have high variability. Wind and solar power output can vary significantly by the minute, hour, and season. Wind speed varies due to weather patterns or diurnal effects. Likewise, solar power output will vary with storms, cloud passes, and ambient temperature/wind. The minute-to-minute variation of power produced from photovoltaic and wind plants is on the same order of magnitude as the average output [6,7]. Finally, similar amplitudes of seasonal variation also occur in wind and solar power plants. Summer capacity at Lake Benton WPP is just over half of winter capacity [7], and winter production from combined PV and CSP is approximately 1/3 of summer peak values [8].

The second significant challenge is that the availability of wind and solar resources is also poorly matched with the typical electrical demand profile. A recent electrical demand curve in California is shown in Figure 1 and illustrates small demand peaks in the morning and evening. The evening peak in particular occurs after solar production has dropped off, resulting in a fast ramp of baseload/import resources that must be brought online very quickly. Another challenge is highlighted during the middle of the day, when the renewable resource is very high and renewable resources (plus baseload generators operating at minimum output) exceed the power demand, requiring curtailment of renewables to achieve power balance. Notably, in California every month since December 2016 has required curtailment of renewable resources, recently exceeding monthly values over 200 GWh in summer months [10]. There is also a strong trend of growing curtailment from year to year, with peak curtailment in the spring and fall.

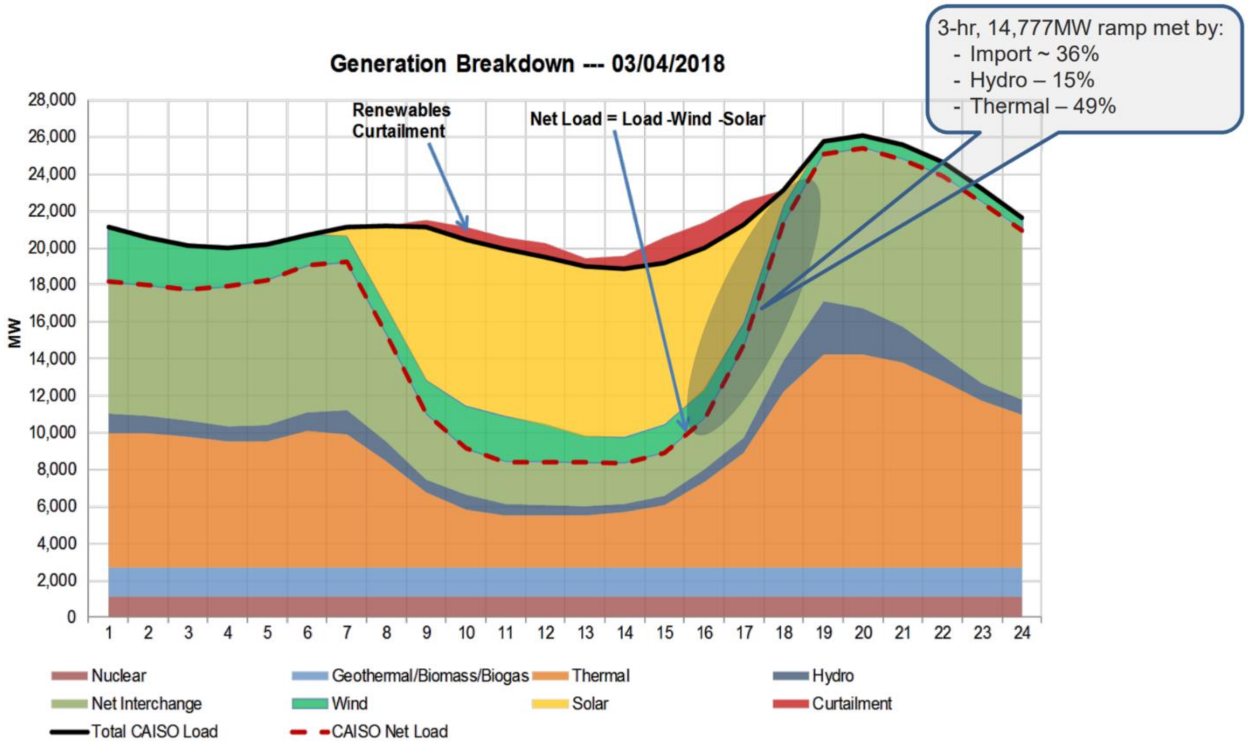

Figure 1. Daily Demand vs. Power Source; CAISO, March 4 2019 [9]

The high variability and resource-demand mismatch associated with renewable power sources impose significant ramp rate and turndown requirements on baseload power generators that were not necessarily designed for this service. Simple-cycle gas turbines are characterized by fast startup times and high turndown capabilities, but with relatively poor efficiency and emissions performance at low load. Combined-cycle gas turbines and steam turbines incorporate large heat exchangers and have reduced ramp rate capabilities to minimize thermal stress, but have higher part-load efficiencies and lower part-load emissions. A recent study [11] summarizes the turndown and ramp rate capabilities of conventional thermal generators and notes that significant performance improvements are necessary for all technologies to provide backup for a high penetration of renewables. Future operation of these conventional generators may include twice as many starts, 70-100% faster ramp rates, 35-70% faster starts, 35-60% increased turndown, and lower emissions than achievable by the current state of the art.

How much storage is needed in the long term? The answer to this complex question depends on many factors including the depth of renewable penetration into the energy mix, the relative mix of wind/solar generators, grid size and diversity, geography and climate trends, degree of allowable energy curtailment, storage system performance capabilities, approach to utility load management, economic policy, etc. A recent review paper [12] highlighted a range of studies showing that the required storage capacity for 70-100% renewable penetration the required storage capacity was equal to 22%-2160% of the average daily demand, a very wide range. It is also relevant to consider the existing fossil fuel storage as a reference. The U.S. capacity for natural gas storage is approximately 1420 TWh of energy (heating value in the gas). Since annual natural gas consumption is 9230 TWh, this corresponds to nearly 2 months of storage. The authors conclude that an optimal solution balancing curtailment and storage may result in storage requirements of at least the average daily average demand, and perhaps significantly higher.

The storage of energy in very large quantities introduces issues of proper location and safety. As an example of the required scale, a large city, such as Tokyo, has an average power demand of approximately 30-40 GW. Thus, the daily energy demand is approximately 840 GWh. This amount of energy is equivalent to approximately 6500 battery banks like those manufactured by Tesla, Inc. for the Hornsdale Power Reserve in Australia, 35 of the world’s largest pumped hydro facility in Bath County, Virginia, or 760 tanks of molten salt similar to those used in the Crescent Dunes concentrating solar power plant. More dramatically, the energy contained is equivalent to approximately 35 of the 20-kiloton nuclear weapons used during World War II. Although the energy amounts are not greater than what is already produced and consumed in a day, the collection and storage of this energy must be done in a safe and secure manner, ideally located for transmission from generators and to loads.

Multiple metrics are important for quantifying the cost and performance of energy storage systems for various applications. A summary of common metrics and their definitions is provided in Table 1. These metrics emphasize that significant details are required to fully characterize an energy storage system that may need to operate flexibly in response to grid demands, i.e. at different charge/storage/discharge profiles and different power rates. One key observation is that both power capital costs and energy capital costs are important and will scale differently for different systems. For example, a 2-hour 100 MW Lithium-Ion battery storage system may have a significantly lower cost per kW than a 2-hour pumped hydro system, but as energy increases to longer durations the pumped hydro system costs will increase much more slowly than the battery system. Thus, meaningful cost evaluations must include both effects. Another important point is that the commercial viability of an energy storage system is typically a function of both performance and cost, i.e. a lower-cost system may be viable even with reduced performance or vice versa.

Table 1. Performance and Cost Metrics for Energy Storage Systems

Performance/Cost Metric	**Typical Units**	**Definition / Explanation**
Power Rating	MW	Maximum output/discharge power allowed from system at nominal conditions. May be different than input/charge power rating.
Power Density	W/kg	Power rating divided by system weight. Emphasizes short-duration systems.
Specific Power	W/m^3	Power rating divided by system volume requirement. Emphasizes short-duration systems.
Energy Capacity or Storage Capacity	Wh	Maximum amount of stored energy that system can deliver, i.e. Power rating multiplied by discharge time at rated power. Will be less than charging energy and stored energy due to system inefficiencies.
Energy Density	Wh/kg	Energy capacity divided by system weight. Emphasizes long-duration systems.
Specific Energy	Wh/ m^3	Energy capacity divided by system volume requirement. Emphasizes long-duration systems.
Charge Efficiency	%	Total stored energy divided by total input energy for nominal charge profile.
Discharge Efficiency	%	Output energy divided by stored energy for nominal discharge profile.
Round Trip Efficiency or Cycle Efficiency	%	Output energy divided by input energy for nominal charge, storage, and discharge profile.
Response Time	Seconds - minutes	Various specific definitions, but generally time required to ramp discharge power up to rated power.
Daily Self-Discharge	%/day	Percentage of energy capacity lost per day due to heat leaks, friction, chemical breakdown, system parasitics, or other energy losses.
Lifetime	Years	Useful system life, may include major maintenance/overhauls.
Performance Degradation	%/year	Loss of system rated power or energy capacity due to degradation, fouling, etc.
Storage Duration	Seconds – months	Time between charge and discharge events.
Turndown	%	Lowest percentage of rated power that the system can be operated at.
Power Capital Cost	$/W	System cost divided by power rating. Emphasizes short-duration systems.
Energy Capital Cost	$/Wh	System cost divided by energy capacity. Emphasizes long-duration systems.
Operating & Maintenance Cost	$	Operating and maintenance costs may be functions of time ($/year), operating time ($/Wh), or cycles ($/cycle).
Siting Requirements	-	Siting requirements other than power/energy density or specific power/energy may include safety, permitting, geographic, noise, environmental, and other constraints.

The cost and performance of energy storage are strong drivers of the overall economics for renewable energy. Figure 2 below shows the result of several trade studies on the cost of electricity for several decarbonized technologies. In all of the plots, capital and operating expenses are plotted vs. a typical 30-year life for utility plants. The plots show several technologies: (1) Solar photovoltaic (PV), (2) Wind, and (3) Gas turbines with carbon capture (CCS) in the exhaust supplemented with direct air capture (DAC) for net zero emissions. The leftmost plot assumes all power generators are sized for the same rated power. The initial capital cost is comparable for all three technologies, but the total lifetime cost is much lower for solar PV and wind systems due to the lack of fuel costs in the operating expenses. However, when the technologies are normalized by the annual capacity factors of 24.5%, 34.8%, and 56.8% for solar PV, wind, and gas turbines, respectively (to produce the same amount of energy), the relative costs of solar and wind generators increase significantly due to the need for additional installed capacity. The rightmost plot incorporates approximate costs to store the renewable energy for when it is needed, assuming 24 hours storage duration at 60% round-trip efficiency and ~$100/kWh. The storage costs further increase the relative costs of renewables, illustrating the need to improve both the efficiency and costs for long-duration energy storage systems.

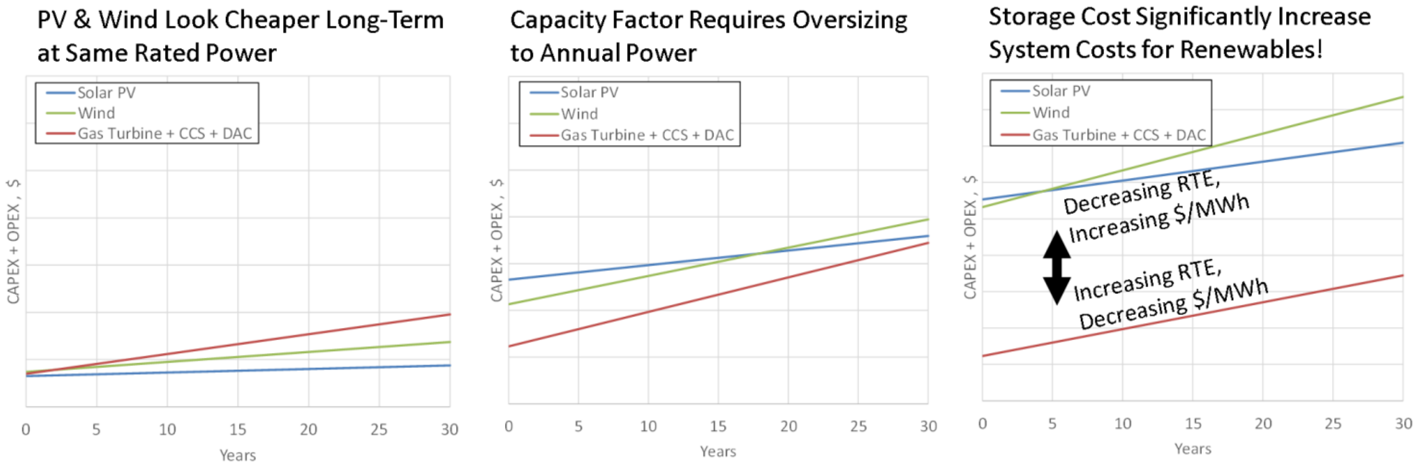

Figure 2. Economic Impacts of Energy Storage on Renewable Technologies

The many forms of energy have resulted in a wide range of technologies that seek to store and convert energy, some of which are commercially mature and others that are currently under development. A graphical summary of mature and developing technologies is provided in Figure 3, identifying nominal discharge times and operating scales for flywheels, various battery and supercapacitor technologies, and large-scale technologies including thermal, mechanical, and chemical storage concepts [13]. The development and cumulative power generation capacity of various energy storage technologies across the world are illustrated for the past several decades in Figure 4. This figure illustrates that pumped hydro comprises over 96% of global capacity, followed by thermal storage (primarily hot oil and molten salt) and electromechanical storage (primarily compressed air energy storage and flywheels). Electrochemical battery storage systems have seen recent growth through 2013 and even more rapid growth in years since due to significant price declines.

