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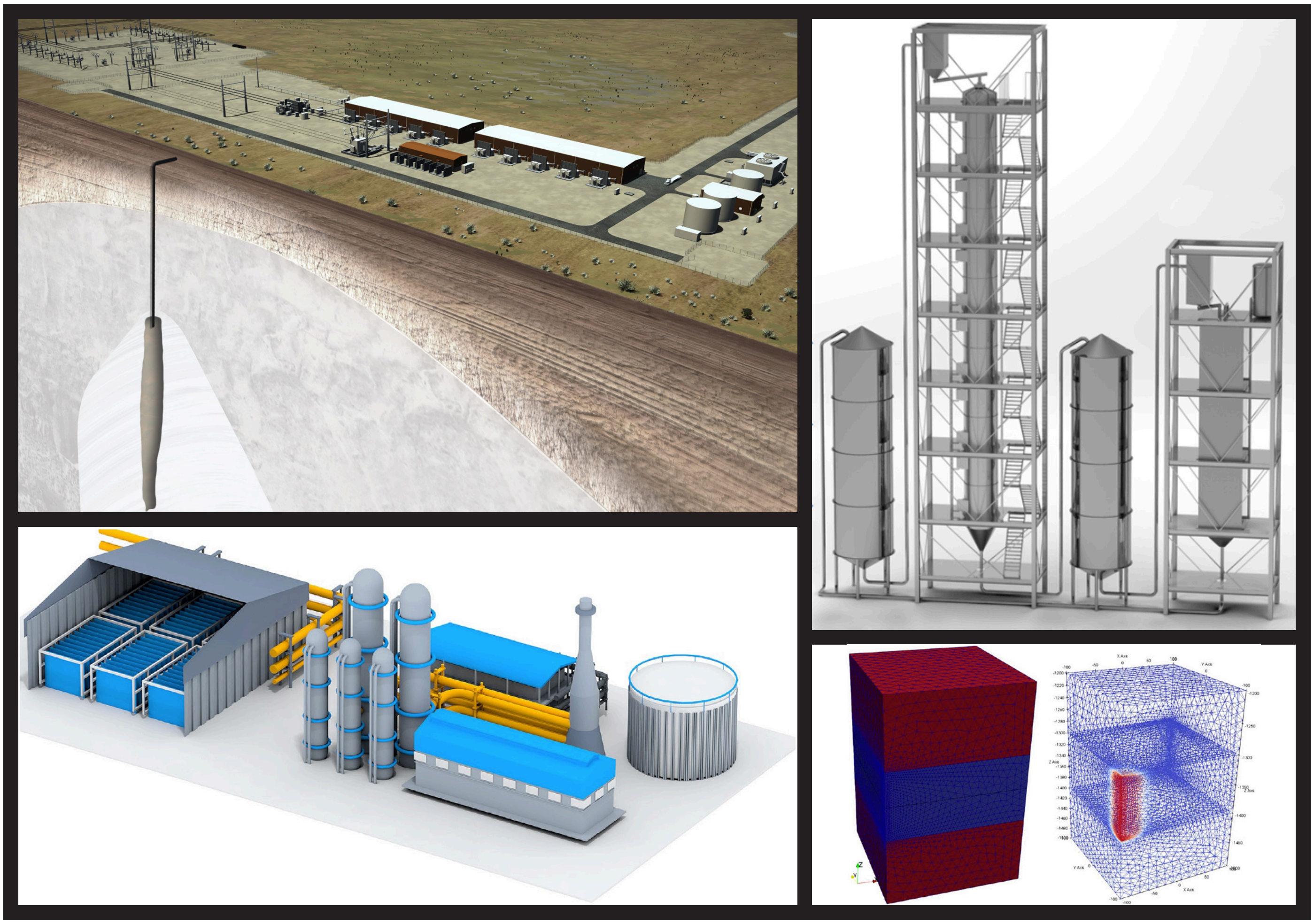
SEASONAL ENERGY STORAGE

A Technical and Economic Framework



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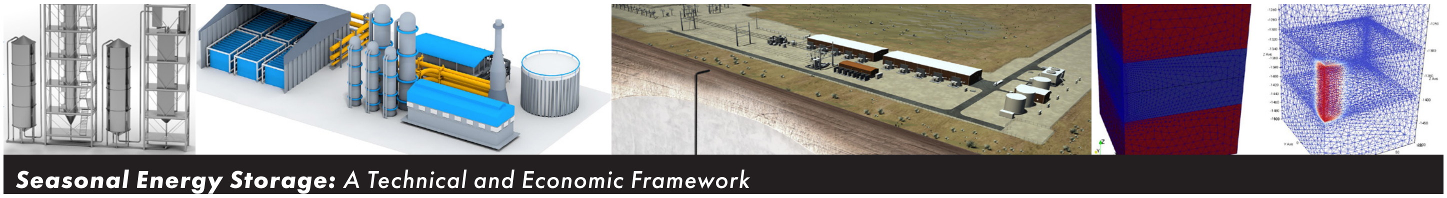

Seasonal Energy Storage:
A Technical and Economic Framework

PROMOTING DOMESTIC AND INTERNATIONAL CONSENSUS ON FOSSIL ENERGY TECHNOLOGIES: CARBON CAPTURE AND STORAGE AND CLEAN ENERGY SYSTEMS

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and
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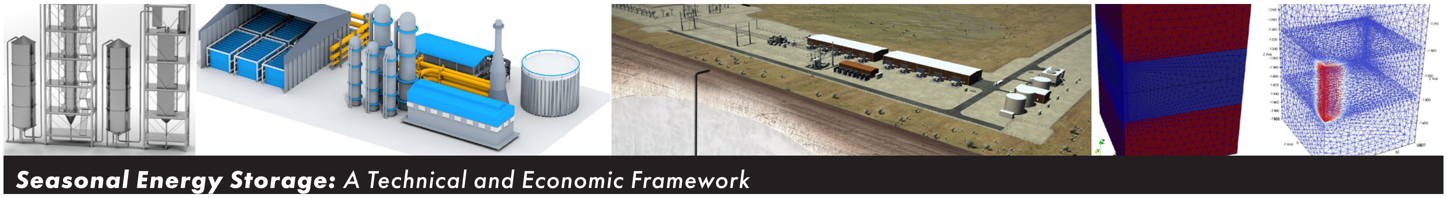

***Seasonal Energy Storage:** A Technical and Economic Framework*

Executive Summary

PRIMARY AUDIENCE: Project developers, legacy energy communities, resource planning staff at electric utilities, and technology developers seeking to increase their knowledge of the costs and benefits of seasonal energy storage resources

SECONDARY AUDIENCE: Project investors and lenders seeking to increase understanding of the challenges and the potential for seasonal energy storage projects

KEY RESEARCH QUESTION

Some sources of renewable energy such as geothermal and bioenergy are available year round in various locations. However, the total generation of variable renewable energy (VRE) including solar, wind, and hydropower in the United States often tends to peak in the spring. These low-carbon energy sources also tend to abate during the fall and winter months. To accommodate the use of this varying energy throughout the year in future decarbonization scenarios dominated by VRE, the grid may benefit from economically viable seasonal energy storage to shift energy from one season to another. There are currently no commercially available technological solutions to address the need for seasonal energy storage. Furthermore, the value streams and fundamental economics of seasonal energy storage projects are not well-developed.

RESEARCH OVERVIEW

The scope of this paper is to outline a framework to define the need for seasonal energy storage, identify a representative list of emerging technologies that may be suitable for meeting the need, and propose key economic structures needed to make seasonal energy storage projects viable. The focus is on the U.S. electric sector; other regions and sectors will differ. The key drivers for the need for seasonal energy storage are highlighted, primarily the increasing deployment of VRE and the seasonal nature of renewable energy sources. Several possible technological solutions to seasonal energy storage are explored, including low-carbon fuels such as hydrogen and ammonia, thermochemical energy storage, and geo-thermal energy storage. The basic costs of a seasonal energy storage resource are categorized. Key benefits of a seasonal energy storage resource are identified, including capacity, energy, and ancillary services. Finally suggested further work is proposed to quantify the roadmap toward commercially viable seasonal energy storage projects.

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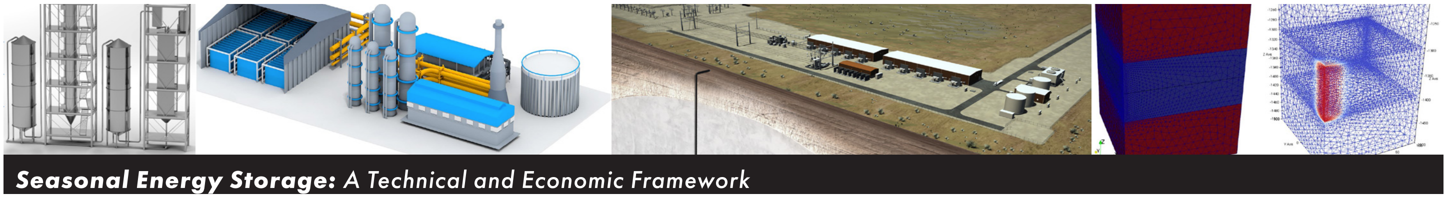
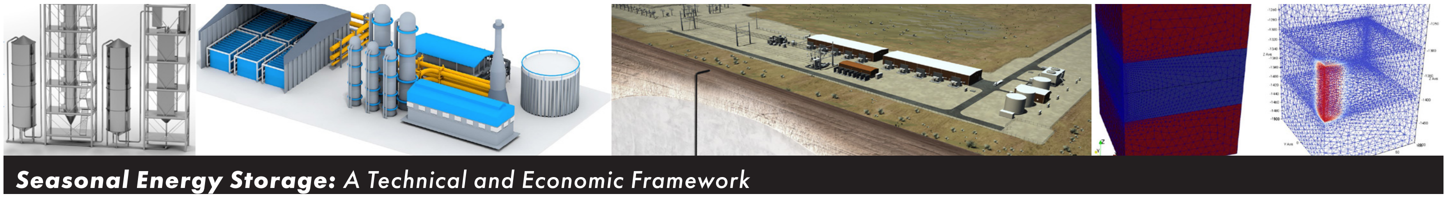


KEY FINDINGS

- Generation of VRE, including solar, wind, and hydropower, broadly coincides at the same times of the year. These resources tend to peak production in the spring and to reduce output during fall and winter months. This produces a highly seasonal energy source which will require careful planning to manage reliably.
- Some low-carbon future scenarios referenced in this paper benefit from an energy storage resource with durations of 500 hours or more. This threshold is used as the definition of "seasonal energy storage."
- Existing commercially available energy storage technologies include pumped storage hydropower (PSH) and lithium ion batteries. PSH could provide seasonal energy storage benefits but it is challenging to permit and often experiences local opposition to new projects due to concerns regarding equity and environmental impacts. Lithium ion batteries would likely cost too much to be economically viable at durations required for seasonal energy storage.
- Hydrogen is a flexible energy carrier that could play a role in decarbonizing several sectors of the economy, including transportation, industrial process, and power generation. Hydrogen storage is a seasonal energy storage option with the potential to provide a significant amount of energy that can be delivered to many locations.
- Ammonia is a low-carbon fuel with a pathway to be synthesized with electricity, stored, and later used to generate electricity for seasonal energy storage applications. Ammonia has different strengths and weaknesses as compared to hydrogen and may be more advantageous to consider in some applications, especially if low-cost underground storage of hydrogen is not available.
- Thermochemical energy storage is an emerging technology that merits further development and scaled-up project demonstrations of the most promising reaction pathways. Calcium oxide for example offers several possible cycles that could enable seasonal energy storage projects.
- Geo-thermal energy storage is a possible technology that develops an artificial geothermal reservoir using electrical heaters. The technology is still at an early stage but offers the potential to produce low-cost energy storage suitable for seasonal durations.
- The revenue from energy arbitrage alone is likely not sufficient to produce a financially viable seasonal energy storage project. Given the expected low value of ancillary services, a capacity payment is expected to be the primary source of additional revenue for an energy storage project. Capacity payments as high as \$20–30/kW-month or more may be required in some scenarios to achieve acceptable return on investment.
- Given varying resource mixes and seasonality, the particular use case, duration, and size of a seasonal storage resource that is suited for California, the Pacific Northwest, or other regions may differ substantially.
- Many possible technologies suitable for seasonal energy storage are thermal in nature and offer the possibility to repower existing thermal power plants and re-use assets and infrastructure at those sites. This approach could benefit legacy energy communities by generating tax revenues and deploying a skilled workforce to operate and maintain such plants.



