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Technology Strategy Assessment

Findings from Storage Innovations 2030
Compressed Air Energy Storage
July 2023

About Storage Innovations 2030

This technology strategy assessment on compressed air energy storage (CAES), released as part of the Long-Duration Storage Shot, contains the findings from the Storage Innovations (SI) 2030 strategic initiative. The objective of SI 2030 is to develop specific and quantifiable research, development, and deployment (RD&D) pathways to achieve the targets identified in the Long-Duration Storage Shot, which seeks to achieve 90% cost reductions for technologies that can provide 10 hours or longer of energy storage within the coming decade. Through SI 2030, the U.S. Department of Energy (DOE) is aiming to understand, analyze, and enable the innovations required to unlock the potential for long-duration applications in the following technologies:

- Lithium-ion Batteries
- Lead-acid Batteries
- Flow Batteries
- Zinc Batteries
- Sodium Batteries
- Pumped Storage Hydropower
- Compressed Air Energy Storage
- Thermal Energy Storage
- Supercapacitors
- Hydrogen Storage

The findings in this report primarily come from two pillars of SI 2030—the SI Framework and the SI Flight Paths. For more information about the methodologies of each pillar, please reference the SI 2030 Methodology Report, released alongside the ten technology reports.

You can read more about SI 2030 at https://www.energy.gov/oe/storage-innovations-2030.

Acknowledgments

DOE acknowledges all stakeholders who contributed to the SI 2030 industry input process. Further information about the stakeholders who participated in the SI Framework and SI Flight Paths activities can be found in Appendix A. The SI activities were coordinated by Benjamin Shrager (Office of Electricity, DOE) and the Flight Paths listening session for CAES was facilitated by Shabbir Ahmed (Argonne National Laboratory) and co-facilitated by Daniel Flowers (Lawrence Livermore National Laboratory). The authors also would like to thank Kate Faris, Whitney Bell, and others from ICF Next for their excellent organization of the SI Flight Paths sessions and other support they provided for the SI activities.

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Background

Compressed air energy storage (CAES) is one of the many energy storage options that can store electric energy in the form of potential energy (compressed air) and can be deployed near central power plants or distribution centers. In response to demand, the stored energy can be discharged by expanding the stored air with a turboexpander generator. An attractive feature of this technology is the relative simplicity of the process—a compressor is powered by available electricity to compress air (charging), which is then stored in a chamber until the energy is needed. During discharge, the compressed air is run through a turboexpander to generate electricity back to the grid.

The attributes of CAES that make it an attractive option include a wide range of energy storage capacity (from a few megawatts to several gigawatts), an environmentally friendly process (especially when no fossil fuel is used for combustion), long life and durability, low self-discharge (due to a loss of pressure and temperature), and the low cost of the energy stored. Some of the challenges of this technology include high upfront capital costs, the need for heat during the expansion step, lower round-trip efficiency (RTE), siting and permitting challenges, difficulty in identifying and preparing natural caverns for storage, low depth of discharge, and longer response times.

History

Compressed air has been used for mechanical processes around the world since 1870. Buenos Aires, Argentina, used air pulses to move clock arms every minute. Starting in 1896, Paris used compressed air to power homes and industry. Beginning in 1978 with the first utility-scale diabatic CAES project in Huntorf, Germany, CAES has been the subject of ongoing exploration and development for grid applications. The U.S. Department of Energy (DOE) has a history of supporting CAES development. In 2009, DOE awarded a $29.4 million grant for a 300-MW Pacific Gas and Electric Company installation that uses a saline porous rock formation in Kern County, CA. In 2010, DOE also supported the development of a 150-MW project in Watkins Glen, NY [1].

Current Commercial Usage

Current operational CAES plants include the following:

1. A utility-scale facility located in Huntorf, Germany, with a 321-MW plant and 532,000 m^3 of underground storage [2]
2. A 110-MW plant in McIntosh, AL, with 270,000 m^3 of underground storage [3], [4]
3. Hydrostor Inc.’s 2.2-MW/10-MWh adiabatic system in Ontario, Canada [1]
4. An adiabatic CAES 200-MW plant commissioned in Germany in 2013 [3]
5. A 60-MW/300-MWh facility located in Jiangsu, China [1]
6. A 2.5-MW/4-MWh compressed CO2 facility operating in Sardinia, Italy [1]
7. A 100-MW/400-MWh adiabatic CAES system located in Zhangjakou, China [1]

The longest running CAES systems in Huntorf and McIntosh can be classified as diabatic processes, and they use underground salt caverns to store the compressed air at pressures in the 4- to 7-bar range. Recent CAES deployments are pursuing advanced adiabatic and isothermal technologies.