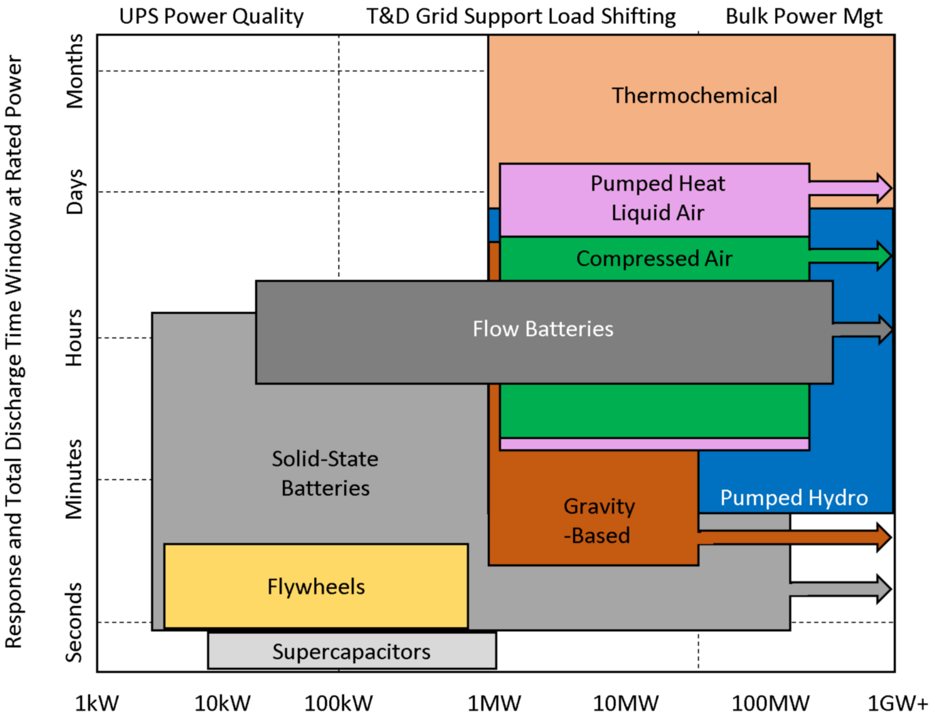

Figure 3. Energy Storage Technologies [13]

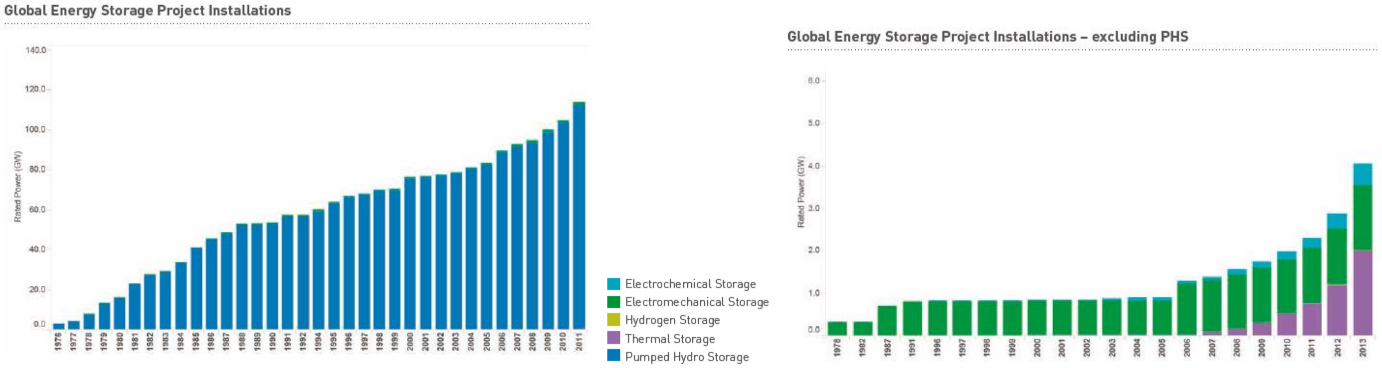

Figure 4. Global Growth of Energy Storage Projects Including (left) and Excluding (right) Pumped Hydro [14]

Battery technologies store energy chemically and charge/discharge electricity via ion movement between electrodes. Although historically limited to small-scale applications, batteries have decreased dramatically in price in recent years and are considered for many large-scale applications, including 100+ MW applications for 1-4 hours of storage. Lithium-Ion batteries are the current market leader with 80% market share [15], although many other technologies exist. Batteries are advantageous in that they have high round-trip efficiencies of approximately 81-87% and relatively low cost for high-power short-duration applications. Despite these advantages, batteries suffer from a number of drawbacks that may limit their widespread application to grid-scale energy storage. Most importantly, although battery costs have dropped significantly on a cost per kW basis, most applications have a short duration (the median is only 1.7 hours). Battery technology costs will (approximately) scale proportionally with duration (duration is increased by adding parallel cells), so batteries are still prohibitively expensive for long-duration applications greater than about 2-6 hours (depending on many factors). Lithium-Ion batteries require rare earth metals including lithium, cobalt, and others; there is significant disagreement in the literature about whether global reserves are adequate and/or can be sustainably accessed to scale battery production up to the necessary scales for supporting high renewable penetrations for decades and centuries to come [16]. Geopolitics are also a complicating factor for many countries, as these materials are sourced from relatively few locations worldwide. Battery degradation reduces battery capacity and efficiency below initially specified values. The life of most utility-scale battery banks is limited to 10 years, with major maintenance required after 5-8 years [17]. There is also no methodology for recycling of lithium-ion battery materials with sufficient purity for reuse in batteries [18]. Finally, commercial battery systems are susceptible to thermal runaway and fire [19], requiring thermal management to avoid abuse/environmental hazards.

The need for significant amounts of energy storage combined with the drawbacks of electrochemical batteries create a development opportunity for thermal, mechanical, and chemical technologies. Many of these technologies rely on thermodynamic cycles for charge and discharge cycles, thus requiring machinery for their implementation. The applications are diverse, and specific performance, costs, and needs of each technology are still being defined through research and commercialization efforts. This tutorial provides a broad overview of these technology concepts, current state of the art, and development needs.

EXISTING COMMERCIAL TECHNOLOGIES

Several machinery-based storage technologies that are commercially available include pumped hydro, compressed air, and flywheel energy storage systems. Pre-commercial development activities for these technologies also exist that are also described in this section.

Pumped Hydro Storage (PHS)

The earliest grid-scale energy storage technology is pumped hydroelectric storage, introduced to the grid in the 1930s. Significant capacity growth has continued since, and pumped hydro is still the dominant technology in energy storage on a capacity basis. For pumped hydro systems, electrical energy is converted to potential energy by pumping water from low to high elevation (Figure 5), where it can be stored for long durations. The system is discharged by using the high-pressure water to drive a turbine and produce electrical power. Pumped hydro is cost advantageous over batteries for multi-hour storage durations, but has a high capital cost and can only applied where suitable geography and permitting opportunities exist. Pumped storage plants can either be closed-loop systems (isolated upper and lower reservoirs) or open-loop (lower reservoir is a river or ocean). Pumped storage systems can have high power output and storage capacities; the world's largest system in Bath County, VA has 3 GW of generation capacity and 24 GWh or storage capacity. The round trip efficiency is also quite high, typically ≥80%. One significant limitation of pumped hydro systems is that they require geography with significant elevation changes and significant space (with associated permitting difficulties).

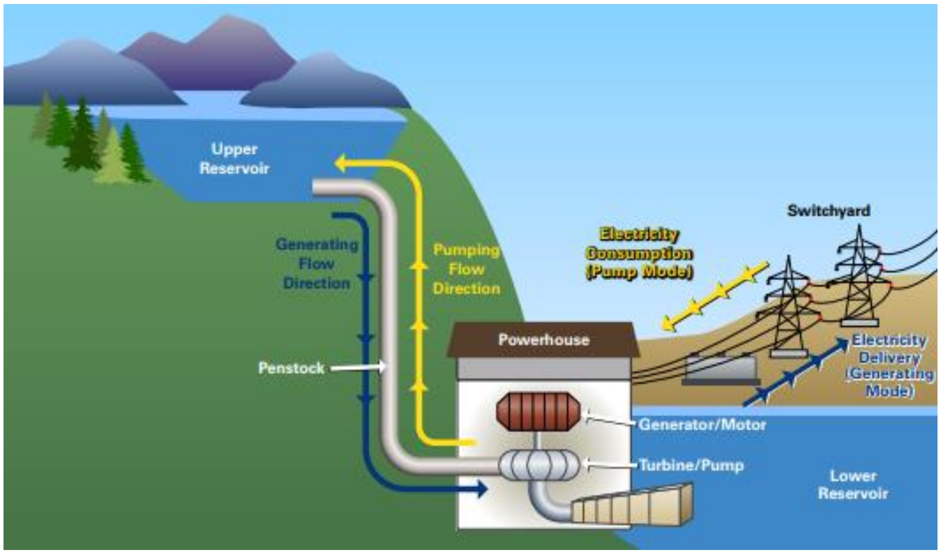

Figure 5. Pumped Hydro Stores Potential Energy in Water at Different Elevations

The machinery for a pumped hydro system includes motors, pumps, and turbine components that are generally arranged in one of two architecture: reversible pump-turbines and ternary sets [20]. The reversible pump-turbines utilize a single-stage pump-turbine wheel that reverses direction of rotation during operation. Ternary sets typically utilize multi-stage centrifugal pumps, generally with either Francis/Pelton turbines for moderate/high head applications, respectively. Typical operating ranges for these architectures and turbine types are provided in Figure 6 and Figure 7. For very low head applications, other turbine types (Deriaz, Bulb, Kaplan) may be employed. The choice of turbine/pump type and architecture is driven by the head and power (flow) requirements as well as variation in pump head and turndown requirements. Ternary sets have the capability to operate both pump and turbine simultaneously, hydraulically short-circuiting the reservoirs to increase the turndown capabilities of the plant. Notably, single-stage pump-turbines require higher net positive suction head than multistage pumps used in ternary sets.

Machinery advancements for pumped hydro systems focus on variable-speed operation and startup improvements. Variable-speed motor/generator architectures allow for improved operating range and part-load efficiency in both charging and discharging modes. The use of a torque converter during startup vs. a stationary clutch or starting turbine also increases startup ramp rate capabilities significantly. System advancements seek to reduce the capital cost of pumped hydro systems, e.g. small modular open-loop pumped hydro) or subsea pumped hydro. Other advancements combine pumped hydro storage with other industrial processes, e.g. desalination [21].