WHY THIS MATTERS

Achieving greenhouse gas reduction targets will require a portfolio of low-carbon resources. Very long duration (seasonal) energy storage projects are one possible part of this portfolio. It is important to understand the possible solutions to seasonal energy storage to inform resource planning, procurement, and regulatory efforts.

HOW TO APPLY RESULTS

The information in this white paper will provide a useful framework to engage a broad range of stakeholders regarding the possibility of seasonal energy storage projects. The results of this study can be used to speak to technical audiences (such as academia and technology developers), financial groups (project developers, investors, and lenders), energy communities, and non-governmental organizations (NGOs) involved with energy-related work. Future workshops convened on the topic of seasonal energy storage will benefit from the approach and results outlined in this paper.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- An upcoming workshop hosted by EPRI and the U.S. Energy Association (USEA) on seasonal energy storage is scheduled for November 9, 2022.
- The USEA has supported this study and related work regarding thermal energy storage retrofits at fossil plants.
- The DOE Office of Fossil Energy and Carbon Management has supported this work and has related efforts underway regarding low-carbon technology development and deployment.
- Additional EPRI programs involved with resource planning and economics may find this work useful, including Resource Planning for Electric Power Systems (Program 178) and Energy, Environmental, and Climate Policy Analysis (Program 201).

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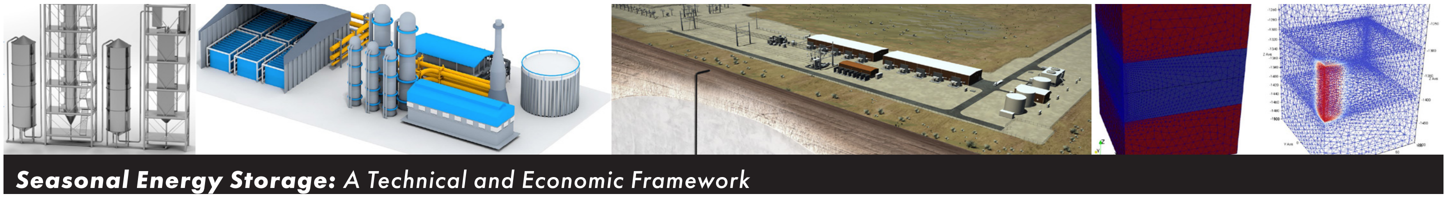
PROGRAM: Bulk Energy Storage, Program 221

Abstract

The total generation of variable renewable energy (VRE) including solar, wind, and hydropower in the United States often tends to peak in the spring. These low-carbon energy sources also tend to abate during the fall and winter months. To accommodate the use of this varying energy throughout the year in future decarbonization scenarios dominated by VRE, the grid may benefit from economically viable seasonal energy storage to shift energy from one season to another. Storage of this nature is expected to have output durations from 500 to 1000 hours (21 to 42 days) or more. No clear technological solutions have been demonstrated at scale, although several concepts may be viable—including low-carbon fuels such as hydrogen and ammonia, thermochemical energy storage, or geo-thermal energy storage. There is also a lack of a clear business case to generate a return on investment and make seasonal energy storage projects financeable. The scope of this paper is to outline a framework to define the need for seasonal energy storage, identify a list of technologies that may be suitable for meeting the need, and propose key economic structures needed to make seasonal energy storage projects viable. This work focuses on the U.S. electric sector, additional work will be needed to address the specific needs of other regions and sectors.



Introduction

Growing Deployment of Variable Renewable Energy

Government agencies and utilities across the United States and many other countries have adopted aggressive low-carbon energy goals and greenhouse gas reduction targets for the electric sector in recent years. Significant reductions in carbon dioxide (CO_2) emissions by 2030 and net-zero decarbonization by 2045–2050 are expected in many regions [1]. Achieving these goals is likely to require a portfolio of solutions including a combination of accelerated deployment of renewables such as solar and wind power; low-carbon firm power such as hydropower, geothermal, and nuclear; additional transmission capacity; demand response and energy efficiency; carbon capture and storage including point source emissions and possibly direct air capture; and a range of energy storage technologies and durations. EPRI recently conducted a study evaluating several low-carbon scenarios in 2035, including a net-zero scenario (renewables, nuclear, fossil plants with carbon capture and storage [CCS], and carbon dioxide removal) and a carbon-free scenario (renewables and nuclear only with no fossil combustion or carbon dioxide removal) [2]. Scenarios that allowed fossil combustion and CCS did not require storage longer than eight hours of duration; the fossil plants performed the role of low-carbon firm power. However, scenarios without fossil combustion and CCS required a large amount of seasonal energy storage greater than 500 hours in duration. Low-carbon firm power from fossil with CCS and seasonal energy storage may embody complementary portions of a reliable low-carbon grid. Given the uncertainty regarding the cost and scalability of these technologies it will be beneficial to have multiple options for low-carbon firm power, including fossil fuel with CCS and seasonal energy storage.

The deployment of VRE in the U.S. is expected to accelerate in the coming years as shown in Figure 1. The U.S. Energy Information Administration (EIA) projects electricity generation increases by 2050 of 8x solar and 2x wind relative to 2020. However, the output of solar and wind is variable on several timescales. Solar, for example, varies minute to minute (due to cloud cover), hour to hour (due to the position of the sun), day to night, and month to month (due to seasonality). Wind also exhibits variable output with less regular patterns than solar. Hydropower is often not considered VRE because it is dispatchable on short timescales. However, if reservoirs exceed maximum levels, hydropower must generate energy or spill water. Alternatively, dry periods reduce hydropower output and sometimes even halt its generation altogether. Solar, wind, and hydropower all vary year to year in average output. Incorporating energy storage of various durations and use cases is one part of the solution to managing the variability of renewable energy.

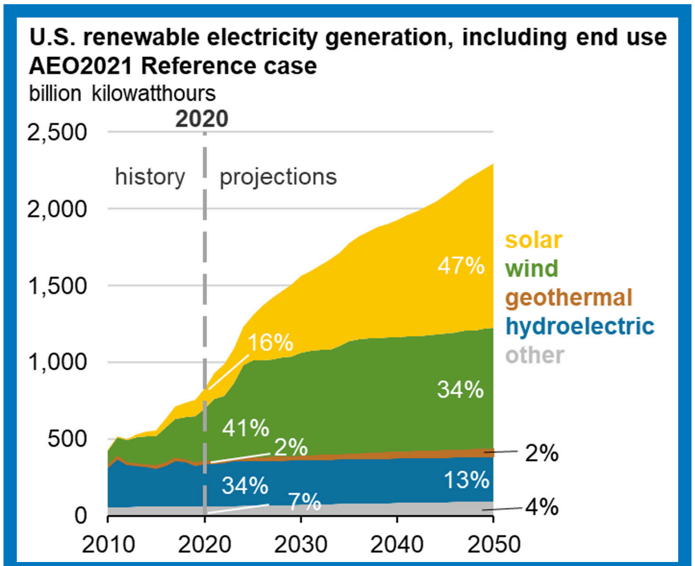
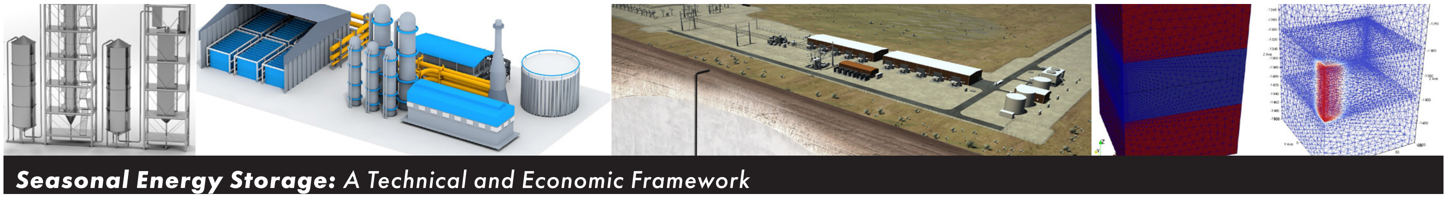


Figure 1: Rapid growth of renewable energy to 2050. Source: U.S. EIA, 2021.



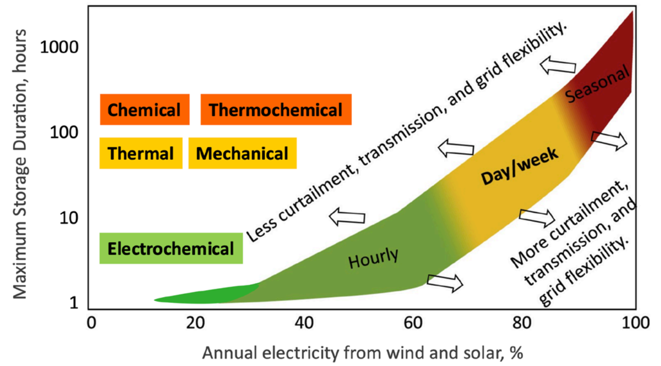


Figure 2: Maximum duration of energy storage required as renewable energy penetration increases. Basic energy storage types are shown with indicative durations. Figure adapted with permission from Elsevier.

Annual Production of Wind, Hydro, and Solar Largely Coincide

Recent studies have shown that as the penetration of VRE grows, the maximum duration required of energy storage increases as shown in Figure 2 [3]. This is due to the increasingly variable nature of energy generation from the hourly, daily, and seasonal variation of renewable energy. There are times each year on a grid dominated by VRE when solar and wind energy are not available or are generating low outputs. To help maintain reliability, there must be adequate energy storage capacity to discharge and meet the demand. The problem is often exacerbated by the tendency of renewable energy to vary in sync. The production of solar, wind, and hydropower typically peaks in the late spring and early summer. Solar and hydropower tend to have reduced output in the winter. The sum of all three sources of energy is highly seasonal in the U.S. as shown in Figure 3. This example shows data from the overall U.S. generation in 2019. Regional variations may differ substantially. The seasonal variations of generation will grow more severe at higher penetrations of renewable energy and may also increase because of climate change.