The Process

The process of CAES involves compression, storage of high-pressure air, thermal energy management and exchange, and expansion. Compression generates heat, which optionally can be stored in a thermal energy storage (TES) medium, rejected, or used in other integrated applications, thereby improving the RTE of the process. During discharge, the air needs to be heated to compensate for the expansion cooling. This heat can come from TES (if available), with direct or indirect contact with the TES medium or by burning fuel. Figure 1 shows a schematic of the major elements of the process.

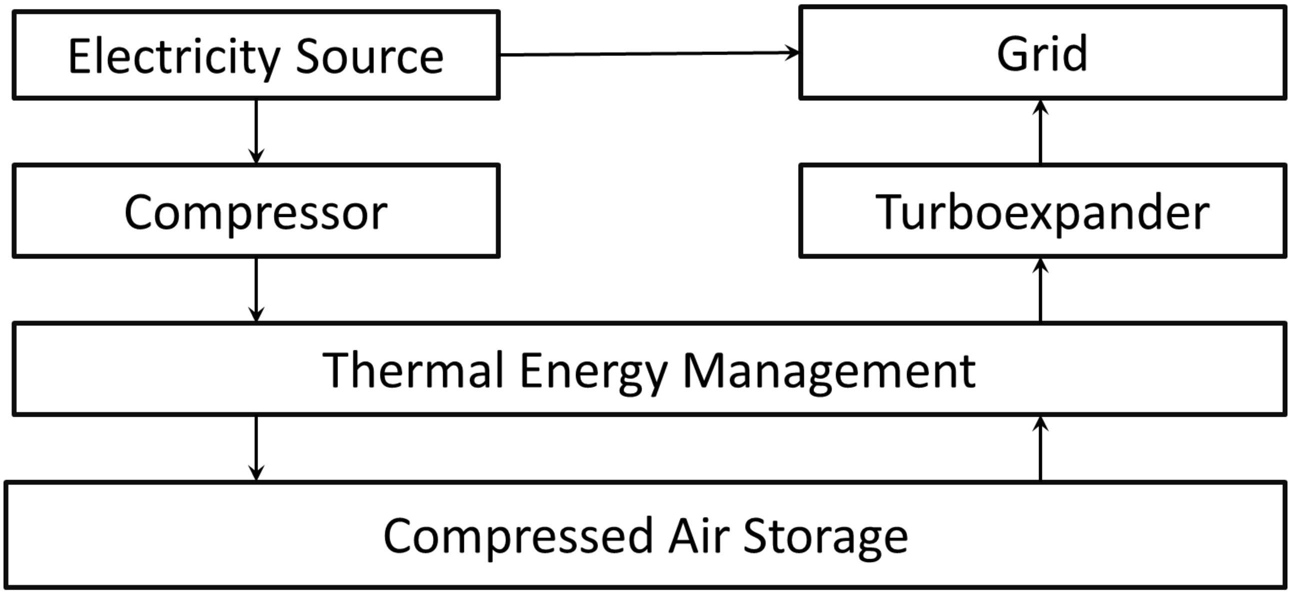

Figure 1. Simplified schematic of a CAES process

The management of thermal energy is a key element in the design of the process, each with its own merits and demerits. CAES processes can be classified as (1) diabatic, where the heat during compression is either rejected or recovered and fuel is burned during the expansion process, with an RTE of 46% to 54%; (2) adiabatic, where the heated and compressed air is either stored in the reservoir during charging and is available at discharge, with an RTE upper bound of 70%; or (3) isothermal, where the air is compressed, stored, and expanded at close to constant temperature. The temperature is controlled to a set temperature using electric heat. The isothermal process is thermodynamically more efficient, with the potential to reach 80% [3] with the various innovative processes being studied; however, many of these processes are still considered to be developmental. There are multiple variations of these processes, depending on the temperature and pressure, the use of TES, the type of reservoir, and other integration options.

Architectures

Figure 2 shows a simplified overview of the CAES classifications. Variations of the basic process (electricity to compression to storage to expansion to electricity) are the result of configurations that are designed to match the location. Depleted gas wells, salt mines, porous rocks, and caverns are well suited for CAES (80% of the United States may be geologically suited for CAES [3]). These available storage volumes can be either underground at a constant volume and variable pressure (isochoric) or in underwater tanks with a constant pressure and variable volume (isobaric). The storage volumes need to match the following:

- The scale of the application (e.g., individual factory, grid)
- Storage duration needs
- Power and energy needs
- The mode of thermal management
- The availability of fuel
- Other considerations

Ultimately, the plant must balance the needs of energy storage (megawatt-hours, MWH), power (megawatts, MW), initial and operating costs, and plant life. The last two factors, together with RTE, result in the cost per kilowatt-hour of stored energy.