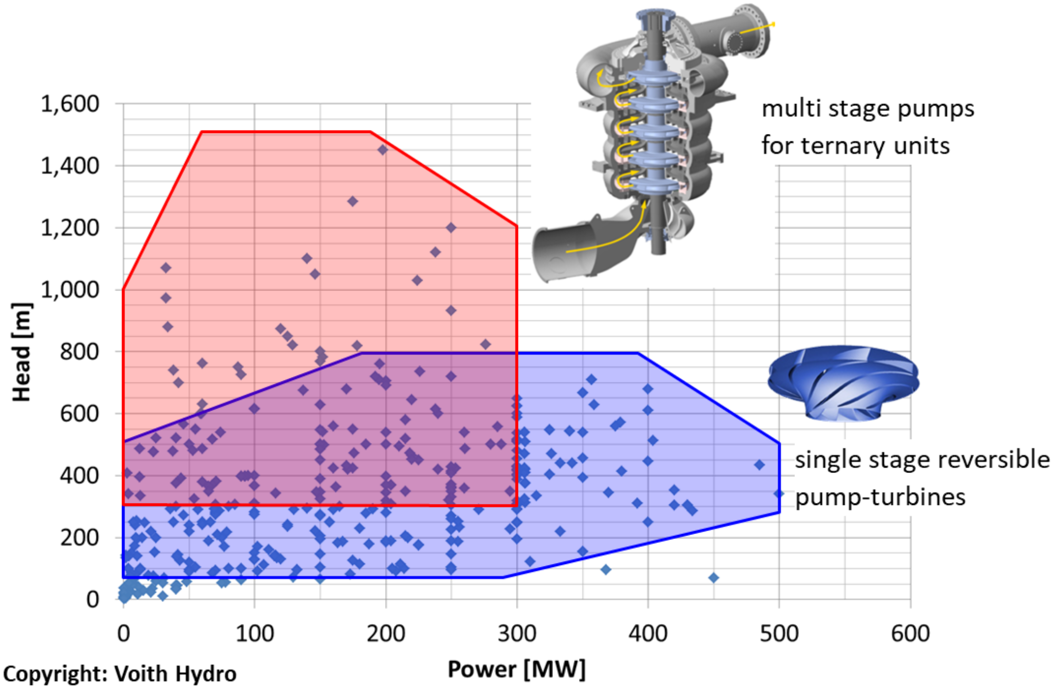

Figure 6. Application range for single stage reversible pump-turbines (charging & discharging) and multi stage pumps for high head (charging) [20]

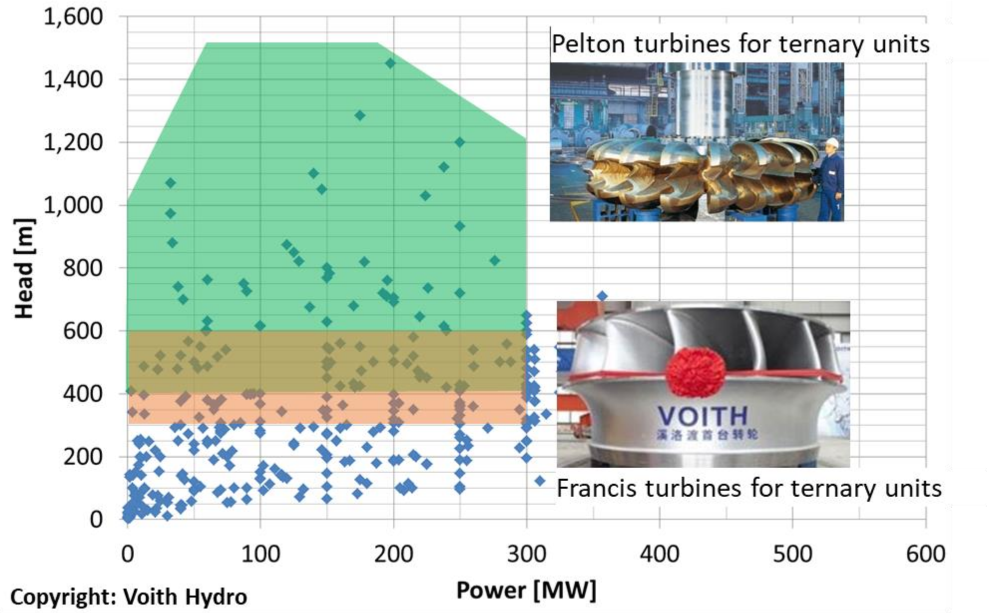

Figure 7. Application range for Francis and Pelton turbines (discharging) [20]

Compressed Air Energy Storage (CAES)

There are two existing commercial CAES systems in operation today, one in Huntorf, Germany (290 MW; 3 hours storage) and the other in McIntosh, AL, USA (110 MW). These existing commercial compressed air energy storage (CAES) systems are charged by compressing air into underground solution-mined salt dome caverns. To discharge, the compressed air is released from the cavern, fired with natural gas, and expanded through a turbo-generator as illustrated in Figure 8. The process of natural gas combustion for improving turbine output is termed diabatic CAES. The McIntosh plant recuperates heat from the turbine exhaust to increase efficiency. Newer pre-commercial concepts seek to improve round-trip efficiency and achieve zero-carbon operation by storing the heat of compression to preheat expansion air during discharge mode and, for a zero-carbon solution, eliminating the combustors (adiabatic CAES). Due to cavern use, both diabatic and adiabatic CAES are inherently limited to areas with suitable geology.

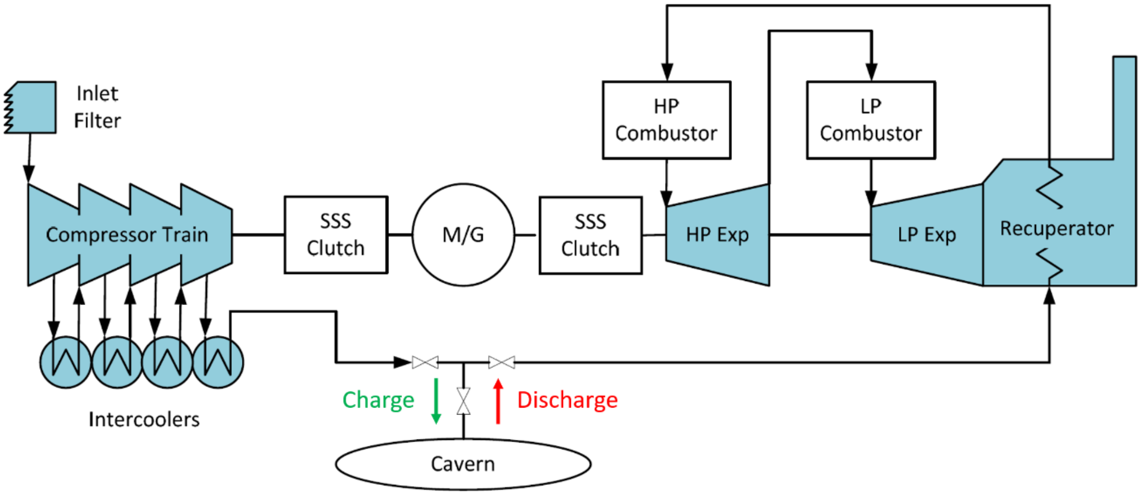

Figure 8. Concept Illustration of Diabatic CAES System (modified from [22])

Commercial machinery solutions are available for both diabatic and adiabatic CAES that leverage products from other applications. CAES systems run open-loop with air (ambient inlet and exit), but decouple compressor and turbine operation. Adiabatic CAES in particular may favor integrally-geared compressors for charging the system rather than axial compressors due to the ease of intercooling for power reduction and heat storage. Kerth (2019) [22] presented the compressor and expander trains for diabatic CAES shown in Figure 9, including an integrally-geared LP compressor with intercooling plus HP barrel compressor, steam-turbine-based axial HP expander, and a gas-fired LP expander based on the a 62 MW-class single-shaft industrial gas turbine.

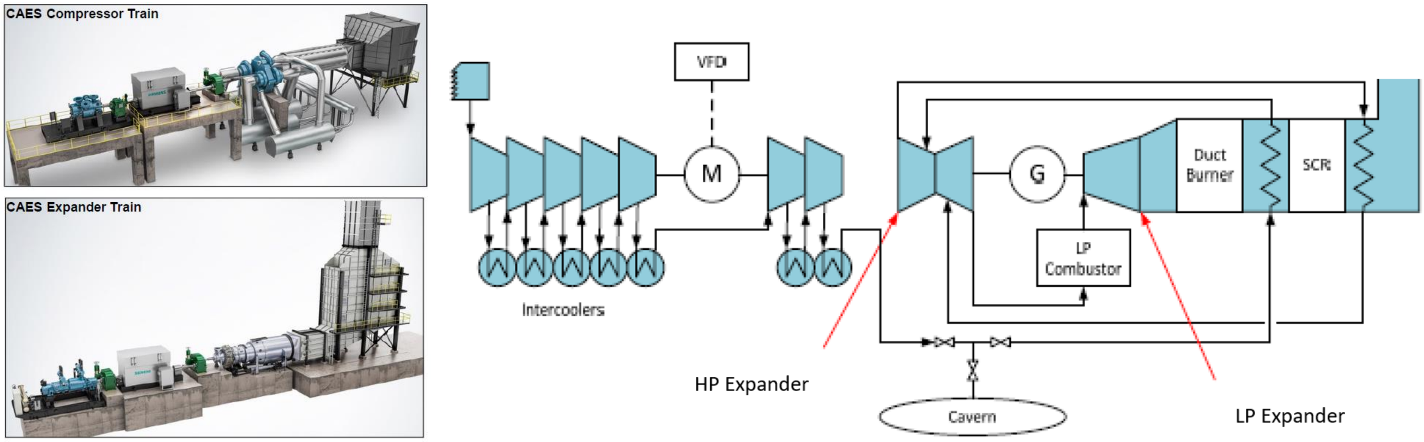

Figure 9. Advanced Diabatic CAES Machinery Based on Integrally-Geared Compressor, Steam Turbine-Based HP Expander, and Gas Turbine-Based LP Combustion Turbine (modified from [22])

There have been numerous development efforts to improve the performance of CAES systems. Several efforts have sought to minimize compression power via isothermal compression. A variety of companies (General Compression, Lightsail Energy, and SustainX) have envisioned multiphase reciprocating compressors achieving isothermal compression via direct water cooling in a reciprocating compressor. Challenges associated with these systems are high cost of large low-speed compressor cylinders coupled with an aggressive operating requirement for valves in order to avoid hydraulically locking the piston and causing severe damage. Other efforts have sought to reduce the variable head requirement (a function of cavern backpressure) with subsea or hydrostatic CAES as illustrated in Figure 10. In these configurations, the compressor head is set by the water column height and not the state of cavern charge.

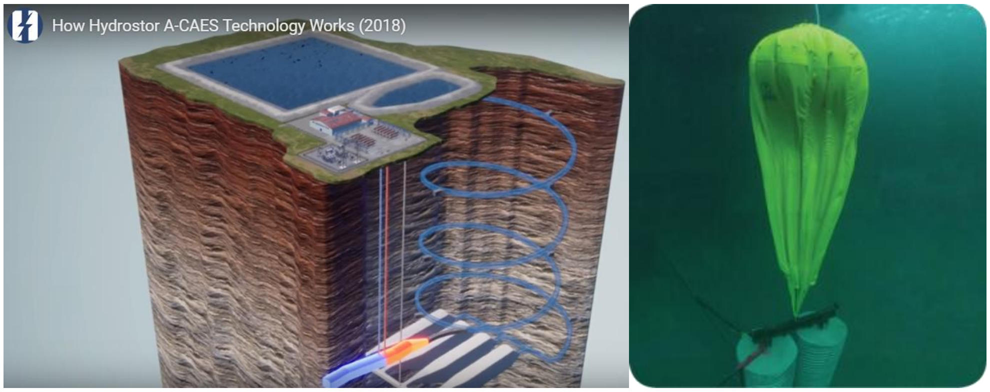

Figure 10. Advanced Concepts of Hydrostatic CAES (left) [23] and Subsea CAES (right) [24]

Flywheel Energy Storage (FES)

Flywheels also employ potential energy as a storage form, but store the energy in a rotating mass instead of changing the elevation of large volumes of water or increasing the pressure of a gas. The rotor typically operates in a vacuum environment to minimize parasitic drag losses. Flywheels offer high round-trip efficiencies of 90-95% but even in a vacuum environment have a high self- discharge rate and generally a very short response time, typically limiting their application to power quality/frequency regulation use. There are numerous flywheel architectures targeting high power density or low cost with different materials for the rotating mass, including concrete, fiberglass, steel, and composites. Although power density with all of these materials is lower than that of Li-Ion batteries, flywheels are capable of very fast charge/discharge rates 2-3 orders of magnitude better than batteries and have virtually no degradation.