Seasonal Energy Storage Reduces Overgeneration, Provides Firm Capacity

Given the increasing role of VRE in the U.S. energy mix, one potential part of the solution to maintaining grid reliability is to deploy seasonal energy storage. Figure 4 shows the estimated U.S. electricity demand assuming a 1% annual growth rate from 2050 onward. Also shown is the estimated low-carbon energy

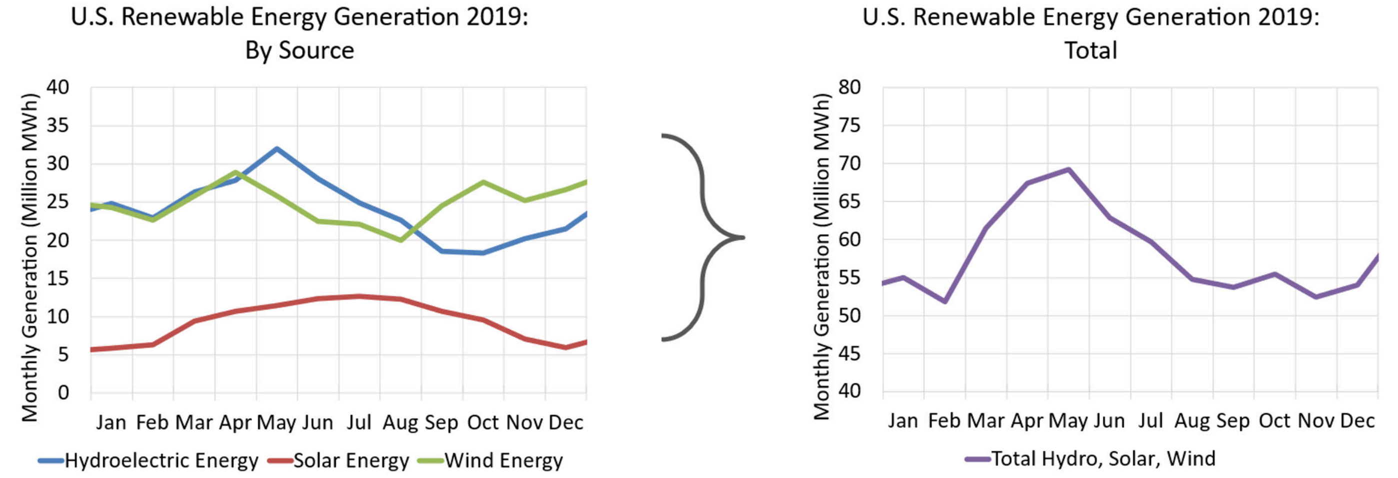
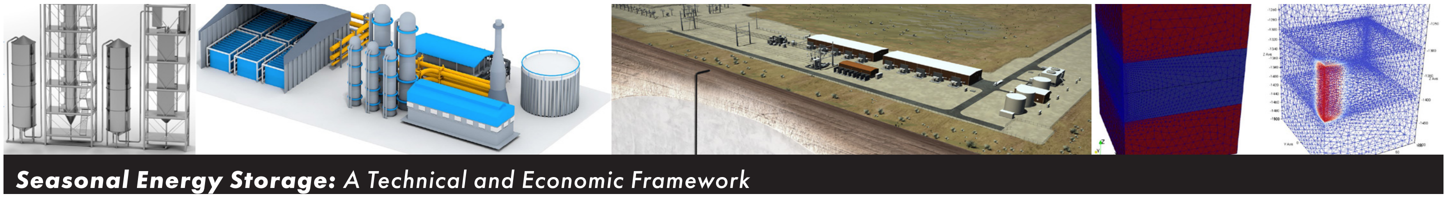


Figure 3. Renewable energy tends to coincide seasonally.



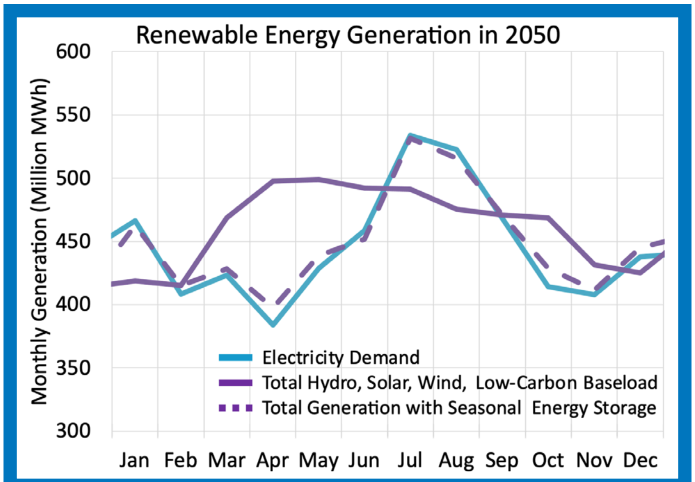


Figure 4. Example scenario of U.S. renewable energy generation in 2050.

generation, in an example scenario assuming 12x the current solar generation, 4x the current wind, and an additional 300 GW of low-carbon baseload power. The result shows severe overgeneration in the spring and fall months when VRE generation exceeds demand as well as a shortfall in the summer and winter when VRE generation is insufficient to meet peak loads. Seasonal energy storage could help alleviate this problem by charging during the spring and fall months when low-carbon energy production exceeds demand and discharging during the summer and winter peak periods. The dispatch profile of 110 GW of seasonal storage is shown in Figure 5. The daily to weekly dispatch profiles of storage resources would vary in this scenario, but assuming an average capacity factor of 50% or higher during the discharge periods, a storage resource would require 700 hours or more of duration to meet the energy needs.

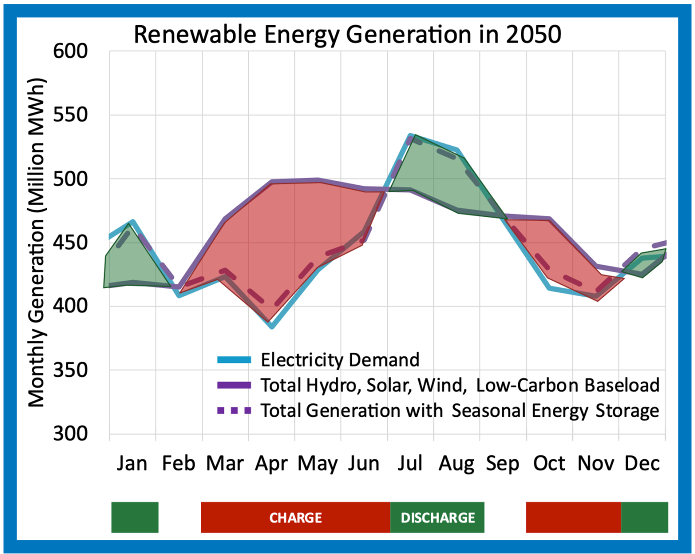
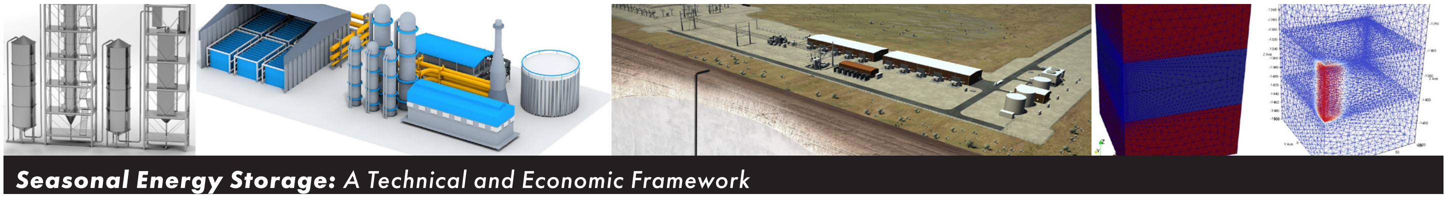


Figure 5: Example dispatch profile of seasonal energy storage.

The need for seasonal energy storage (or similar low-carbon firm energy resources) will become more acute at high VRE penetration levels expected in the coming years. California, for example, obtained 25% of its energy in 2021 from wind and solar [4]. The portion of California's electricity coming from wind and solar is projected to grow to 68% by 2045 [5]. Most of the renewable energy in California is expected to come from solar, a highly seasonal resource. Alternatively, Washington state received 65% of its energy in 2021 from hydropower and 9% from wind with a very small amount from solar [6]. Washington has a commitment to achieve 100% zero-carbon electricity by 2045, with the majority of that energy expected to come from hydropower [7].

Wind and hydropower resources vary from week to week and month to month on a different cycle than solar and tend to drive the need for longer durations of storage. For example, in California—a solar-dominated region—storage resources receive full capacity credit for resource adequacy at four hours of duration [8]. In the Pacific Northwest—a hydropower-dominated region—a four-hour storage resource would receive only 15% capacity credit (with Avista [9]) or 25% (with Puget Sound Energy [10]). A storage system in this region



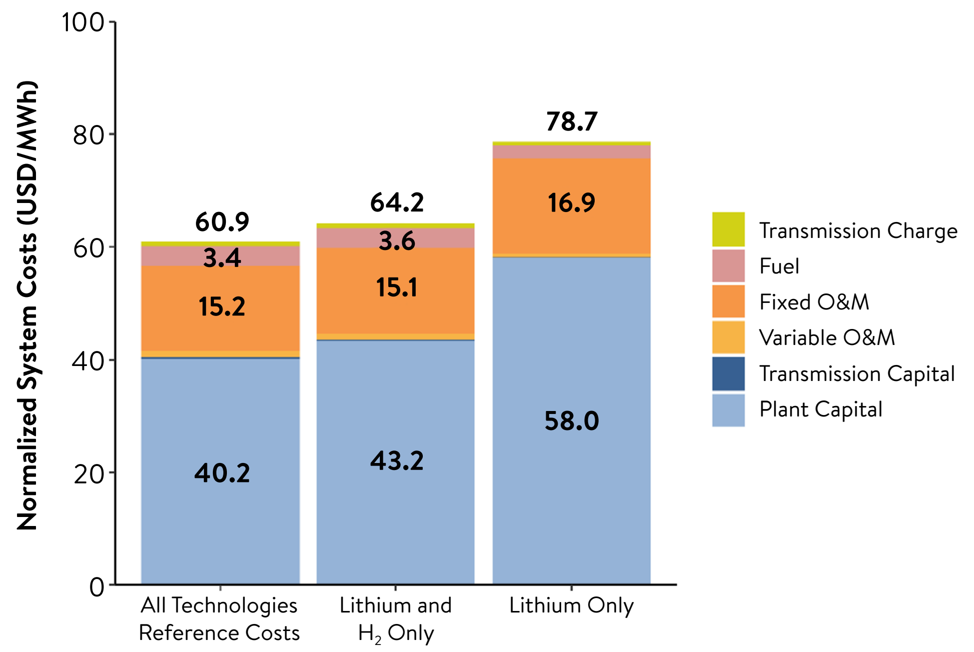


Figure 6: A portfolio of storage technologies (including thermal, mechanical, chemical, and electrochemical solutions) reduces total system cost in a zero-carbon scenario in 2035 [2].

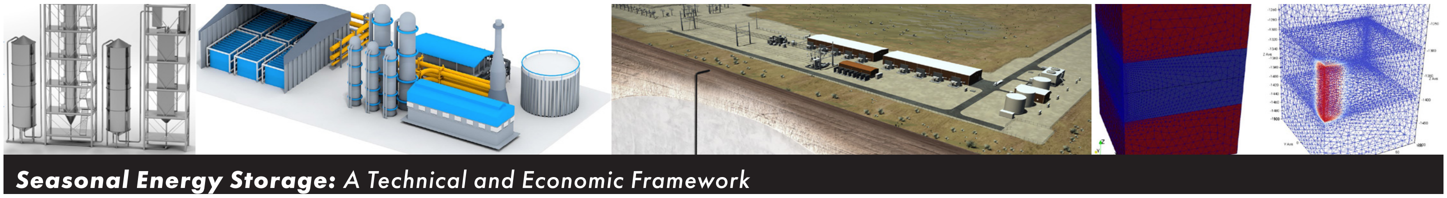
would require 24–70 hours of duration to achieve an 80–90% capacity credit.

Given varying resource mixes and seasonality, the particular use case, duration, and size of a seasonal storage resource that is suited for California, the Pacific Northwest, or other regions may differ substantially. However, the ability to deploy a large amount of seasonal energy storage in the 2030–2045 time frame may be beneficial to help maintain grid reliability and reduce the overbuilding of shorter duration storage and renewable energy plants. A recent study focused on a VRE-dominated grid scenario shows that overbuilding is reduced and the total system cost of delivering energy is minimized when short-duration energy storage (less than 10 hours) is used in combination with long-duration energy storage [11]. The recent EPRI study previously referenced evaluated the system costs using a capacity expansion and dispatch model and various low-carbon scenarios in 2035 [2]. Figure 6 shows that the system cost in a VRE-dominated grid is lowest when batteries are combined with a variety of energy storage types including thermal, mechanical, and chemical storage technologies. Adding additional technologies to the system with different characteristics may further reduce the cost. This result relies on cost assumptions which will likely change as the technologies mature and cost information improves.

Candidate Technologies for Seasonal Energy Storage

Two commercially proven energy storage technologies represent the majority of installed capacity of energy storage projects today: pumped storage hydropower (PSH) and lithium ion batteries. Each technology, in principle, could be used for new projects for seasonal energy storage applications. However, two important criteria must be satisfied: the requirements of scalable deployment ability and low cost. These challenges are further discussed below.