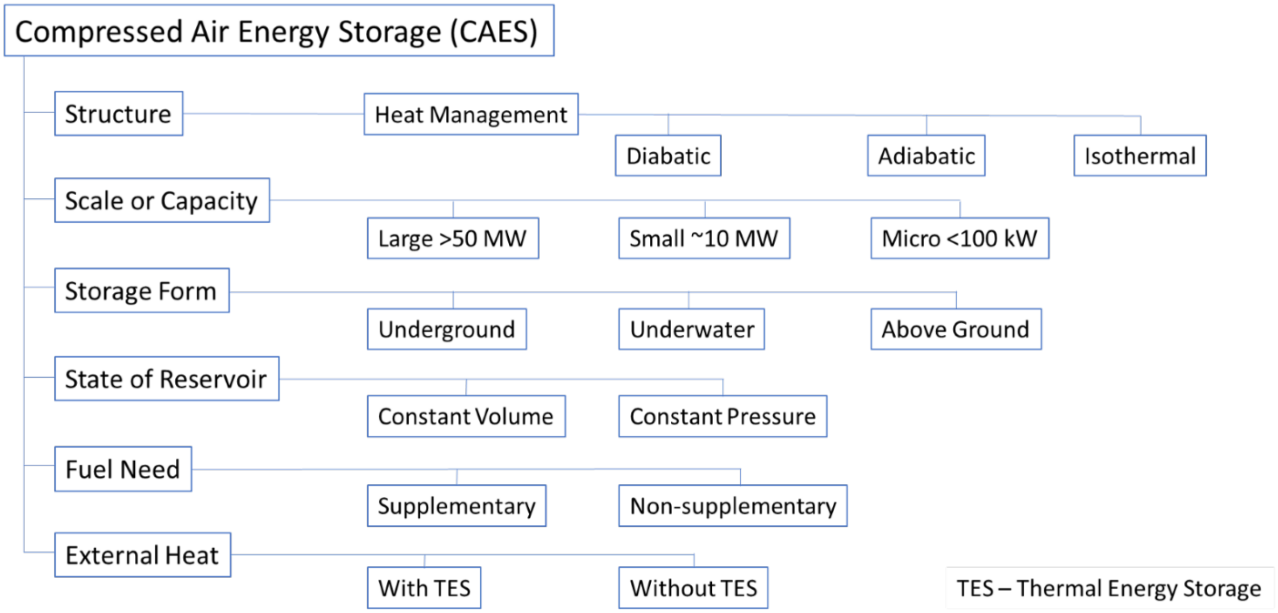

Figure 2. CAES systems classifications (adapted from [3])

Baseline Cost

A number of recent techno-economic studies have estimated CAES-based stored electricity costs at \$0.15 to \$0.60/kWh [5], [6].

The Framework Study identifies promising RD&D pathways to reduce the levelized cost of storage (LCOS) of key storage technologies. Step 1 of the Framework Study was to assess the RD&D trajectory status quo for a given technology or to project the performance and cost parameters out to 2030, given no marginal increase in industry investment over currently planned levels. These values, presented in Table 1, represent the baseline against which all future impacts are measured. The cost and performance values are derived exclusively from V. Viswanathan et al. (2022) [7], as defined for a 100-MW, 10-hour CAES system. There are no interim capital costs defined for this system, instead, high annual fixed operations and maintenance (O&M) costs are used as a proxy for all operations, maintenance, and system refurbishment costs over the economic life of the system. The 2030 LCOS estimate presented for CAES in V. Viswanathan et al. (2022) [7] is \$0.11/kWh; however, that estimate includes \$0.03/kWh in energy costs. The 2030 LCOS estimates presented in the next section exclude energy costs, except for those associated with losses, and are based on a slightly different LCOS methodology that results in a baseline LCOS of \$0.064/kWh. Note that references to \$/kW and \$/kWh are related to the power and energy capacities of the CAES system, respectively.

Table 1. CAES cost and performance (2030 estimates)

Parameter	Value	Description
CAES System Calendar Life	60	Deployment life (years)
Cycle Life	20,805	Base total number of cycles
RTE	52%	Base RTE
Turbine, Compressor, Balance of Plant, and Engineering, Procurement, and Construction (EPC)	1,153	Base Capital Costs for Compressor, Balance of Plant, and EPC (\$/kW)
Cavern Storage	6.84	Base cavern storage cost (\$/kWh)
O&M Costs	16.12	Base fixed O&M (\$/kW-year)

Pathways to \$0.05/kWh

Once the baseline costs for 2030 had been established, the Framework Team contacted industry representatives to identify individual innovation opportunities and assess the potential impacts of expanded RD&D investment. A group of subject matter experts (SMEs) were identified and individually contacted. These 23 SMEs, representing 15 organizations, primarily included vendors and technology developers (e.g., Apex Compressed Air Energy Storage, LLC; Siemens Energy, Inc.; Themes LLC) and universities (e.g., University of California at Los Angeles, University of Southern California, University of Minnesota). SMEs who contributed individual information to this report are acknowledged in Appendix A. The innovations defined by the SMEs are presented in Table 2. Definitions of each innovation are presented in Appendix B.