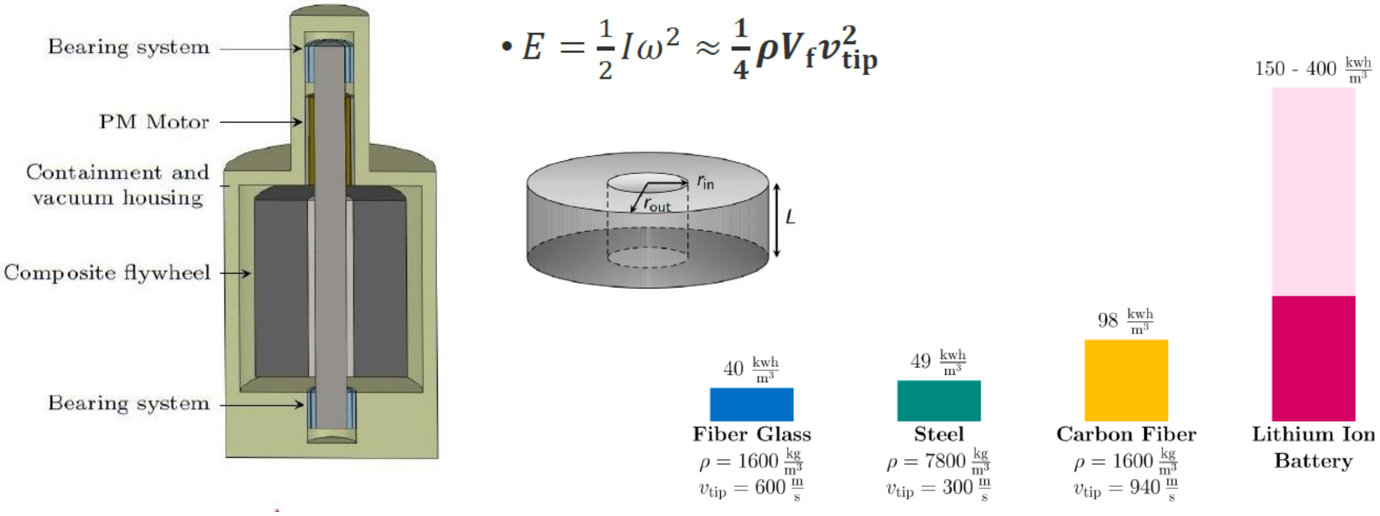

Figure 11. Concept Illustration of a Flywheel Energy Storage System (left) and Power Density of Different Materials (right) [25]

Because kinetic energy increases with the square of velocity, flywheel systems generally have high rotational speeds and require careful design and analysis of the rotor stresses as well as rotordynamic performance. Flywheels typically incorporate magnetic (active or passive) or ball bearings to operate with low losses in the vacuum environment. Multiple motor types are also used, including induction, permanent magnet, and synchronous variable reluctance machines. These are generally VFD-driven with bi-directional power control.

Much of the research into flywheels is focused on minimization of standby losses or improvements to power density. Most of the losses are electrical and generated in the motor or bearings, and improvements including superconducting magnetic bearings and so-called bearingless motors (motors design asymmetrically to provide a net lateral bias forces supporting the shaft) [26] are active areas of development. A novel shaftless flywheel design developed and prototyped by Texas A&M promised to double power density [27], and there has also been research developing a long-duration flywheel prototype with 8 kW capacity discharging to up to 4 hours [28].

DEVELOPING TECHNOLOGIES

Machinery-based storage technologies that are currently under development include various gravity-based, buoyancy-based, pumped heat, liquid air, and a broad range of thermochemical systems including various forms of hydrogen (and hydrogen carriers) and sulfur. Many of these systems utilize thermal storage as part of a thermodynamic cycle, so a brief overview of thermal storage technologies is also provided. Finally, many synergistic combinations of energy storage systems with power generators or industrial heating also exist; a brief discussion of these integration opportunities is also provided.

Gravity-Based Storage

There are several GES concepts under development that will have relevant scale demonstrations in the near future. In general, these concepts offer long life and cost advantages over other energy storage technologies.

Cava et al [29] describe one concept called ARES (Advanced Rail Energy Storage), which incorporates the transfer of weighted rail cars between low and high elevation topographies. It is claimed that ARES can compete with pumped hydro in terms of rated power (thousands of megawatts) and total storage (hundreds of thousands of megawatt-hours) and can provide round-trip efficiencies up to 80%. Advantages over pumped hydro include minimal environmental impact, simpler site requirements and permitting, and lower capital cost (e.g., roughly half on a per-kilowatt capacity basis). Pilot tests for ARES were completed in 2013 at a site in California, and a 50 MW, 12.5 MW-h commercial project is underway in Nevada – see Figure 12. The Nevada project will operate rail cars (8600 metric ton combined weight) on over 9 km of track covering 610 m of elevation differential.

Figure 12. ARES pilot test vehicle (left) and rendering of energy storage rail cars for commercial project in Nevada site (right) [30]

More recently, another concept being developed is called Energy Vault, and it consists of a crane that stacks concrete blocks during charge mode and lowers the blocks during discharge mode [31-33]. Figure 13 depicts the basic configuration. There are six different crane arms roughly 120 m off the ground, and each block weighs 35 metric tons. The cranes stack the blocks in charge mode, then they lower the blocks in discharge mode. Nominal energy capacity is 35 MW-h with 4 MW peak power and up to 90% round-trip efficiency. There are plans to construct such a storage tower for commercial use in India, but there is no additional data at the time of this publication. Advantages of this concept are relatively low cost since there is really no new technology that needs to be developed, and they can be highly modular. It is anticipated that the 35 MW-h unit could be built for $200-230/kW-h, though higher volume would bring costs down to $150/kWh, and levelized cost of storage is anticipated to be $0.05/kW-h compared to $0.17/kW-h for pumped hydro applications [31,33].

Figure 13. Energy Vault storage tower – higher to lower energy storage from left to right [32]

Gravitricity plans to build a 250 kW demonstration and a 4 MW full-scale prototype of a GES system that utilizes unused mine shafts as space to raise and lower weights. Figure 14 shows a rendering of the concept that implements four winding drums that extend and retract cables to move the weight. These systems offer fast response times competitive with lithium-ion battery storage, but with significantly lower cost and long life, and flexible range of power delivery. They cite possible storage depths up to 1500 m and weights up to 3000 metric tons, which equates to 44.1 GJ of energy storage. Round-trip efficiencies up to 90% are also claimed. At the time of this publication, the demonstration has not yet been conducted, and the full-scale prototype site has not been selected [34]. Instead of using conventional rotory motor-generators, a similar concept shown in Figure 15 poses to implement linear electric machine technology to raise a weight with electromagnetic force and extract power as the weight falls, though this concept is mostly theoretical at present [35].

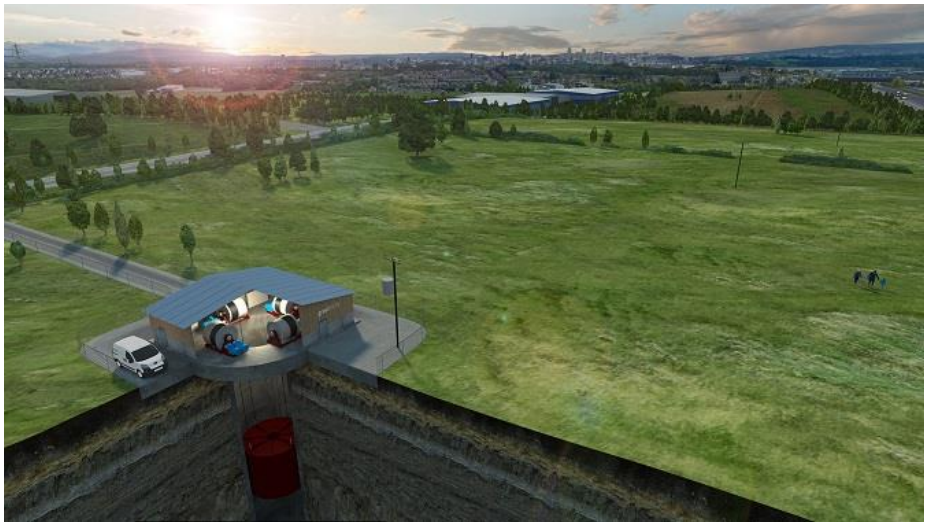

Figure 14. Rendering of Gravitricity concept suspending weight in unused mine shaft [36]

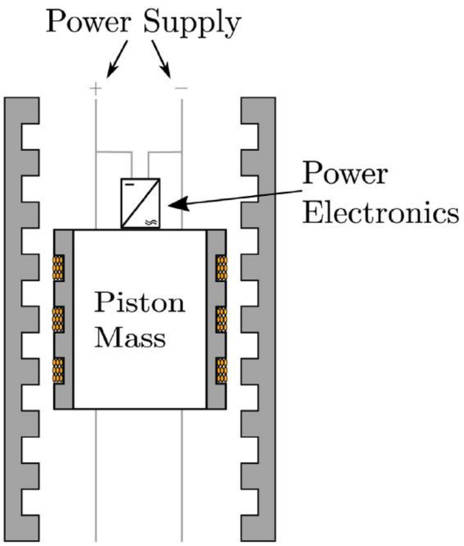

Figure 15. GES concept utilizing linear electric machine technology (image from [35])

Another GES concept is actually a hybrid with pumped hydro storage. The concept, shown in Figure 16, is a closed hydraulic system that incorporates a massive piston. The piston is raised using a pump to pressurize the fluid below the piston, storing gravitational potential energy. When the piston is allowed to fall, water flows through a turbine and energy is recovered. There have been several theoretical studies that have modeled this system for different applications [37-39], though there does not appear to be any relevant test data demonstrating performance to date. Commercial concepts up to 10 GW-h have been proposed by different companies – e.g., Heindl Energy [40] and Gravity Power [41] – and a megawatt-scale demonstration is anticipated in the near future. The economy of scale is inherent in the design, as energy storage scales with size to the fourth power, while cost only scales with size to the second power. A technical challenge of the concept is the seal between the piston and the wall, which must be able to withstand the hydraulic pressure under the piston (up to 60 bar). A concept is shown in Figure 17.

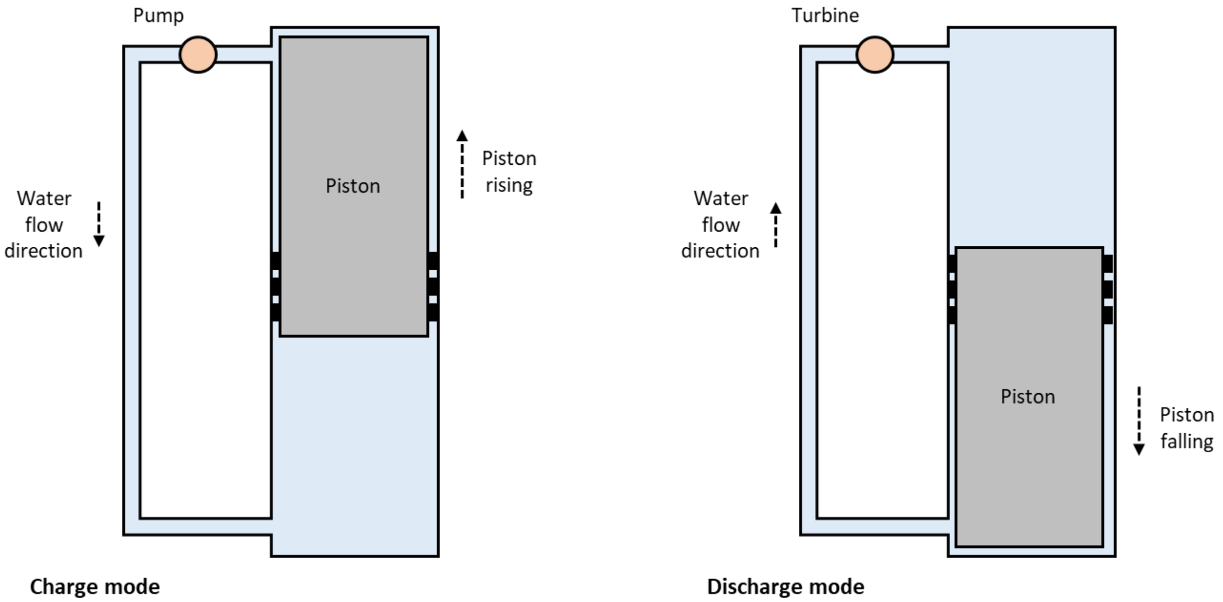

Figure 16. Hybrid gravity and pumped hydro concept: charge mode (left) and discharge mode (right)