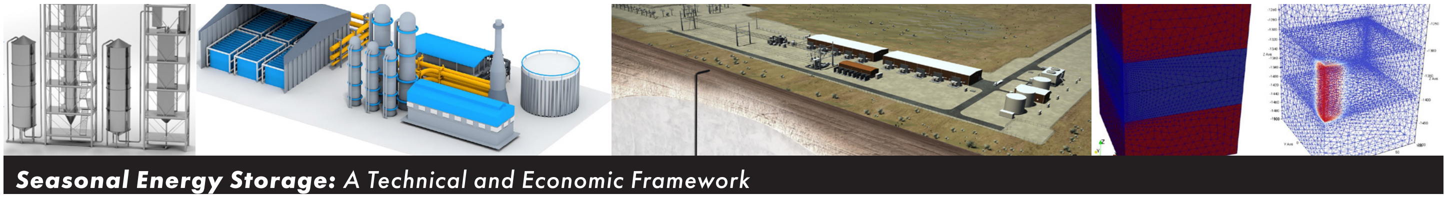
Hydropower is used at very large scale as an energy storage resource with 22,000 MW of installed generating capacity in the U.S. today [12]. These facilities charge by pumping water to an elevated reservoir and

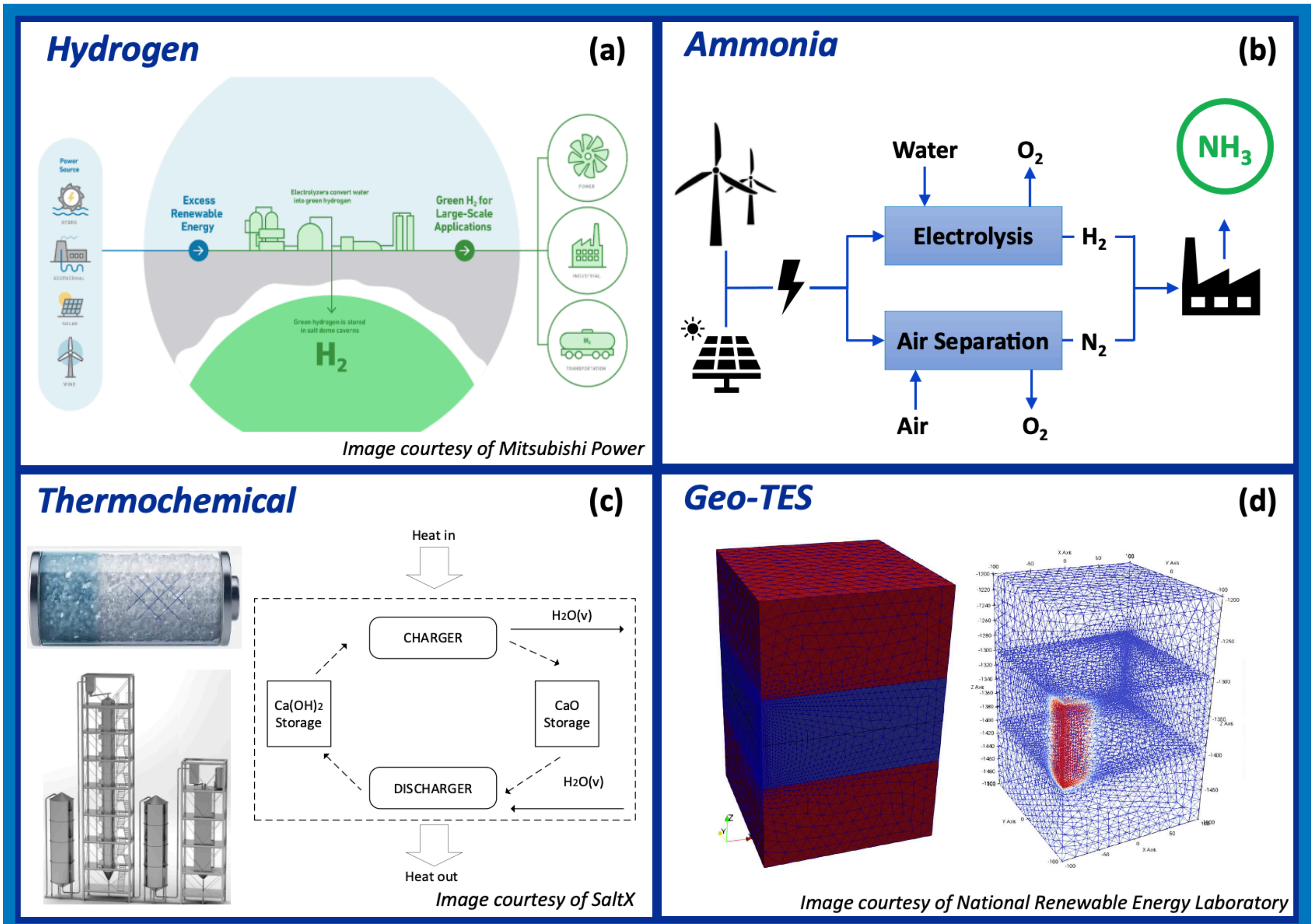


later release the water to drive a turbine and generate power. A few of these facilities have usable energy storage durations approaching hundreds of hours, including the Gianelli Pumping-Generating Plant at the San Luis Reservoir near Los Banos, California[13]. and the Lake Hodges Pumped Storage Facility in San Diego County, California [14]. These PSH facilities can operate as water management resources and could also be used as seasonal energy storage resources for managing electrical power supply and demand. There are significant challenges for new PSH projects with seasonal durations in the U.S. due to lengthy licensing and financing processes, the potential impact on land and waterways, concerns regarding environmental justice and equity, and local opposition to projects [15]. The application queue with the Federal Energy Regulatory Commission (FERC) for new PSH projects shows that many projects take years to move through the licensing and development process [16]. All projects currently on the active permit list are less than 80 hours in duration [17]. Building a PSH plant with a duration over 500 hours would require a very large reservoir, making licensing and financing such a facility more challenging. If PSH projects can be developed and constructed successfully they could represent a meaningful source of very long duration energy storage for seasonal applications.

Given the long durations required for seasonal energy storage applications, the cost of stored energy must be exceedingly low—potentially less than an estimated $10/kWh installed cost for adding marginal storage capacity, assuming that the charge and discharge equipment is fixed [18]. The estimated cost of the most common type of utility-scale, new-build energy storage being deployed today (lithium ion battery storage systems) was estimated recently by EPRI at approximately $300/kWh for a 4–8 hour duration system [19]. This cost would be substantially higher if overbuilding due to expected degradation and contingencies were included. Lithium ion batteries experience little cost decline at longer durations because the majority of the costs are from the energy storage capacity in the cells and associated equipment; the marginal cost of adding storage capacity is expected to be approximately $100/kWh in 2035 [2]. At 500 hours of duration the energy storage capacity alone would cost $50,000/kW, many times higher than most power generation technologies. Therefore, the cost of lithium ion batteries is expected to be too high to be viable for seasonal energy storage applications. Other electrochemical storage technologies are commercially available or in development, including sodium sulfur and flow batteries. These devices, however, are also expected to have marginal energy storage capacity costs near $100/kWh, rendering them too expensive for seasonal energy storage applications. Earlier stage electrochemical technologies such as iron-air batteries are gaining traction, but it is not yet clear whether they will be suitable for seasonal energy storage durations [20].

There are several emerging energy storage technologies that may satisfy the requirements of scalable deployment ability and low cost. Figure 7 shows a selection of technology categories that may be suitable: hydrogen, ammonia, thermochemical energy storage, and geothermal energy storage (geo-TES). Each technology must be assessed in terms of its cost, performance, operating characteristics, safety, siting constraints, and expected benefits. Several of the technologies may be suitable for repowering existing thermal plants by using their existing infrastructure, reducing capital costs and maintaining benefits for the local communities.





Hydrogen (a)

Image courtesy of Mitsubishi Power

Ammonia (b)

Thermochemical (c)

Image courtesy of SaltX

Geo-TES (d)

Image courtesy of National Renewable Energy Laboratory

Figure 7: Candidate technologies for seasonal energy storage: (a) Hydrogen storage using a salt cavern; (b) Ammonia production with low-carbon electricity [21]; (c) Thermochemical energy storage with calcium oxide; (d) Geo-thermal energy storage showing a simulation of heat stored in sedimentary layer underground.

Hydrogen

Low-carbon fuels represent a broad category of energy carriers, some of which may be suitable for seasonal energy storage applications [22]. The primary technology in the low-carbon fuels category is hydrogen. The hydrogen value chain contains three major categories: production, transportation and storage, and end use. Each category has multiple candidate methods, including some well-established processes and many emerging concepts.

One leading pathway gaining interest for seasonal energy storage starts with the production of low-carbon hydrogen from renewable electricity. Electricity can be used to drive an electrolyzer, which splits water into oxygen and hydrogen. The oxygen is typically released to the atmosphere while the hydrogen is stored for later use. Hydrogen use in long duration energy storage will require long-term, large-scale storage. This is likely to require underground geologic storage in large salt caverns, though depleted oil fields or some aquifers may also be suitable [23]. The salt caverns can be solution-mined and made very large with a low marginal cost of storage capacity. Cushion gas is required as permanent inventory in the storage volume to maintain minimum pressure. The amount of cushion gas required varies by storage type—~50% of the total hydrogen storage volume is not uncommon—and adds capital costs which could be significant if the storage system is not frequently cycled. To discharge the system, the hydrogen can be used to power a fuel cell or burned in a combustion system to generate electricity. This pathway is just one example and is not representative of all possible hydrogen-based energy storage systems. This pathway, however, is gaining commercial traction as a proposed solution to seasonal energy storage needs.

Pros: Hydrogen has the potential to provide a significant amount of energy storage. Because it can be created from either fossil fuels (with carbon capture to make the process low carbon) or electrolytically using water, a significant amount can be produced in many regions. Moreover, because it can be stored, transported, and used similarly to existing gaseous fuels, it has the potential to be used with existing equipment and infrastructure to configure a seasonal storage plant—which could lower costs and risk. For example, a project at the Intermountain Power Project in Delta, Utah plans to generate hydrogen with 220 MW of electrolyzers and store the hydrogen in an adjacent salt cavern [24]. The hydrogen will be used to generate power by burning it in an 840 MW combined cycle gas turbine (CCGT). The cavern will be large enough to store hydrogen sufficient for 300 GWh of chemical energy storage or ~200 hours of generation at full capacity of the CCGT [25]. A rendering of the project is shown in Figure 8. Multiple companies are offering, or will soon offer, large-scale electrolyzers suitable for MW-scale projects [26,27,28,29]. Salt cavern storage of hydrogen has been studied for years and is currently utilized commercially in the Gulf Coast of the U.S [30]. Combustion turbines can be modified to co-fire hydrogen with natural gas and new systems may eventually be able to use 100% hydrogen [31].

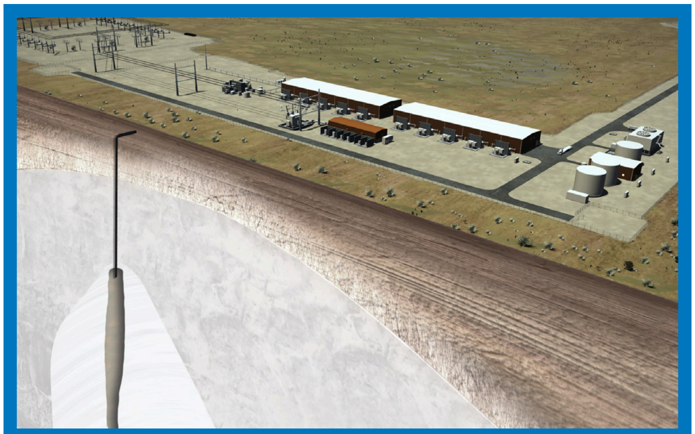


Figure 8: Hydrogen storage project located near Delta, Utah using electrolyzers to generate hydrogen, a salt dome cavern for hydrogen storage, and a CCGT plant for burning the hydrogen and generating electricity. Image courtesy of Mitsubishi Power.

There may be synergies with using hydrogen as a fuel in addition to generating electricity. It is possible to transport hydrogen via pipeline to a load center where it can be used for transportation applications or for industrial process heat [32].

Cons: The total costs of individual hydrogen-based seasonal energy storage projects are expected to be very high. For example, the ACES project in Delta, Utah has an estimated cost of $2 billion including loan commitments and anticipated equity funding [24]. The technology does not scale down favorably to smaller project sizes due to economies of scale in turbomachinery and underground geologic storage. Fuel cells and reciprocating internal combustion engines (RICE) could be utilized for smaller installations albeit at higher unit costs. Therefore, the technology will be most favorable on a unit cost basis when built at large scale.

Hydrogen also has significant safety-related issues. Hydrogen has a wide range of flammability, burns fast and hot, and has a low minimum ignition energy [33]. Its flames are thin, very hot, and nearly invisible. Hydrogen is also a small, "slippery" molecule, creating challenges for sealing technologies needed in pipelines and storage systems. Leak detection is difficult because hydrogen detection requires special sensors and may occur in unexpected locations. Metallurgical challenges in the use of hydrogen fuel derive from its reactive nature, propensity to diffuse into metals, and role in embrittlement and corrosion phenomena, which is particularly nettlesome for applications seeking to utilize existing pipelines. Developing systems that use hydrogen safely is therefore costly because more equipment, operating procedures, and redundancy are required.

Suitable underground geologic formations for hydrogen storage are not widely spread across the country, limiting the locations suitable for such a project. Figure 9 shows a map of salt caverns and other geologic formations in the U.S. that may be suitable for hydrogen storage [34]. Salt deposits are concentrated in the Gulf Coast region and are located at only a handful of locations outside that region. Other suitable formations can be found in some places, but many areas have few options, which may limit the feasibility of long-

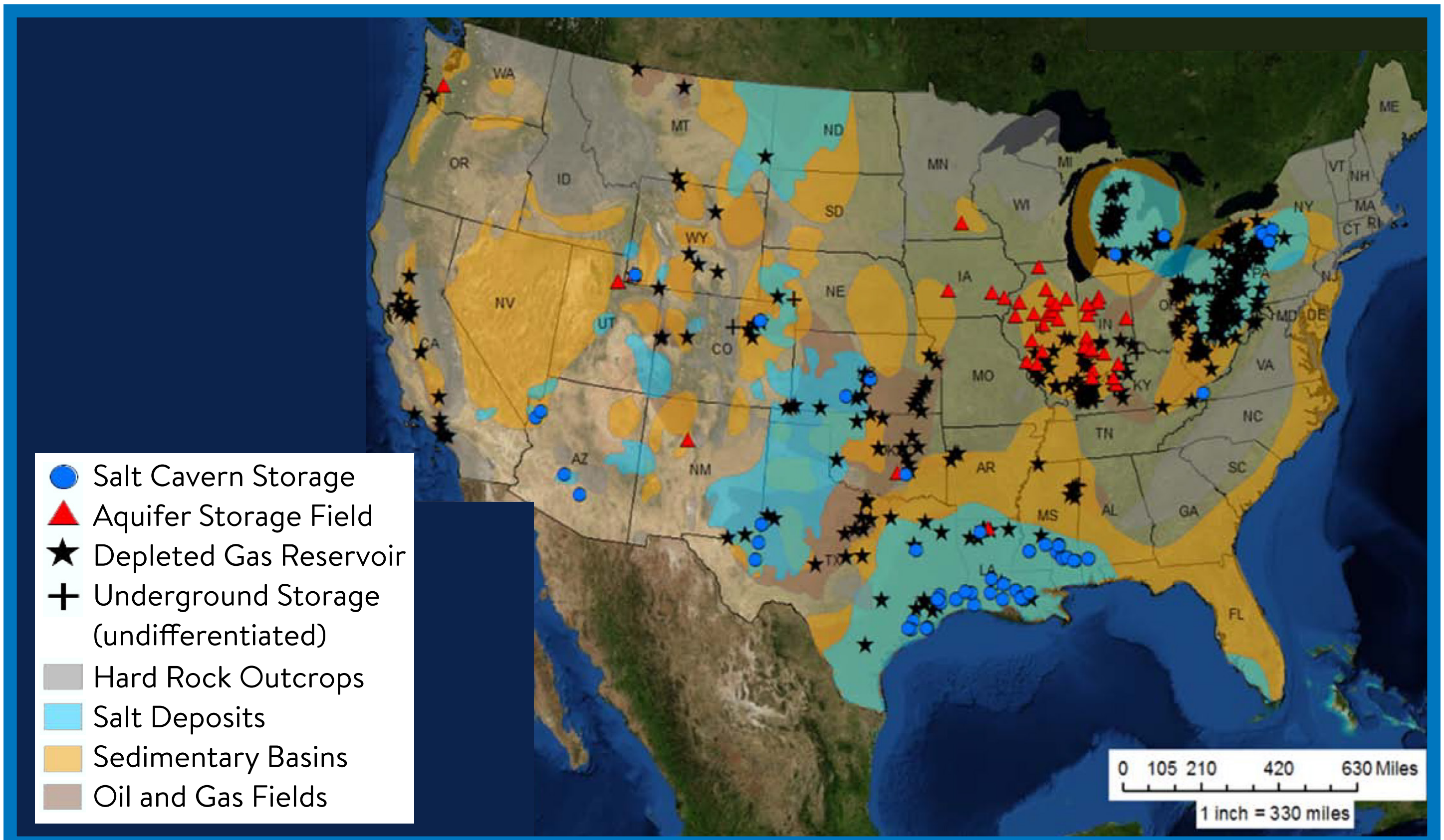
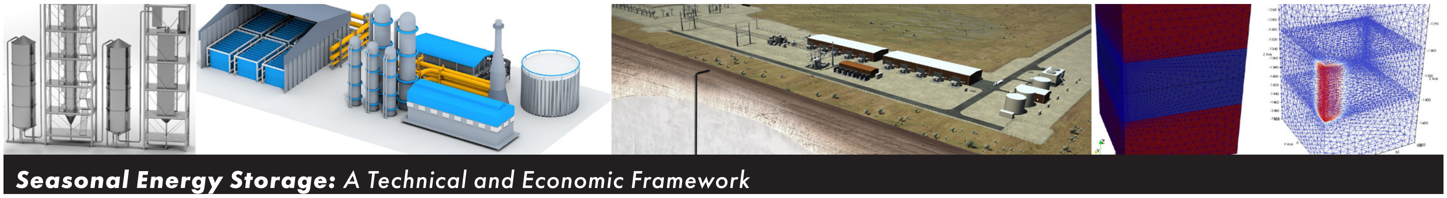


Figure 9: Map of salt caverns and other geologic formations suitable for hydrogen storage. Image courtesy of Sandia National Laboratories.



term hydrogen storage in some regions. This could be overcome by creating a pipeline network for transporting and delivering hydrogen, much as has been done for natural gas in the U.S. However, the leakage rates of hydrogen from pipelines and storage caverns are not well understood and will require further research and mitigation work [35].

The expected round-trip efficiency (RTE) of a hydrogen storage project is expected to be low, ranging from approximately 18% for combustion-based systems up to 46% for systems utilizing advanced electrolyzers and fuel cells [18]. This is due to the efficiency of the electrolyzer in converting electricity to hydrogen (~60%) during the charge process and the corresponding efficiency of converting the hydrogen back into electrical energy either through combustion (35–55%) or a fuel cell (40–60%). Pumping losses and other parasitic loads will further reduce the RTE.

Takeaway: Hydrogen is a flexible energy carrier that could play a role in decarbonizing several sectors of the economy, including transportation, industrial process, and power generation. Hydrogen storage is a seasonal energy storage option with the potential to provide a significant amount of energy that can be transported to many locations. Significant research is ongoing related to hydrogen production, transport, storage, and utilization, with the goal of accelerating it to commercial readiness at larger scales within the next 10–20 years [36]. However, cost and safety will be significant hurdles.

Ammonia

Ammonia is a commonly produced industrial chemical with a wide range of applications. The most common way to synthesize ammonia uses the Haber-Bosch process which requires natural gas to generate hydrogen and then reacts the hydrogen with nitrogen at high pressure and temperature [37].

$$3H_2 + N_2 \rightarrow 2NH_3$$

There is growing interest in producing ammonia using low-carbon processes. There are many variations on the approach but one way to do it is to use low-carbon electricity to generate the primary feedstocks required for ammonia: electrolysis to generate hydrogen and an air separation unit to generate nitrogen. The resulting hydrogen and nitrogen can be used to synthesize ammonia which can be stored as liquid in above ground tanks. The ammonia can then either be cracked to release the hydrogen and burned in a combustion turbine or reacted in a fuel cell, or the ammonia can be burned directly in a combustion turbine, boiler, or reciprocating engine. Figure 10 shows an image of a low-carbon ammonia production plant from an industrial vendor using an integrated 120 MW electrolysis plant and 300 metric ton (MT) per day ammonia plant [38].

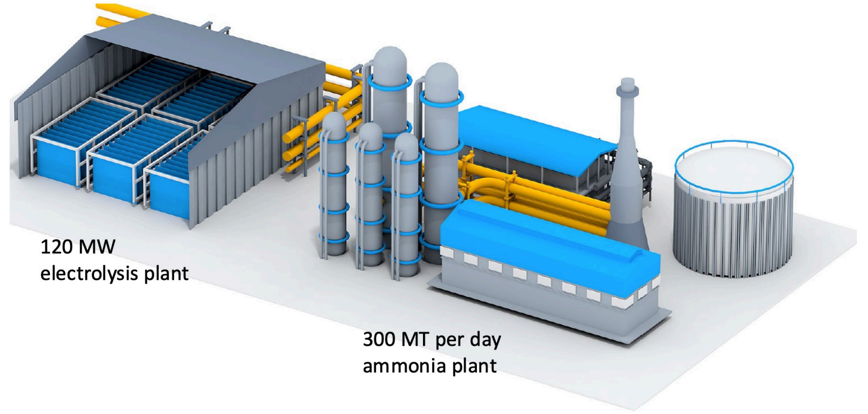
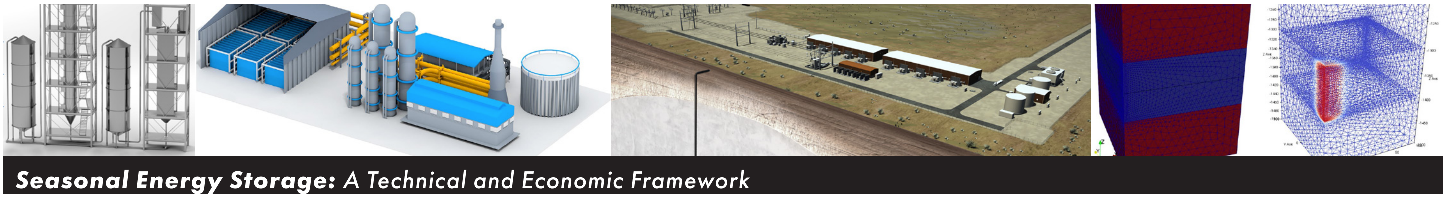


Figure 10: Integrated 120 MW electrolyzer and 300 metric ton per day ammonia production system. Image courtesy of thyssenkrupp.