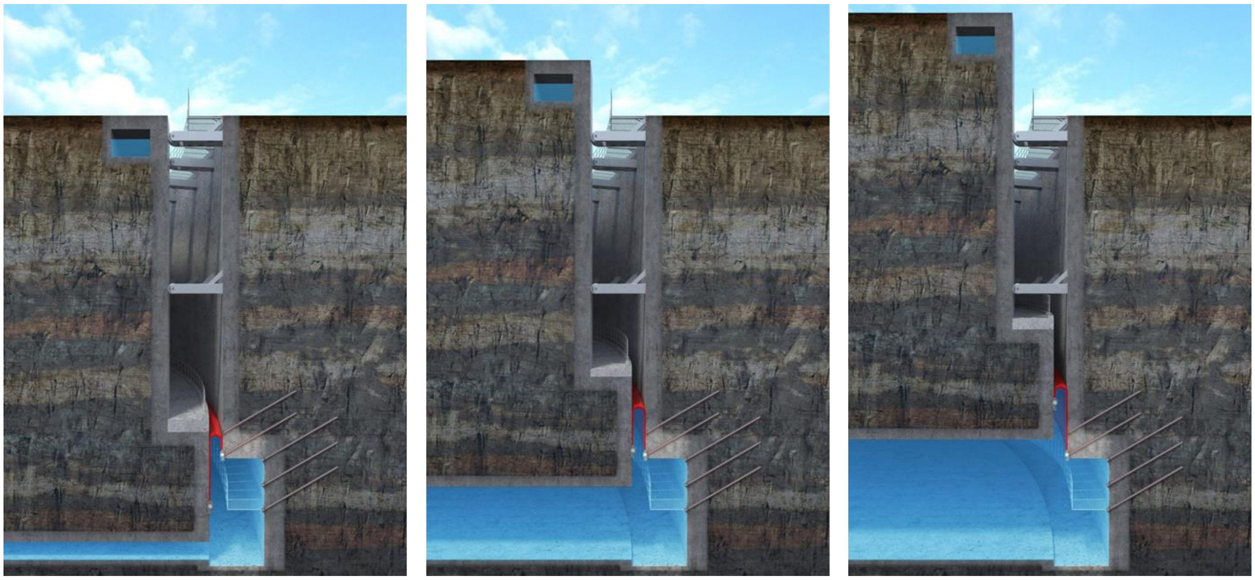

Figure 17. Rolling membrane seal concept that allows piston movement [40]

Bouyancy-Based Storage

There are no commercial-scale BES systems that have been developed to date since the first concepts were proposed about a decade ago [42]. The work to date is mostly theoretical and with small lab-scale experiments. While Figure 65 depicts a single buoy with a submerged motor/generator, the motor/generator could easily be surface-based, either on a barge or on land with the appropriate cable and pulley arrangement (Figure 18). The land-based option would allow larger machinery and simplify connection to the grid. Depending on the design conditions, the buoy would be subject to very large compressive stresses at depths below the surface of the water, which would decrease the volume of the buoy if made from a very flexible structure. Internal pressurization and/or more significant structural design would reduce the volume-reduction effect at the cost of greater weight (which offsets the buoyancy force) and more expensive components.

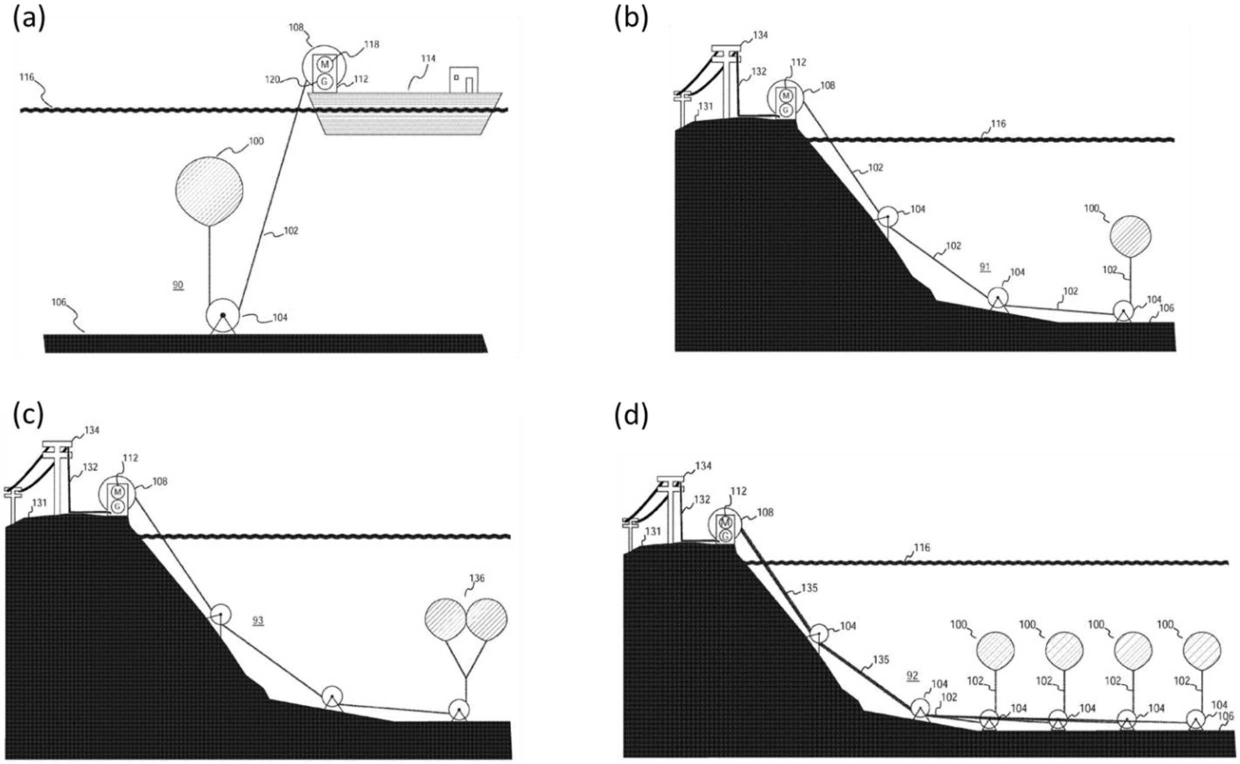

Figure 18. Different motor/generator locations and buoy arrangements [42]

A numerical example [42] of the energy storage capacity of a BES system with a single spherical buoy is as follows: Consider a 10 m diameter buoy pressurized to 10 bar above atmospheric pressure at the surface. The net buoyancy force to submerge the buoy would be 5 MN, so storage at 100 m depth would be 500 MJ or 139 kWh. For comparison, the average household energy usage is about 30 kWh per day. Assuming a discharge time of 3 hours – i.e., 46 kW of power, not including efficiency losses – the average velocity of the rising buoy would be under 10 mm/s, which should be low enough to ignore losses from drag forces. For an actual implementation, losses from motor and generator and friction in the pulleys would need to be considered to determine overall round-trip efficiency. Theoretical estimates suggest losses from motor-generators would be less than 10% and losses from pulley friction would be on the order of 1%, making round-trip efficiency targets of 80% reasonable.

Small-scale tests with BES have been accomplished by a few researchers to demonstrate the operating principle. Alami [43,44] tested with an array of conical-shaped buoys that were allowed to rotate (Figure 19). The buoys also were treated with a helical groove pattern to promote a certain spin rate as the buoy array ascended. The reasoning for this arrangement was to reduce drag during fast ascents ~1.5 m/s. Bassett *et al* [45] tested using spherical-shaped buoys at similar velocities. They mention that the large hydrodynamic drag for their test conditions account for 20% of the input energy compared to ~1% kinematic losses, so decreasing velocity would be a requirement for more realistic efficiencies.

Figure 19. Buoy array with free-rotating conical-shaped buoys tested by Alami et al. (images from [43,44]

It is logical that BES at a relevant scale would need to be located near deep bodies of water. However, BES for high altitude has also been proposed [42]. In these embodiments, balloons or structures filled with lighter-than-air gases – e.g., helium or hydrogen – are positioned in the atmosphere and raised and lowered to release and store energy, respectively. Compared to underwater BES, atmospheric BES would require significantly larger "buoy" structures and considerably more cable travel due to the much lower density of air vs. water (over 800 times lower).

Another concept of BES is actually a hybrid with pumped hydro energy storage. Figure 20 depicts a concept similar to Klar *et al* [46]. A weighted vessel or tank displaces a volume of water and floats on the surface. By pumping water from the inside of the tank to the surrounding body, the tank rises and increases its gravitational potential energy (i.e., charge mode). To extract the stored energy, the outside water is allowed to enter the vessel through a turbine, causing the vessel to lower. There are other variants of the same concept that include more buoyant tanks and tanks anchored to the sea floor via submerged buoys and pulleys.

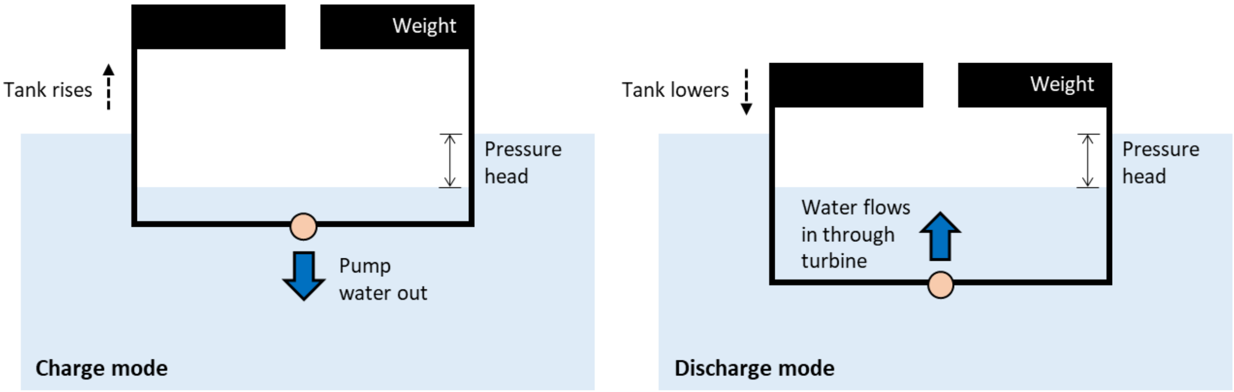

Figure 20. Hybrid buoyancy and pumped hydro concept: charge mode (left) and discharge mode (right)

Thermal Energy Storage (TES)

Large-scale thermal storage of energy for the grid has been pioneered in the 1980s by the concentrating solar power industry, initially using thermal oils and progressing to molten salts for systems with higher temperatures and efficiencies. Thermal storage is generally categorized into sensible and latent (phase change) heat storage, and is most commonly applied (for power generation) at high temperatures although low-temperature (ice or cold water) storage is also used for air conditioning or other cooling applications. Thermal storage typically relies on thermodynamic heat engine cycles for power generation, and heat addition may be obtained directly from existing heat sources such as solar or waste heat, or from electricity via resistive heating or other thermodynamic cycles (heat pumps or heat streams in other processes). There is a significant amount of literature on thermal energy storage technologies; these are not treated in detail in this tutorial due to its focus on machinery aspects of energy storage technologies.

Pumped Thermal Energy Storage (PTES)

Pumped thermal energy storage (PTES) systems (also known as pumped heat energy storage) store energy in hot (and possibly cold) thermal stores, which are charged by running machinery in a heat pump configuration and discharged by running a heat engine cycle [47]. Figure 21 conceptually illustrates one implementation of this concept. PTES systems operate closed cycles decouple the machinery working fluid (typically pressurized air, argon, or carbon dioxide) from the thermal energy storage fluids (refrigerants, water, thermal oils, and molten salts) to minimize the cost of thermal fluid storage vessels. Direct thermal storage with packed bed stores of solid media or phase change media are also considered. The cycles are also typically recuperated to increase efficiency.