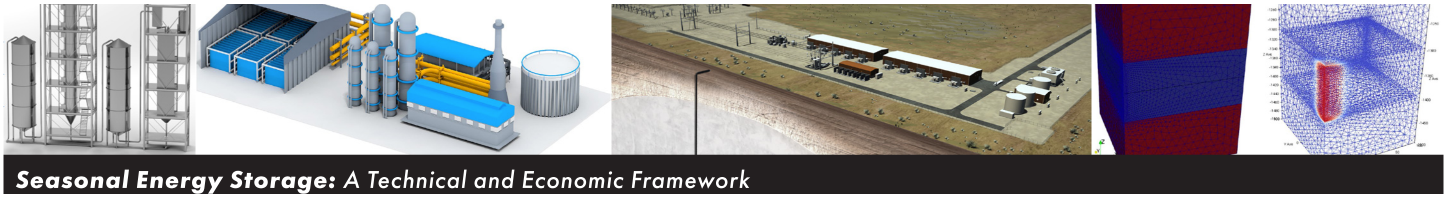
Pros: The storage of ammonia can be done using above ground tanks at modest pressure (16–18 bar) and ambient temperature (77°F or 25°C); this approach would have no standby losses. Alternatively, much larger and lower capital cost tanks could be used that store liquid ammonia at -27°F (-33°C) and atmospheric pressure; these tanks would require some parasitic load (and higher operating expenses) to operate the refrigeration system and keep the ammonia cold. Either tank option precludes the need for specific geological conditions like the need for underground storage formations with hydrogen. This allows more flexibility in siting a seasonal energy storage project using ammonia. Ammonia is a relatively energy-dense fuel with a lower heating value of 18.6 MJ/kg; this is less than 1/6th that of hydrogen on a mass basis but the volumetric energy density of ammonia is many times higher than hydrogen at the same pressure. The tanks suitable for ammonia storage are well-established and low cost; the estimated installed cost of atmospheric pressure ammonia storage tanks is less than $1/kWh [39].

Cons: The synthesis of ammonia would require more equipment and process integration than generating hydrogen. In addition to a hydrogen electrolyzer, an air separation unit must be installed to generate nitrogen, and a Haber-Bosch unit must be installed to synthesize the ammonia. Therefore, the capital cost of the charging equipment in a seasonal energy storage project using ammonia would likely be higher than a similarly sized project using hydrogen as the storage media.

Ammonia is poisonous so safety considerations will be important to reduce the risk of exposure to acceptably low levels. The permissible exposure limit to ammonia is very low: 50 ppm [40]. Anhydrous ammonia readily dissolves in water and vaporizes at ambient conditions so an accidental leak could diffuse quickly. Ammonia is used for NOx control at many power generation facilities and is often stored on-site so significant know-how is available for safe storage equipment and procedures [41]. However the quantity stored for seasonal energy storage applications would be far larger than current industry practices and would therefore be subjected to greater scrutiny regarding safety procedures. Large-volume storage of ammonia near residential locations is expected to encounter resistance from local communities due to the perceived safety risk. This may limit the deployment of ammonia-based seasonal energy storage in many locations.

Ammonia is a difficult fuel to burn relative to other liquid fuels due to its low reactivity, so combustion systems must be adapted to effectively control combustion [42]. The fuel has a low combustion speed and therefore requires a larger combustor. The combustion of ammonia also generates higher levels of NOx relative to natural gas or hydrogen, due to the fuel-bound nitrogen, which must be cleaned up to comply with emissions standards [43].

Takeaway: Ammonia is a low-carbon fuel with a pathway to be synthesized with electricity, stored, and used to generate electricity for seasonal energy storage applications. Many low-carbon ammonia projects are planned around the world over the next 10 years, primarily for non-power end uses [44]. Ammonia has different strengths and weaknesses as compared to hydrogen and may be more advantageous to consider in some applications, especially if low-cost underground storage of hydrogen is not available. Further work, however, is required to develop combustion equipment and establish safety standards for ammonia-based seasonal energy storage projects.



Thermochemical Energy Storage

Thermochemical energy storage technology developers are exploring a variety of pathways to exploit the energy contained in chemical bonds for generating heat. To charge a material, heat is applied to break up a molecule into separate reaction products. These products are typically stored at ambient temperature and pressure, allowing extended storage standby time with little or no self-discharge losses. To discharge the material, the reaction products are recombined to release heat and generate steam to drive a steam-Rankine power cycle, heat a gas to drive a Brayton power cycle, or provide the heat for commercial or industrial purposes. These thermochemical reactions are reversible and can be used for multiple charge/discharge cycles.

Multiple pathways using thermochemical reactions have been explored via modeling and experimental efforts [45]. Calcium oxide (CaO) represents one good example of thermochemical energy storage. It uses a low-cost, non-toxic reactant, the reaction products are non-flammable and can be stored at ambient conditions, and the heat generated is at a useful temperature for conversion to electricity through an existing power cycle. Two possible thermochemical pathways suitable for seasonal energy storage use calcium oxide. One pathway uses calcium oxide/calcium hydroxide; the other uses calcium oxide/calcium carbonate.

Calcium Oxide/Calcium Hydroxide

Calcium oxide releases heat when exposed to water. This reaction produces calcium hydroxide ($Ca(OH)_2$) and heat with the following reaction.

$$CaO + H_2O \rightarrow Ca(OH)_2 + 104.4\ \text{kJ/mol}$$

This reaction releases approximately 1.9 MJ/kg of heat on a calcium oxide mass basis. The temperature of the hydration reaction is approximately 932°F (500°C), meaning that it is possible to generate superheated steam at 752–842°F (400–450°C) and 40–60 bar in a reactor. Steam at this quality is suitable for driving a steam-Rankine cycle to generate electricity. Several companies are developing technology using this process for energy storage applications. The largest installation with this technology to date is a 0.5 MW, 10 MWh system in Berlin [46].

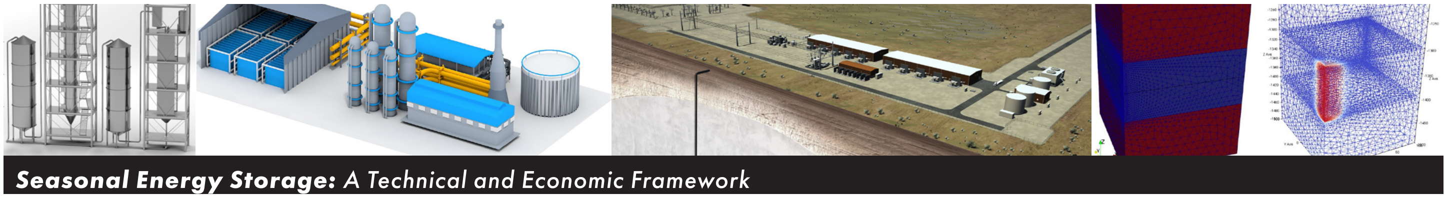
Calcium Oxide/Calcium Carbonate

An interesting alternative pathway involves using calcium oxide and CO_2. Calcium oxide undergoes a carbonation reaction when exposed to CO_2, which releases heat and generates calcium carbonate ($CaCO_3$).

$$CaO + CO_2 \rightarrow CaCO_3 + 178.4\ \text{kJ/mol}$$

This reaction releases approximately 3.2 MJ/kg of heat on a calcium oxide mass basis, substantially higher energy density than the hydration pathway. Furthermore, the carbonation reaction occurs at approximately 1472°F (800 °C), which is hot enough to generate superheated steam at higher quality than via hydration. The carbonation reaction could also be used to generate supercritical CO_2, which as a working fluid can generate electricity at a higher efficiency than a steam-Rankine cycle. Research projects have been conducted to develop equipment suitable for generating heat using the carbonation pathway shown in Figure 11 [47,48]. However, no pilot systems or commercial installations using this technology have been built to date.

Pros: The thermochemical energy storage pathways have the advantage of storing reactants at ambient conditions. This reduces the cost of the system because no insulation or pressure vessels are required for the storage containers. This also eliminates self-discharge losses



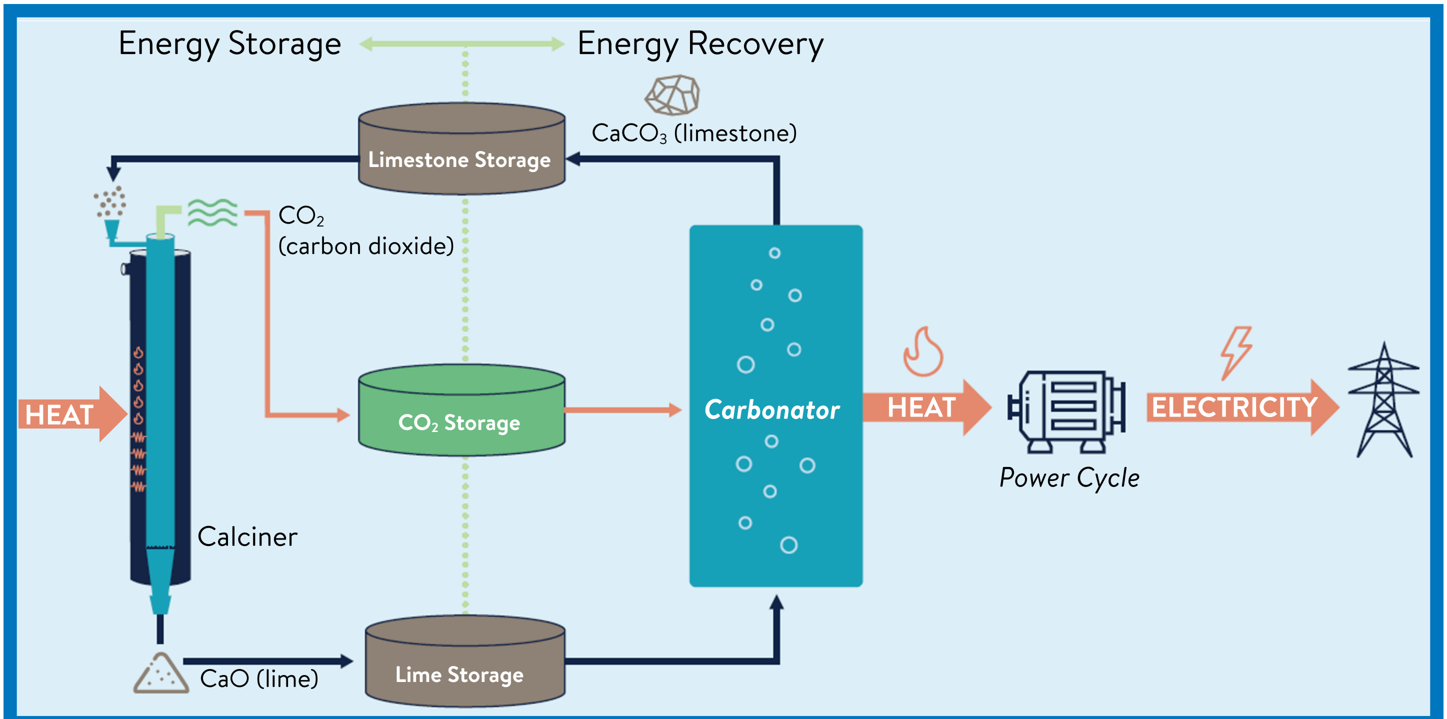


Figure 11: Calcium looping process for thermochemical energy storage. Image courtesy of Calix.

if the reactants are stored in the charged state for an extended period. The chemical reactants can be stored for very long periods, akin to coal, providing both seasonal energy storage potential and the opportunity to provide resiliency. The processes are relatively safe and straightforward in design, and the components used are relatively mature.

Cons: The high reaction temperatures for thermochemical energy storage require the development of industrial equipment capable of withstanding the reaction conditions. Furthermore, the charging and discharging reactions are typically solid-gas reactions that are challenging to control. Several industries, including the cement industry and the coal power generation industry, have developed equipment capable of handling solids in high-temperature reactive conditions. However, this equipment must be adapted to function optimally with the desired materials and process conditions suitable for seasonal energy storage. The overall efficiencies of these systems for producing electricity will likely be low, in part because they rely on power cycles during discharge that have inherently low efficiencies. Finally, the maturity of these systems is low because only small-scale pilots have been done in some cases and in others the processes are still conceptual.

Takeaway: Thermochemical energy storage is an emerging technology that merits further development and scaled-up project demonstrations of the most promising reaction pathways.

Geo-Thermal Energy Storage

A large amount of thermal energy can be stored by heating a volume of rock underground and later extracting the heat when needed. This geo-thermal energy storage (geo-TES) concept involves using resistive heaters buried underground to directly heat the rock or mounted above ground and using a heat-transfer fluid in a loop that indirectly delivers the heat to the rock underground. A volume of rock consisting of low-permeability caprock and bedrock layers is heated slowly during the charging process. When energy production is required, a heat transfer fluid is pumped through the rock to extract the heat and use it to drive a power cycle [49]. Several groups have pursued variations of this approach for seasonal energy storage using different heat sources, such as nuclear reactors or solar thermal energy [50,51,52]. Electrical heating of the ground has been explored for oil and gas production and has been demonstrated at small scale [53]. The *in situ* conversion process demonstrated the feasibility of heating the ground up to 650–700°F (343–371°C), which would be sufficiently hot to create superheated steam from the extracted heat. However, the heat losses due to conduction to surrounding rock can be relatively high and are proportional to the surface area of the heated volume with neighboring rock. To reduce heat losses to an acceptable level, the volume of heated rock must be very large so that the surface area to volume ratio is reduced. For example, one study estimated that a 1640 ft (500 m) cube of heated rock volume can store 1 GW-year (8760 GWh) of energy. At this volume, heat losses would be 3–4%/year [50]. This self-discharge rate reduces the effective RTE of a geo-TES system and would have a negative effect on the overall cost of energy delivered by such a system. However, it may be feasible to develop a sufficiently large geo-TES system so that the self-discharge rate is acceptably small.

The National Renewable Energy Laboratory (NREL) has explored the feasibility of creating an artificial geothermal reservoir in a sedimentary layer between impermeable caprock and bedrock layers as shown in Figure 12. The design injects heat at 482°F (250°C) with pressurized water and allows the water to flow through the porous rock. The heat can be extracted when desired and used to generate steam to drive a steam or organic Rankine cycle power block. The economics appear to be favorable for such a system at energy storage durations exceeding 1000 hours [52].

Pros: No reactive chemicals or toxic materials are needed for a geo-TES system. It can use established technologies to heat the ground and to extract the heat and convert it to electricity, lowering project risks. Although costs are still being developed, they have the potential to be low for this technology, especially if an

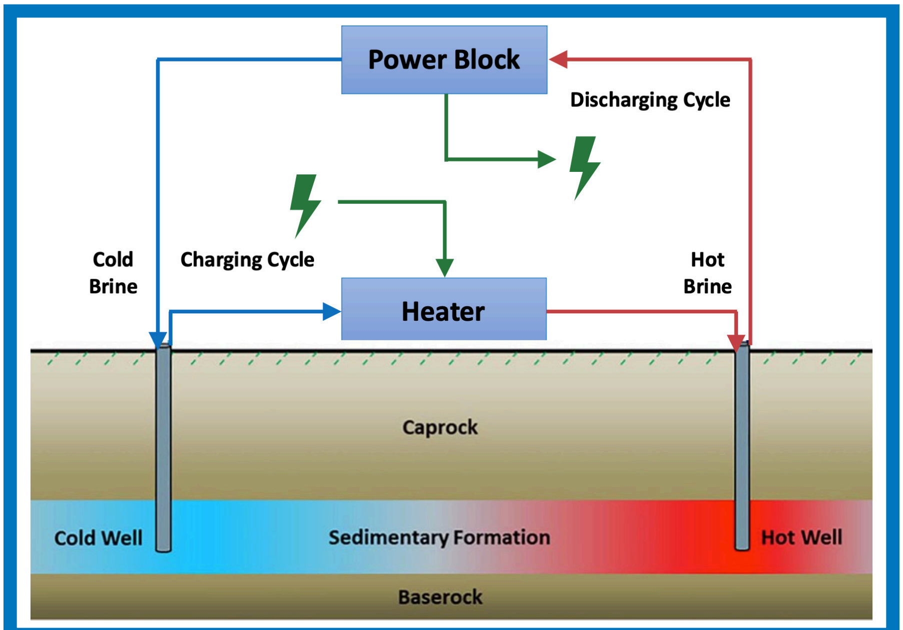
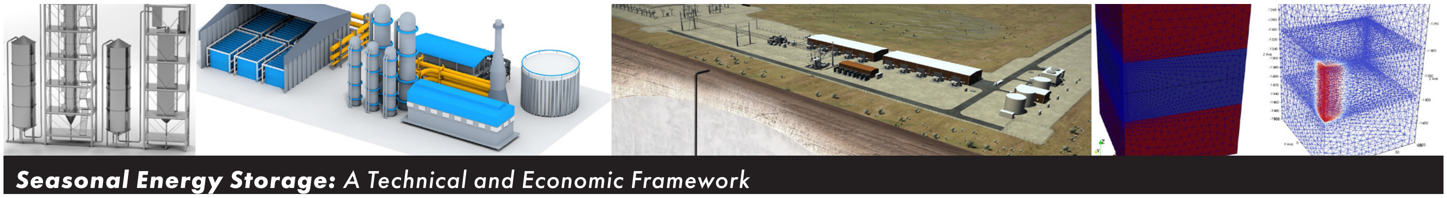


Figure 12: Geo-thermal energy storage model using water as a heat-transfer fluid. [48] Caprock and bedrock layers contain the heat to the sedimentary layer in between. Image courtesy of National Renewable Energy Laboratory.



existing steam-Rankine cycle and grid interconnection can be used.

Cons: Self-discharge losses due to heat conduction are unavoidable; they can be minimized but not eliminated. The technology will likely have a relatively low RTE as well. The application will be limited to suitable geology with the requisite rock structures and types. Environmental impact studies will likely need to be undertaken to assess potential impacts to water aquifers or other sensitive geological formations. These site-specific constraints may further limit the geographical suitability of large geo-TES projects. The minimum viable project size is likely quite large due to the unfavorable effects of heat losses on smaller scale systems.

Takeaway: Geo-TES is still at the concept stage and may encounter practical limitations as further engineering work is done and technology demonstrations are built. It has the potential to provide a significant amount of stored energy potentially at low cost.

Economic Evaluation of Seasonal Energy Storage Systems

The challenges associated with seasonal energy storage are not only technical in nature, but also economic. To successfully deploy commercial seasonal energy storage projects, basic economic constraints of the system must be satisfied: it must generate a return for the owner or investors (equity), it must generate sufficient revenues to pay debt obligations (if any), and the revenues it generates must be sufficiently reliable to attract low-cost project finance capital.

The outline of a cost-benefit analysis is presented here that involves first estimating costs and then solving for the required revenues to make a seasonal energy storage project financeable. First, the high-level design of a seasonal energy storage system is chosen (charge and discharge rates, storage duration). Then the system cost is estimated (both capital cost and operating cost). Next, the benefits (revenue streams) associated with the resource are estimated. Financial metrics such as simple payback can be used to assess the economic viability of the project as designed. Finally, strategies to maximize revenues and technology gaps that could reduce costs are discussed.

Seasonal Energy Storage Costs

A seasonal energy storage system can be divided into three basic subsystems: the charging equipment, the energy storage equipment, and the discharging equipment. The charging equipment converts electrical energy into the form of energy used by the storage technology—thermal, mechanical, chemical, or electrochemical. Because this process is not perfectly efficient, there is a charge efficiency associated with this conversion. The cost of the charging equipment scales with the rated power capacity in kilowatts ($/kW).

The storage equipment stores this energy until it is needed. There may be a self-discharge rate associated with the storage equipment while the system is in standby mode, which can be expressed as a percent of the total stored inventory lost per day. The cost associated with the storage equipment scales with the energy storage capacity ($/kWh). It is typically more convenient to use the native form of energy storage as the basis in the cost figure; for example, a hydrogen storage system would quantify the cost of the hydrogen cavern in terms of cost per unit of chemical energy storage. A thermal storage system by contrast would use the thermal (heat) energy stored.

The discharging equipment converts the stored energy back into electricity. As with charging, there is a discharge efficiency associated with this conversion. The cost associated with the discharge equipment scales with the rated electrical power capacity ($/kW). The round trip efficiency of the energy storage system is the product of the charging efficiency and the discharging efficiency (assuming no other losses due to standby or parasitic loads). Figure 13 shows the basic subsystems of a seasonal energy storage system as described.

The relative rankings of each technology type will vary on a case-by-case basis and should be quantified in detail for a given cost-benefit analysis. Recent legislation provides substantial tax incentives for low-carbon technologies which will reduce the effective capital cost of seasonal energy storage, improving the economic favorability of projects [54].

Seasonal Energy Storage Benefits

A seasonal energy storage resource is expected to provide value from multiple grid services.

Capacity. The seasonal energy storage resource is available to discharge and meet loads when needed but does not follow a regular daily cycle. Many utilities procure capacity to provide "resource adequacy" or sufficient reserve capacity to ensure grid reliability. Capacity value is typically denoted as a cost per unit generating capacity per month ($/kW-mo).

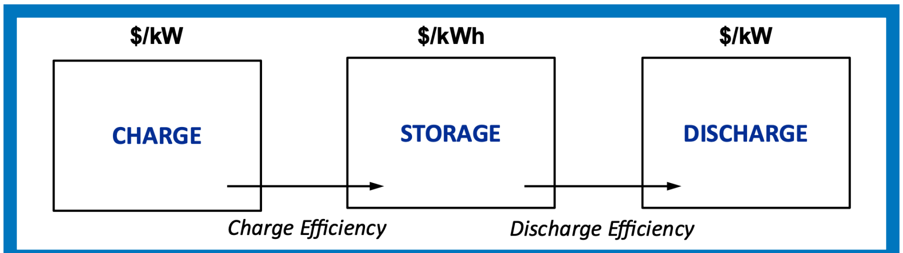


Figure 13: Basic energy storage subsystems.

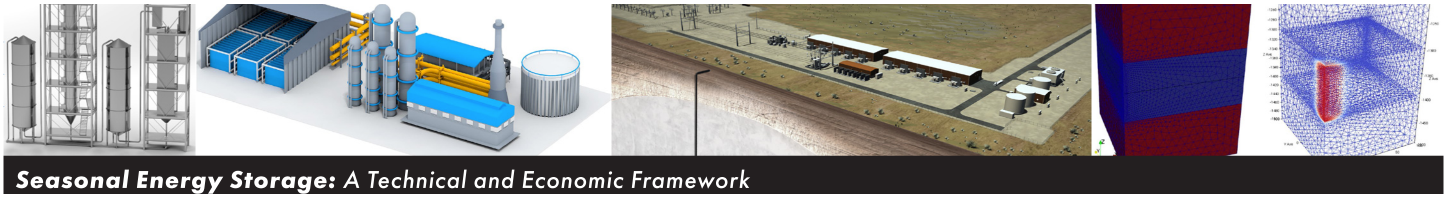
Energy shifting (arbitrage). Charge with excess generation when available and discharge to meet peak loads. The typical cycle is daily (in solar-heavy regions) or more variable (in wind-heavy regions). The seasonal energy storage project can receive revenues assuming that the sales of high-value energy exceed the cost of charging with low-cost energy.

Resiliency. Providing firm backup power to the grid or to a large energy consumer for resiliency events often requires 24–96 hours of storage duration, which will be easily attainable from seasonal energy storage sources. Seasonal energy storage may generate value from this use case. Most seasonal energy storage technologies have a low marginal cost of duration (cost per kilowatt-hour of storage capacity), making them competitive at extended durations vs. lithium ion batteries.

Ancillary services. Many seasonal energy storage technologies can provide frequency regulation, spinning reserve, and inertia. These services are important for grid power quality and reliability.

Carbon credits. The potential for a carbon or CO_2 market to be created (or for existing ones to be enhanced) to provide value for low-carbon power is possible and maybe even likely as targets are announced for deeper reductions in CO_2 emissions globally.