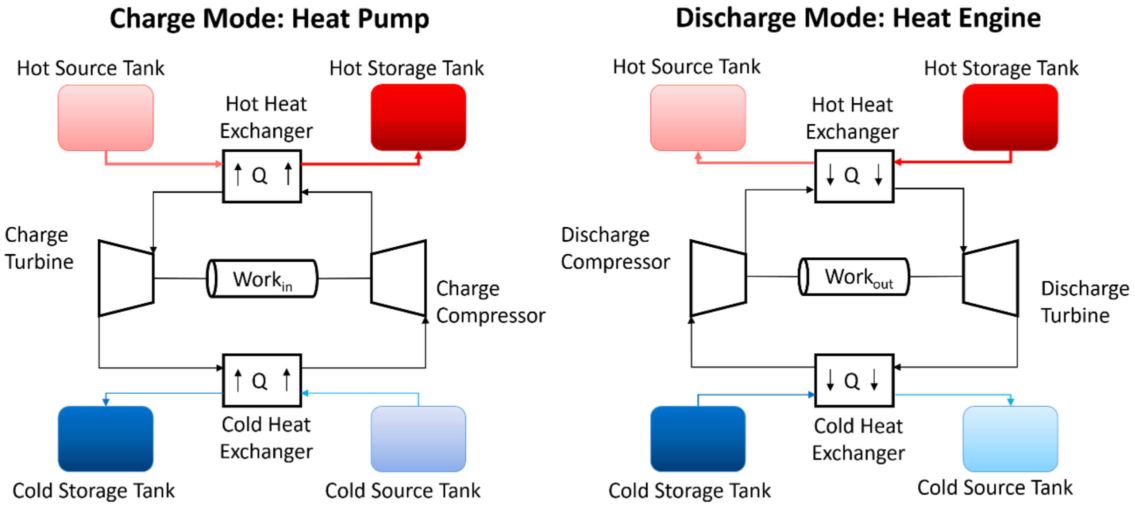

Figure 21. Concept Illustration of PTES System [48]

Although the concept outlined above is relatively simple, there are numerous variations and practical turbomachinery design/operation challenges that are the focus of current development activities. Most Brayton cycles with gas turbines are open cycles, necessitated by combustion. Closed-cycle systems enable higher-pressure operation to improve power density and decrease costs, but a closed-cycle machine has significantly different requirements than a typical gas turbine for startup, settle-out pressure condition, sensitivity to leakage, etc. Part-load operation of closed cycles is managed most efficiently by adjusting system inventory, which leads to significant differences in off-design operation than a conventional gas turbine. These design adaptations and control strategies are similar to those under development and validation for other closed Brayton cycles such as supercritical carbon dioxide cycles and may include significant changes to the mechanical design for higher operating pressures, e.g. low-leakage end seals, hermetic machinery, rotordynamics, casing design, blade aeromechanics, etc. An example expander for supercritical carbon dioxide is shown in Figure 22, highlighting unique design features as described above. The charge mode turbomachinery for an air-based PTES system will also require high compressor operating temperatures (heat engine efficiency is maximized by storing heat at high temperatures; existing molten salts are stable up to 565 °C) and low turbine operating temperatures for charge mode. Existing high-temperature industrial compressor designs have maximum discharge temperatures near 480 °C [49]. CO_2-based PTES system efficiency increases if suitable multiphase compressors and expanders can be developed. Finally, the round-trip efficiency of a pumped heat system is a strong function of the machinery efficiency, so efficiency is a strong design driver. There is also some research underway to incorporate a reversible turbine-compressor design that can be used in both charge and discharge modes to minimize system cost [50], although this will inevitably reduce efficiency. Variable geometry may be another way to utilize the same machinery system for charge and discharge modes.

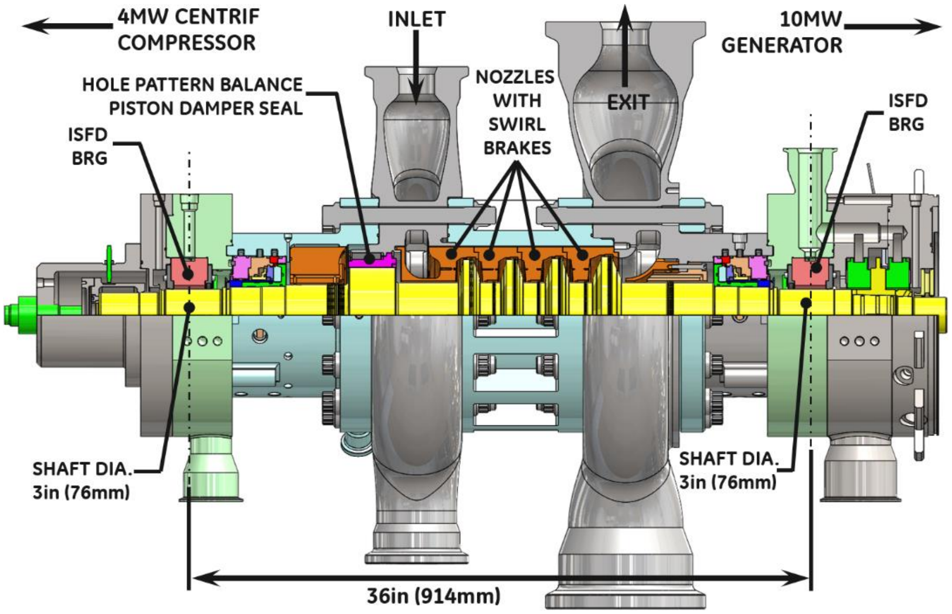

Figure 22. 10 MWe Axial Expander Design for a Closed Brayton CO2 Cycle Incorporating Dry Gas Seals and Rotordynamic Stabilization Features [51]

Current research efforts for PTES systems include a turbocharger-based air Brayton demonstration loop under development at SwRI [52] to demonstrate and validate system operation and transient performance. The development effort, illustrated in Figure 23, involves significant cycle optimization and matching with commercial off-the-shelf (COTS) hardware with some modifications, and transient modeling of the as-built system for investigation and finalization of control strategies. Echogen Power Systems is developing a similar system utilizing supercritical carbon dioxide as a working fluid, noting potential efficiency advantages at lower storage temperatures [53]. Malta, Inc. is developing a pilot-scale 10 MWe system for commercial demonstration [54], illustrated in Figure 24.

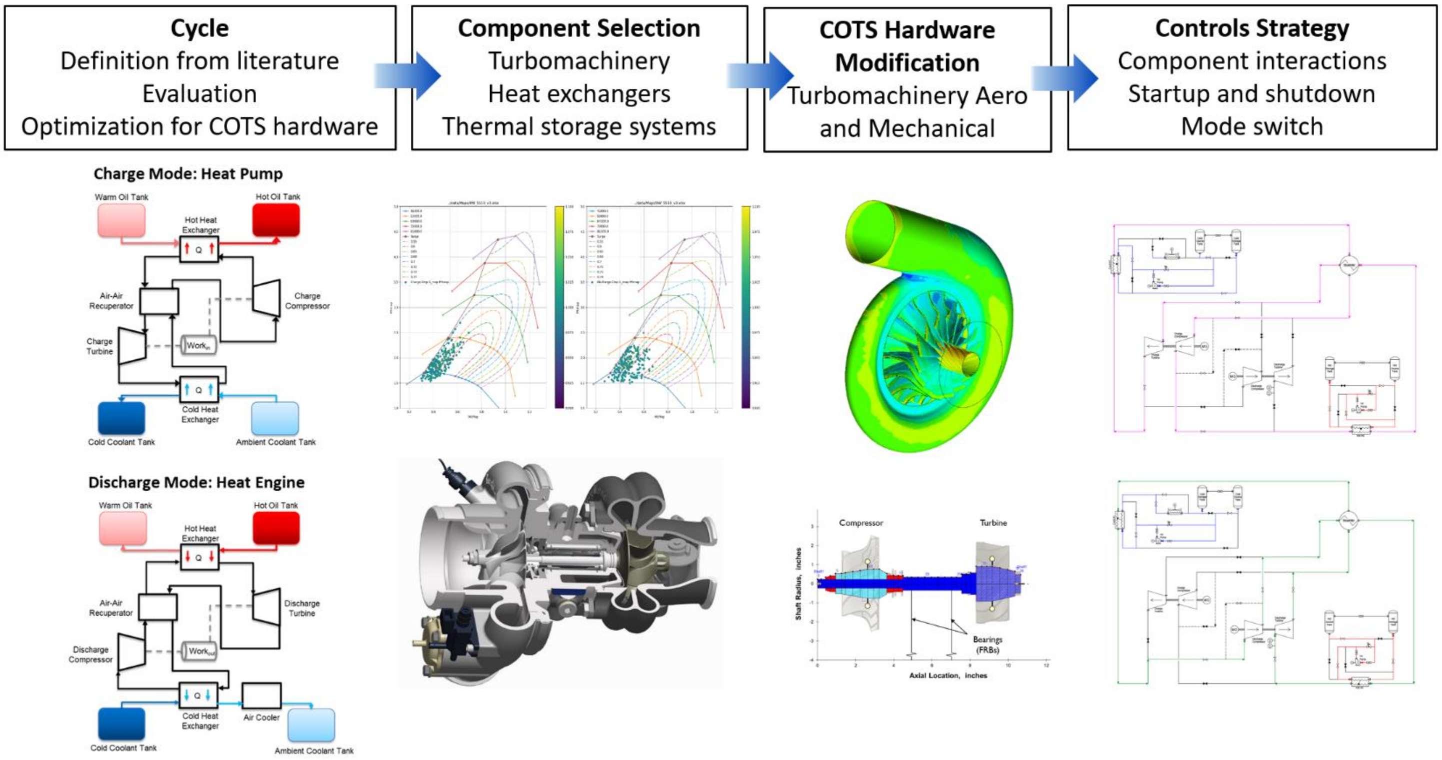

Figure 23. Development Effort for PTES Demonstration System [52]

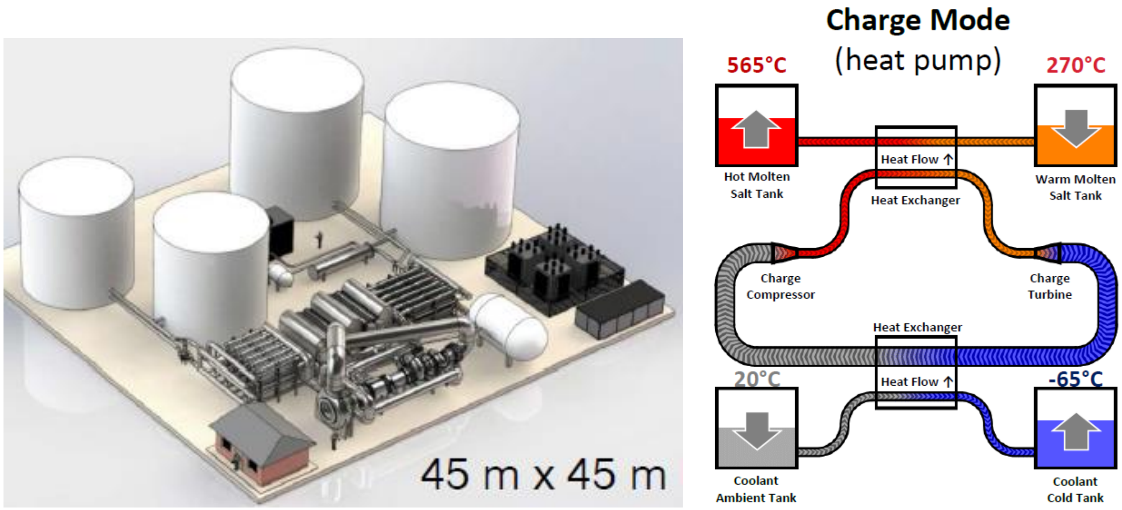

Figure 24. Pilot Plant Layout for 10 MW/100 MWh PTES Plant [54]

Liquid Air Energy Storage (LAES)

Liquid Air Energy Storage (LAES) is a noteworthy variation on CAES in that the air is liquefied for storage and heated (similar to CAES, diabatic and adiabatic variations exist) and expanded for discharge. Liquid air can be stored at relatively low pressure in commercial storage tanks, thus eliminating the geographic dependence of CAES. Liquefaction may be performed with any refrigeration cycle, although existing commercial efforts focus on the Claude cycle with integrated heat storage. The discharge cycle vaporizes the air, typically with recuperation, adds heat, and expands across an expander during discharge mode. An example LAES cycle is illustrated in Figure 25.

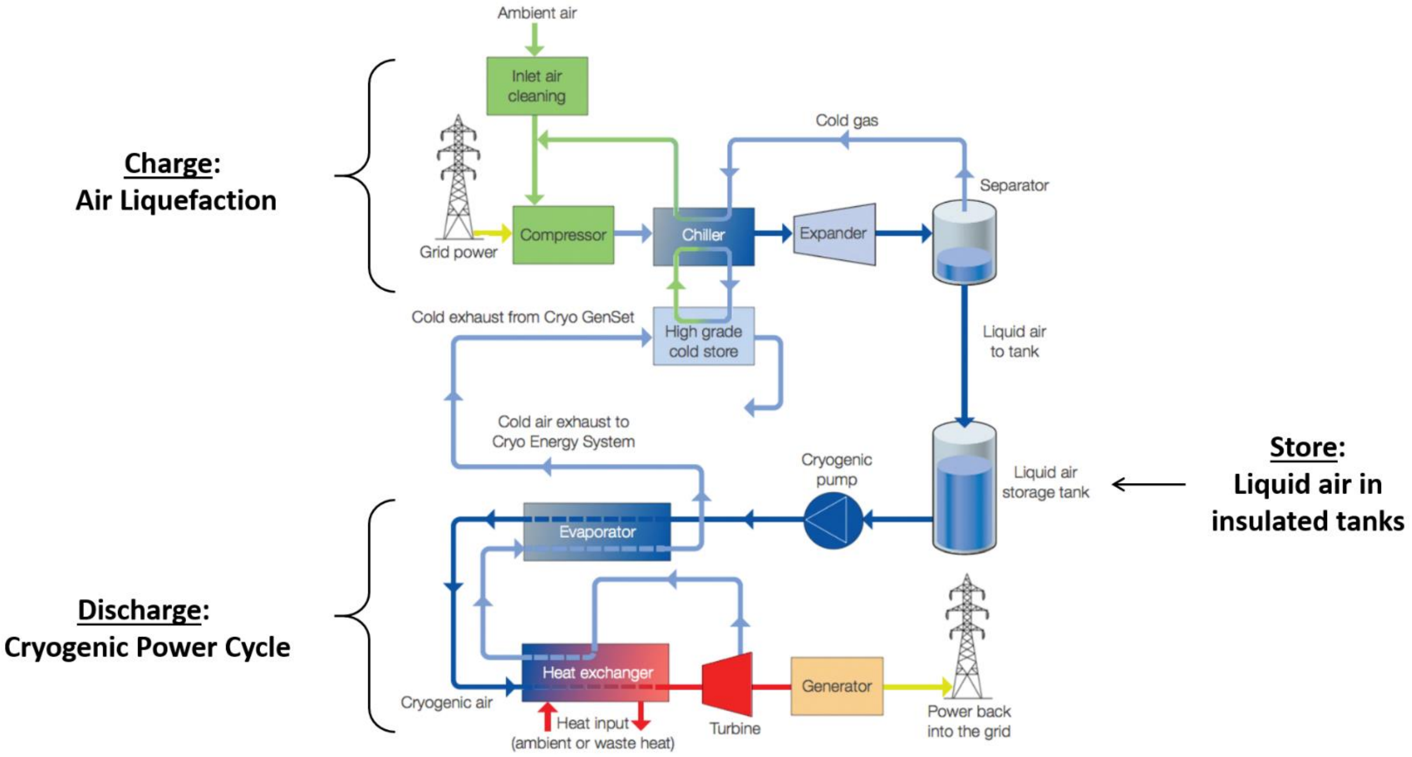

Figure 25. Example LAES System (modified from [55])

As with PTES systems, many variations exist including different implementations of heat exchange/storage and coupled with different external heat sources. The round-trip efficiency and cost are a strong function of machinery and heat exchanger performance, so improvements to these components will improve overall system performance. Significant development and commercialization work has been performed by Highview Power, who is currently operating a 5 MW/15 MWh plant in Pillsworth, UK. The system incorporates waste heat recovery from landfill gas turbines and a multiphase expander. The company has also recently announced a plan for a 50 MW/400 MWh system to be located in Vermont, USA. An example image of a LAES plant is provided in Figure 26.

Figure 26. Example LAES Plant [56]

Like CAES, LAES systems operate in an open-loop fashion with decoupled turbomachinery trains for charge mode and discharge mode. The choice of charge compressor (centrifugal vs. axial) is determined by the system power rating and air flow rate as well as potential advantages of intercooling. The charge mode expansion can be performed with an expander and J-T valve; systems may incorporate multiphase cryogenic expanders and require development for long life and high operating efficiencies. The machinery for a large-scale system at 50+ MWe is expected to include cryogenic feed pumps similar to those used in LNG re-gasification terminals, and multistage axial turbines for power turbines [57].

Thermochemical Energy Storage

Hydrogen technologies are among the most well-known thermochemical storage option and include a wide range of generation, storage, transmission, and electrical conversion systems. Thermochemical storage is an attractive storage medium due to its zero-carbon formulation and long-term stability enabling seasonal storage. Most existing hydrogen is formed by steam reforming using coal or natural gas, although electrolysis of water via renewable or nuclear power is being developed for a carbon-free solution. Hydrogen is already stored in large volumes in underground salt caverns, but poses challenges in compression and transportation due to its low mole weight (requiring significant compression power) and lower heating value than methane. Various hydrogen carriers are considered (ammonia, metal hydrides, sorbents, formic acid, methane, etc.). Power conversion with hydrogen and hydrogen products can be accomplished via combustion in a gas turbine or other process or electrochemically via fuel cells.

Hydrogen can be stored in many forms, including as a high-pressure gas, liquid, adsorption with various materials, and metal (many materials including magnesium and aluminum) or chemical hydrides (formic acid, ammonia, methane, methanol, or liquid organic hydrides). Two carrier synthesis methodologies are described in Figure 27: ammonia synthesis and natural gas synthesis. Ammonia is transportable as a liquid and has been explored as a gas turbine fuel, but is also valuable as its own product for fertilizer use. There is broad experience with methane transportation ("CO2 to fuel" or "power to gas"), which effectively utilizes the natural gas pipeline infrastructure as a storage system. There are many challenges with these approaches, including NOx formation associated with ammonia combustion and the low efficiencies of the synthesis processes (stacked with the low efficiency of a hydrolysis or methane reformation process!).

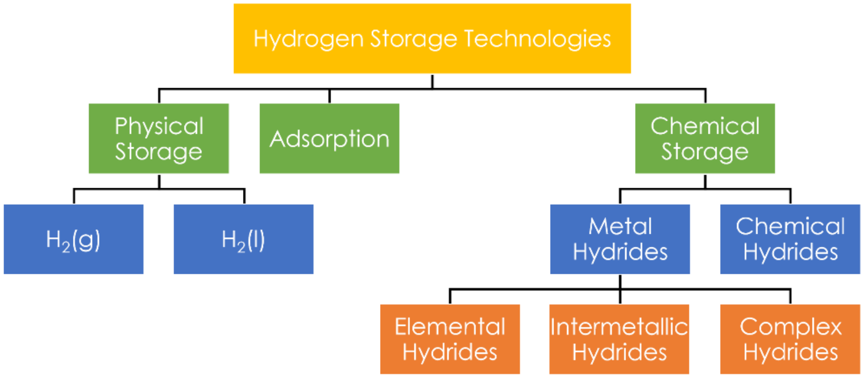

Figure 27. Hydrogen Storage Technologies [58]

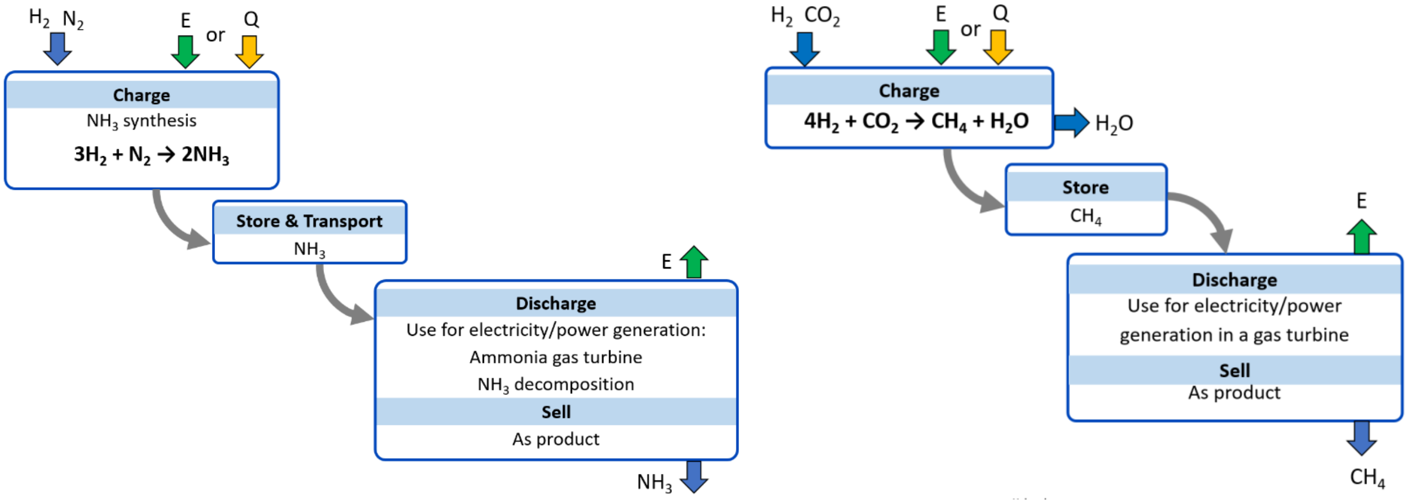

Figure 28. Ammonia (left) or Methane (right) as Hydrogen Carriers

Most thermal-mechanical energy storage uses relatively conventional turbomachinery. However, hydrogen energy storage is generally more complex for various reasons. Using centrifugal compressors to compressor hydrogen or high hydrogen process gases poses special technical challenges because of the physical properties and flammability of hydrogen. Although hydrogen is processed in many industrial applications, most hydrogen compressors are found in refineries for hydrotreating, hydrogen plant, and hydrocracker applications. Within these refinery applications, feed-gas, recycle, net-gas, and booster compressors are used to compressor hydrogen over a wide range of pressures and flows. Other hydrogen compressors are found in gasification, electrolysis, and many chemical and petro-chemical plants.

The three major technical challenges of compressing hydrogen are that it is (i) an extremely light gas, (ii) it can cause hydrogen embrittlement in ferrous alloys, and (iii) it has a low auto-ignition temperature in the presence of oxygen. Light or low molecular weight gases are difficult to compress and result in a low head rise per centrifugal stage in the compressor. Even at relatively high impeller tip speeds of 350 m/s, typical pressure ratios per stage seldom exceed 1.1. This means that long compression trains with many stages per barrel are required if a significant pressure rise is desired. For example, Figure 29 shows a compression train for a refinery net-gas application. Here each of the compressor barrels operating in series has 8 centrifugal impeller stages which results in a total pressure rise from 7 bara to 18 bara. To achieve higher pressure ratios either higher impeller tip speeds or longer compression trains with increased compression power are required. Another example centrifugal compressor prototype designed for H2 service required 6 stages with tip speeds exceeding 700 m/s in order to achieve a 3:1 pressure ratio [59]. Kurz *et al* [60] explored the effect of mixing up to 20% hydrogen into natural gas pipelines, noting a significant increase of up to almost 60% in power consumed vs. transported due to the increased compression power and lower energy density and also a requirement to add compression stages and/or units.

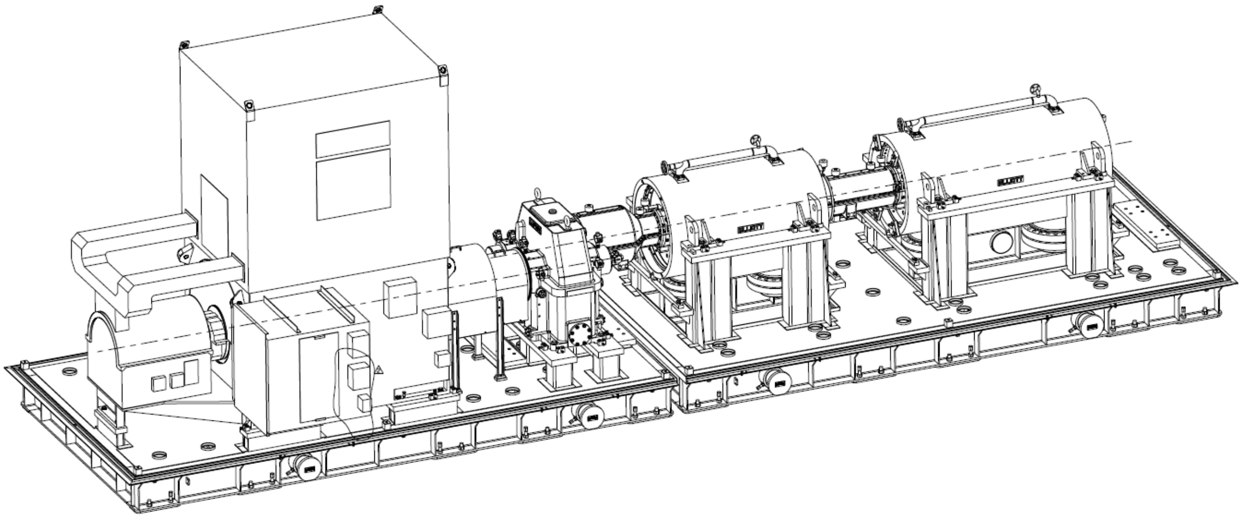

Figure 29. Two barrel tandem net-gas hydrogen compressors driven by an electric motor

Hydrogen embrittlement is a metallurgical interaction between ferrous metals and hydrogen gas at certain pressures and temperatures that can lead to rapid yield strength deterioration of the base metal in the compressor. Special surface coatings are available to minimize exposure and direct penetration of hydrogen into the metal. However, as a safety precaution the design yield strength of the exposed alloys must be limited to below 827 MPa. This further limits the operating speed of the compressor and its pressure rise per stage. Hydrogen molecules are small compared to most hydrocarbon gases, which makes case-end and inter-stage sealing challenging. Most hydrogen compressors utilize tandem dynamic dry gas seals and multiple static o-rings to minimize leakage flows. Nonetheless, hydrogen detection and scavenging is often required to minimize the risk of hydrogen exposure to the atmosphere and the associated explosive hazards.