The services outlined above are all important for maintaining a reliable supply of electricity to ratepayers. However, as VRE grows to dominate the grid and many short-duration energy storage projects are deployed, not all services will generate substantial revenues for a seasonal energy storage project. Capacity is expected to be the primary source of revenues. Arbitrage revenues

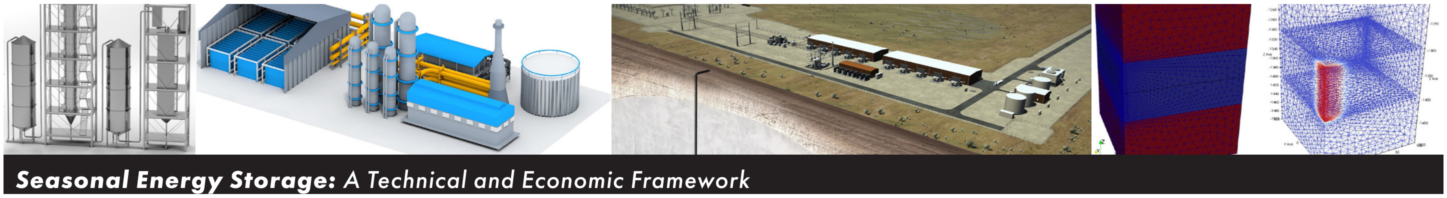


are expected to be secondary. Resiliency will be important, but it is assumed that this value may be included in the capacity value assigned to the seasonal energy storage project. Ancillary services are expected to generate little revenue. Frequency regulation and spinning reserve can be provided by short-duration resources and, given the amount of these resources expected to be online in future years, the market values for these services are expected to be low. Inertia is not currently compensated in U.S. markets but given the proliferation of inverter-based resources (solar photovoltaic projects and lithium ion batteries in particular), the need for inertia is expected to grow. It is possible that in future years there will be an explicit value assigned to resources providing inertia but for now it is assumed that any inertia value can be captured in a higher capacity value. As for carbon markets, some exist but are generally small in value, and energy storage does not currently qualify—so these are also not included in the present framework. However, this revenue stream could be significant in the future.

Simple payback is used as a basic economic screening tool to assess the viability of a project. It is not a sophisticated metric but is useful as a quick check on the economics. The *simple payback* is defined as the capital costs divided by the annual net revenues (gross revenues minus operations and maintenance costs). This results in an estimate of the number of years required for the system to "pay for itself." A seven-year simple payback is approximately equivalent to a project internal rate of return (IRR) of 13%, which is a reasonably favorable value.

Capacity Revenue for Seasonal Energy Storage

In future years there are expected to be long periods of low-cost (close to zero or even negative) energy prices due to the variability of solar and wind production that often exceeds demand. However, a seasonal energy storage project will require up to thousands of hours to charge during the year, so the cost of charging energy will vary. Wholesale electricity prices often peak at high values for periods of time. These are the favorable periods for discharging a seasonal energy storage resource to capture the higher value hours throughout the year. The revenue from energy arbitrage alone is likely not sufficient to produce a financially viable project. Given the expected low value of ancillary services, a capacity payment is expected to be the primary source of additional revenue for the energy storage project. To achieve an acceptable simple payback, a capacity payment of $20–30/kW-mo or higher may be required in some scenarios. This value is substantially higher than recent values of capacity. For example, the Midcontinent Independent System Operator (MISO) 2022 capacity market auction cleared at the upper limit of $7.01/kW-mo [55]. The Pennsylvania, New Jersey, and Maryland (PJM) market capacity values recently ranged from $1.02 to $2.10/kW-mo [56]. The California Independent System Operator (CAISO) 2020 local resource adequacy values ranged from $3.86 to $7.70/kW-mo, with an overall average system capacity value of $4.75/kW-mo [57]. None of these current market values are sufficiently high enough to pay for a seasonal energy storage resource. Therefore, it will be necessary to reduce the cost of seasonal energy storage technologies substantially, justify a higher capacity payment for the resource, or have the additional potential revenues not considered in the analysis grow in importance. Achieving lower cost seasonal energy storage will result in additional capacity being deployed as the technologies are selected in resource planning and procurement efforts. If costs are not substantially reduced, seasonal energy



storage may be deployed only in smaller amounts where it is the least-cost option to provide capacity in lieu of other higher cost options.

Potential Areas for Further Work

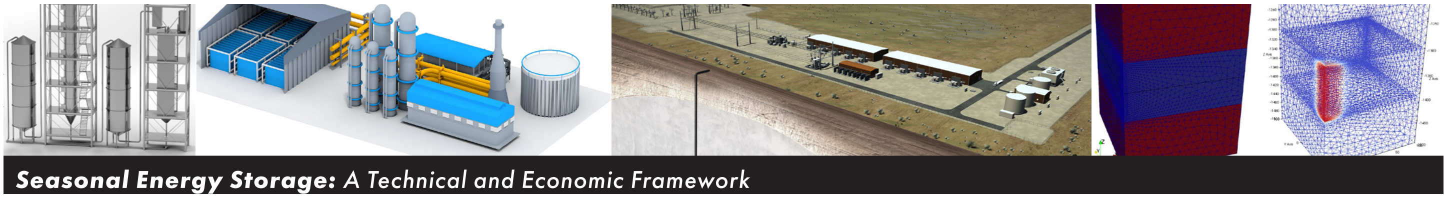
Given the technical and economic challenge of deploying viable seasonal energy storage resources, there are several areas for suggested further work.

Technology Development

Technological gaps can be closed by directed R&D funding at a variety of scales. Grant funding and corporate research funding allocated to early-stage R&D at the laboratory scale may identify promising materials or reactants that show promise for seasonal energy storage systems. Patents obtained in adjacent fields of study by academic research institutions and national laboratories could have potential value in seasonal energy storage applications. Further technical risk reduction may result from funding allocated to larger scale testing for technologies that show promise at small scale. For example, grants to fund pilot-scale (MW size) projects could be made for a variety of technologies to obtain more realistic performance and cost data. Once a technology is proven at MW scale, it is more likely to succeed in competitive procurement efforts by electric utilities seeking to deploy that technology in their portfolio.

Market and Economic Development

The markets and financial structures of seasonal energy storage projects require additional development to secure investment for deploying resources of this nature. Capacity products could be developed by independent system operators that would generate revenue for a seasonal energy storage resource. For example, the resource adequacy construct in CAISO currently requires a four-hour duration for energy storage resources to qualify. Similar products could be developed that require hundreds of hours or more of duration for system resiliency. This sort of product makes market revenues and offtake agreements more certain, spurring investment. In vertically integrated utility markets, the value of seasonal energy storage could be modeled and quantified relative to alternative resources. Positive results from this cost-benefit analysis would be required to justify procuring and rate-basing such resources based on system needs.



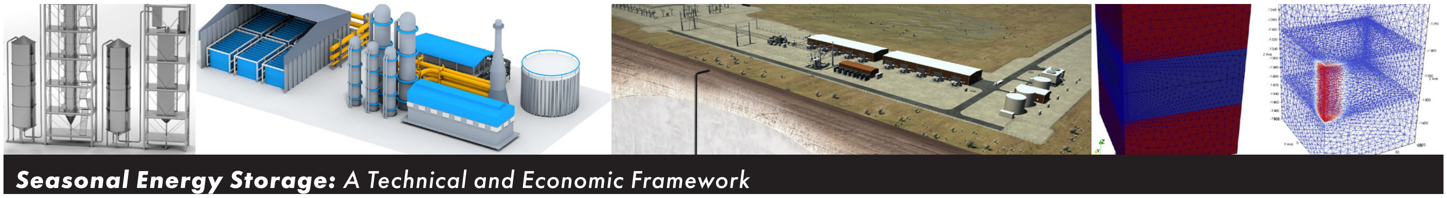
Conclusion and Path Forward

This paper has highlighted the need for seasonal energy storage, identified several potential technologies that could provide solutions, and suggested ways to value energy storage projects and assess their financial viability. Other questions remain unanswered and will require further discussion, analysis, and development work before seasonal energy storage resources become a viable part of grid planning and procurement efforts. In the near term, workshops convened with key stakeholders could further define the need for seasonal energy storage and discuss research and market reforms needed to make it a financially viable resource for the electricity grid. Stakeholders in the following categories may be part of the discussion:

- Electric power generators. Inform power generators, utilities, and other load-serving entities about the approach to modeling seasonal energy storage, what it may cost, and how it may provide value for achieving low-carbon energy goals and resiliency.
- Federal and state governments. Obtain feedback on economy-wide incentives and goals for low-carbon energy. Identify early-stage R&D efforts for possible support. Engage diverse set of stakeholders in discussions and deployment of energy storage projects.
- Investors and debt providers. Understand their criteria for investable projects.
- Project developers. Discuss needs for siting, interconnection, and permitting seasonal energy storage projects.
- Regulatory bodies. Inform resource planning work to incorporate the expected costs and benefits of seasonal energy storage.
- Research institutes, national laboratories, and universities. Provide independent research on developing technologies, perform techno-economic assessments, support demonstrations, inform the public, and provide technology transfer.
- System operators. Discuss energy market products that would provide reliable compensation for seasonal energy storage resources. Consider mechanisms such as a 1000-hour resource adequacy product.
- Technology developers. Guide R&D efforts to reduce technical risk and provide a range of technologies that may be suitable for seasonal energy storage.

In the short term over the next two to three years, cost and performance studies on selected seasonal energy storage technologies could be conducted. These studies are most valuable when done impartially to vet the claims by technology developers. Cost-benefits analysis could be conducted using capacity expansion models to select a diverse resource mix (including seasonal energy storage technologies if competitive). Modeling could be done to develop optimal dispatch strategies to maximize the revenue of seasonal energy storage resources.

Next, technologies could be demonstrated at increasing scale. Pilots could be built in the next few years (2023–2030). Later, (2030–2035) commercial demonstration projects could be built at utility sites to demonstrate real-world performance of emerging seasonal energy storage technologies. Finally, competitive procurement efforts could be launched to deploy a growing fleet of seasonal energy storage resources.



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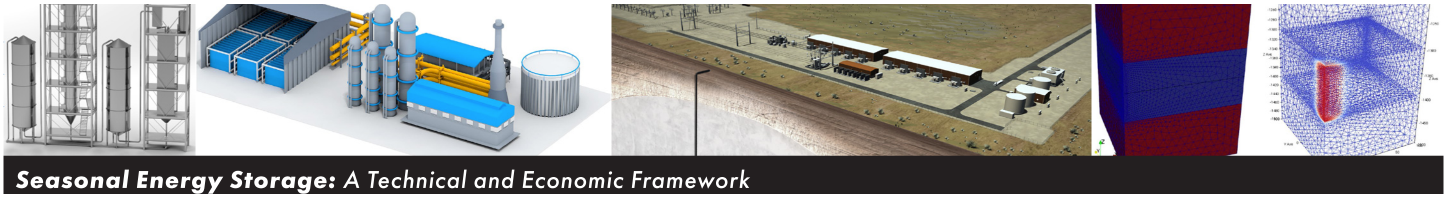

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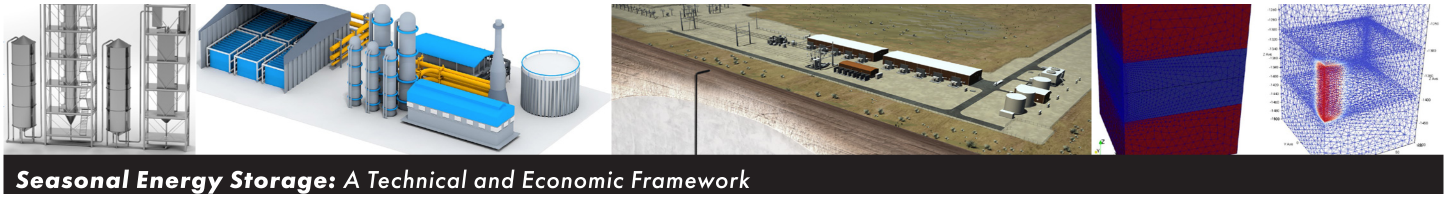

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