Hydrogen combustion in gas turbines is an area that has been widely explored and demonstrated by many OEMs, yet challenges remain. This topic is broadly covered in other literature [61], but in general challenges associated with hydrogen combustion stem from its high flame speed and very broad flammability limit compared to methane. Hydrogen has a safely high autoignition temperature, but very low ignition energy, thus requiring significant safety precautions. The high flame speed and high combustion temperatures create combustor design challenges to avoid flashback, combustor instabilities, and NOx formation. There is significant experience with hydrogen combustion in diffusion flame combustors with good results, although NOx emissions increase to almost twice the levels experienced with pipeline natural gas combustion due to higher flame front temperatures. There is less experience with lean premixed combustion systems. General consensus among OEMs is that existing lean premixed combustion systems can operate with 5-15% hydrogen mixed into natural gas, requiring no significant modifications. Commercial operating experience with lean premixed combustors has been documented ranging from 5-33% hydrogen (by volume). Higher concentrations of hydrogen require more advanced combustor architectures, including multitube, multi-cluster, or micromix designs that can perform at concentrations up to 50-65% hydrogen by volume and have been tested in some cases up to 100% hydrogen.

Integrated Energy Storage Systems

Until now, this discussion has focused primarily on energy storage systems as standalone technologies, where electrical power is input, converted to a form mechanical, thermal, or chemical form of energy for storage, and converted back to electrical power as the system is discharged. Although the systems in these forms may offer sufficient benefits, additional synergies are likely available if the storage system is coupled with other power generation or industrial processes. For some systems, this coupling may be as simple as waste heat utilization. Other concepts are much more tightly coupled, where the primary process is modified and leverages inputs/outputs/stored energy of the storage system for improved performance.

An existing example of an integrated system is available at many concentrating solar power (CSP) plants. These plants focus sunlight on a central receiver tower (or parabolic trough), heating a medium for storage (typically a thermal oil or salt). The thermal storage medium is used to heat steam for power generation via a Rankine cycle. The incorporation of thermal storage allows for dispatchable power generation even after solar energy inputs are unavailable during the day, and increases utilization of the power block. One proposed development for concentrating solar power plants is to supplement the solar input with low-cost electrical input (e.g., from a photovoltaic solar plant) to create thermal energy in addition to the concentrating solar field. This example is shown in Figure 30.

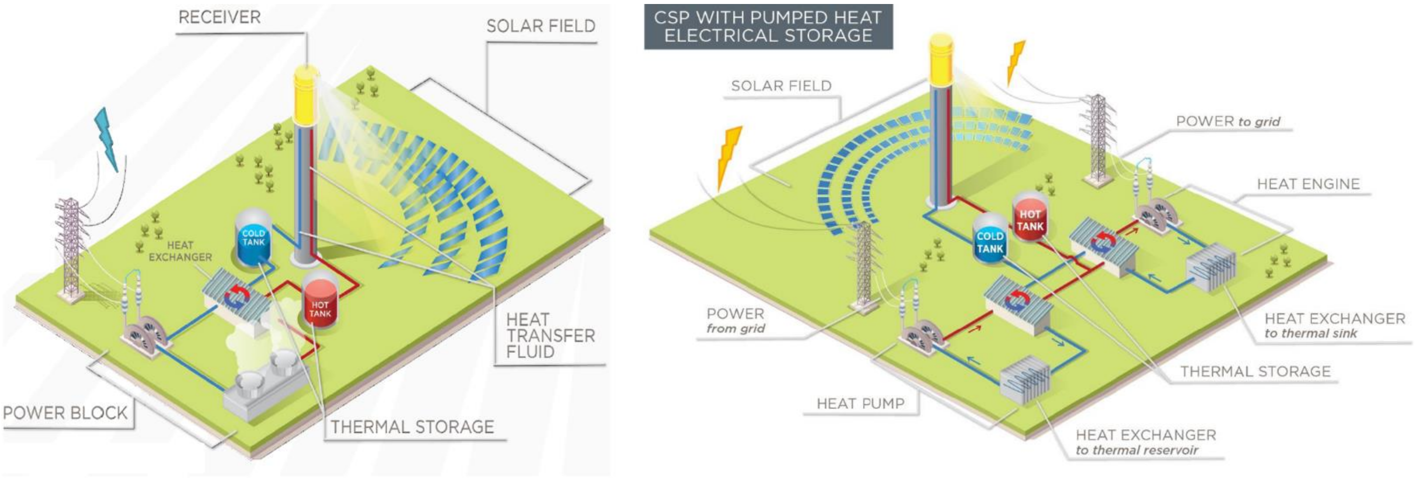

Figure 30. Conventional CSP Plant (left) and Integrated with PTES System (right) [62]

Another example of an integrated system is the electrothermal energy storage (ETES) system under development by MAN Energy. This PTES system utilizes supercritical carbon dioxide as working fluid but can discharge energy as electrical power, heat, or cold directly from the thermal stores. This process (with 60% thermal share of energy export) is illustrated in a Sankey diagram in Figure 31. The combination of electrical and district heating/cooling functionality is known as sector coupling, and this application lends itself particularly well to thermal energy storage systems.

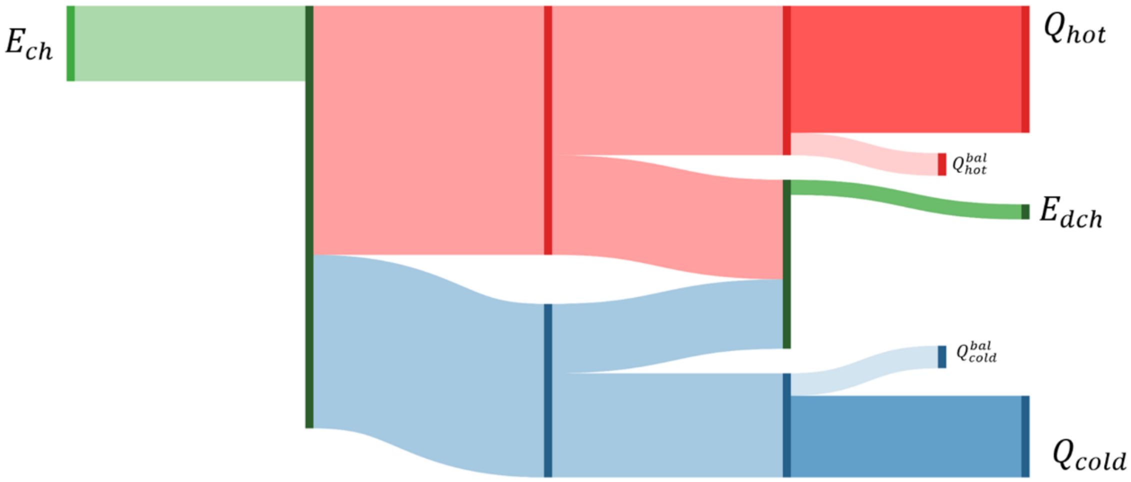

Figure 31. Energy Flows for an Example PTES System with Electrical and Thermal Outputs [63]

Although there are virtually unlimited variations for integrated systems, a few concepts listed in the literature are provided in the list below:

- Thermal storage integration with coal-fired power plants to improve efficiency and ramping capabilities
- Oxygen storage with oxy-combustion power systems to time-shift the air separation unit power consumption
- Amine or liquid carbon dioxide storage to time-shift the power requirements of carbon capture and sequestration systems
- Sector coupling for low, medium, and high-temperature thermal needs including industrial heating
- Liquid air energy storage integrated as a combined cycle with a gas turbine
- Pumped hydro storage integrated with desalination plants
- Waste heat recovery with thermal storage for dispatchable bottoming cycles
- Pumped thermal energy storage combined with concentrating solar power plants
- Hydrogen-fired compressed air energy storage

MACHINERY DEVELOPMENTS FOR ENERGY STORAGE SYSTEMS

Turbomachinery for energy storage applications has to satisfy many operational and performance requirements. These are primarily driven by the type of energy application, the service duty, and the plant's commercial and operational design requirements. Fundamentally most energy storage applications aim for high roundtrip efficiency, low capital cost, wide operating range, frequent starts and stops, and a very high availability. Obviously, some of these requirements are inherently contradictory and require compromise design decisions. For example, while it is desirable to keep the stage count in a compressor for CAES or PTES to a minimum to reduce capital costs, the resulting high stage loading will often lead to lower efficiency and limited operating range. Similarly, advanced technologies such as magnetic or gas bearings can help to reduce parasitic losses but often have an impact on the reliability of the plant. Finally, the frequent starts and stops required for almost all energy storage applications can have a significant life reducing impact on the turbomachinery caused by thermal-mechanical stresses.

The objective for thermal-mechanical energy storage scheme is not to isolate turbomachinery components design from the thermodynamic cycle but to design them as an integrated system so as to increase the efficiency of the entire process rather than just the machine. This requires some customized solutions that are often not-commonly available with off-the-shelf or turbomachinery products. Specific speed is well-known design parameter that helps determine the shape and size of turbomachine for a given duty. The equation in Figure 32 shows how the overall expected turbomachinery performance can be combined with thermodynamic cycle toward determining the overall specific speed of the system. This in turn can be used for turbomachinery specific speed that works synergistically with the cycle to enhance overall efficiency. The specific speed can be effectively used for creating a novel turbomachinery architecture that are highly custom to the chosen thermodynamic cycle.

Overall Compressor Basic Specific Speed

$$\boldsymbol{N_s} = \underbrace{\left(\frac{1}{\eta_p}\right)^{1/2}}_{\text{Expected Overall Performance}} \quad \underbrace{\left\{\frac{v_s}{H_p^{\,5/2}}\right\}^{1/2}}_{\text{Specified Gas \& Thermodynamic Cycle Conditions}} \quad \underbrace{\left(\Omega\sqrt{P_{sh}}\right)}_{\text{Driver Requirements for Given Application}}$$

v_s – Suction Specific Volume; P_{sh} – Overall Required Shaft Power; H_p – Overall Polytropic Head

Figure 32. Connecting Turbomachinery Overall Performance with Thermodynamic Cycle Design

The success of machinery-based energy storage systems requires the development of application-specific machinery in order to meet fast transient response requirements with high round-trip efficiency at low cost. Large-scale adiabatic CAES, LAES, and air-based PTES systems are all likely to use adaptations of gas turbine technology for their machinery, but with various advancements/modifications. Below presents a list of design challenges that turbomachinery OEM's have to consider. Clearly, some of these requirements are contradictory and fine-balance is required for an optimal solution.

- System Performance (efficiency) , and Operability (variability)
    - Efficient and flexible architectures, including blading shape
    - Off-design performance matching, and flow range (Surge)
- Cyclic Operation
    - Frequent startups and shutdowns at potentially high ramp rates
    - Fatigue life
    - Rotary inertia
- High Pressures and Temperatures
    - Materials
    - Clearances, seals, and bearings
    - Thrust management
    - Rotor assembly
    - Equipment protection in hostile environment
- Hostile Environment
    - Internal
    - External
    - Freezing concerns in expander

As discussed throughout the paper, advancements in machinery design will significantly improve the performance of various energy storage systems through improved efficiency, operating range, and application-specific design for each system. A few areas of potential improvements that are relevant to multiple energy storage systems that were not discussed earlier are provided below:

- CAES, PTES, and LAES systems require large amounts of heat exchange at low cost, so technologies that improve reheating/intercooling for turbomachinery (such as cooled compressor diaphragms/stators or even direct heat exchange and multiphase compression/expansion) are an attractive area for development. Figure 33 shows prior research activities and concepts for implementing both indirect and direct heat exchange in centrifugal compressors.
- Finally, improvements to turbomachinery efficiency, transient response, and operating range can significantly enhance the commercial viability of both standalone energy storage systems and systems coupled synergistically with other industrial thermal/electrical processes.

Figure 33. Examples of Advanced Heat Exchange in Turbomachinery: Cooled Diaphram Concept (left) and Prototype (center) [64]; Air-Water Compression with Direct Cooling (right) [65]

CONCLUSIONS

The effort to decarbonize our energy mix and significant penetration of variable renewable power sources is expected to increase the need for grid-scale energy storage at significant durations. A broad variety of machinery-based energy storage systems have been presented that are being developed to address this need with the potential for low-cost long-duration storage. This tutorial provided a specific focus on machinery technologies and developments needed to maximize cost and performance of these systems.

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