Table 2. Taxonomy of innovations

Innovation Category	Innovation
Supply chain	Supply Chain Analytics
Technology components	Mechanical Compression/Expansion

Innovation Category	Innovation
	Lower Temperature Turbines
	Compressed-Air and Hydrogen Energy Storage Systems
	Hydraulic Compression/Expansion
	Technologies for Subsurface Evaluation of Porous Rock for Storage
	Alternative Approaches to High-Temperature Thermal Storage
	Alternative Approaches to Storing Compressed Air
	Advanced Heat Exchanger Technologies
	Advanced Pressure Regulation Technologies
Manufacturing	Advanced Manufacturing Techniques
Advanced materials development	Advanced Alloys
	Novel Materials for Lining Wells for Storage
	Organic Phase Change Materials
	System Modeling and Design/Operation Optimization
Deployment	Demonstration Projects

Individual input from SMEs was used to define the investment requirements and timelines for investment, potential impacts on performance (e.g., RTE, cycle life), and the cost impacts of each innovation. The Monte Carlo simulation tool then combined each innovation with two to seven other innovations and, based on the range of impacts estimated by industry, the tool produced the distribution of achievable outcomes by 2030 with respect to LCOS (Figure 3). The LCOS range with the highest concentration of simulated outcomes is in the $0.03 to $0.04/kWh range. However, some portfolios reduce LCOS further, with the highest impact portfolios (the top 10%), which are indicated on the figure by the marked region, resulting in LCOS between $0.021 and $0.030/kWh.

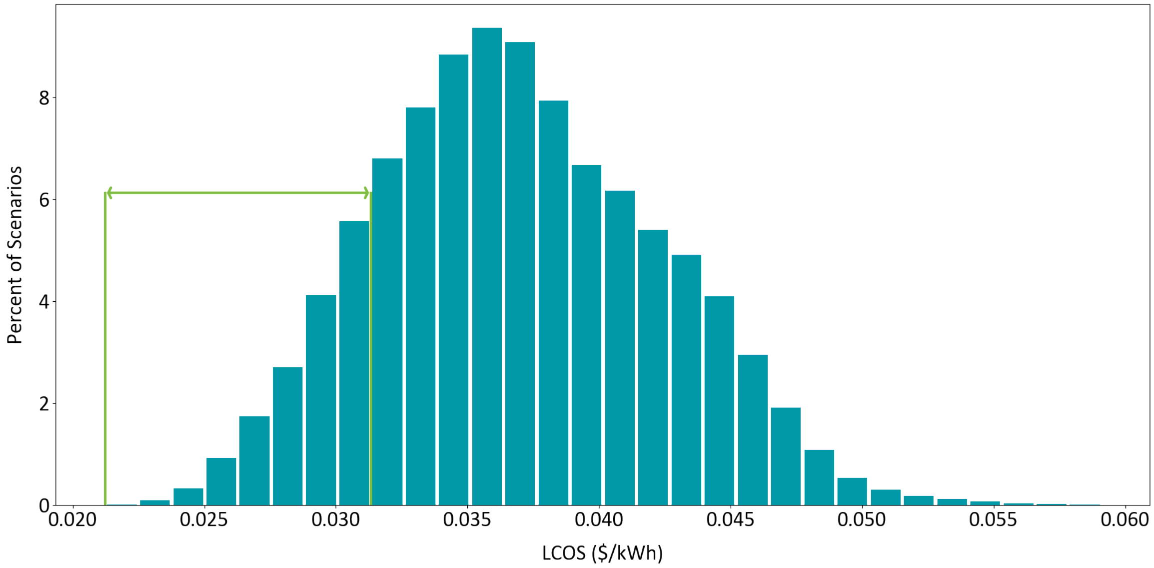

Figure 3. Portfolio frequency distribution across LCOS

The results of the Monte Carlo simulation for the thousands of portfolios that fall within the top 10% in terms of LCOS impact are presented in Figure 4. The scatter plot of portfolio values demonstrates that the top 10% of the portfolios reach their lowest level at roughly $0.021/kWh LCOS. The vertical line demonstrates that the mean portfolio cost is $745 million, which represents the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements. Total industry expenditure levels with the highest portfolio densities in the top 10% are in the $600 million to $900 million range. With that noted, there is an unusual pattern that emerges, driven by the costs of the different innovations. There is a small subset of portfolios that achieve deeply discounted LCOS levels without requiring investment in some of the higher cost innovations, such as demonstration projects and technologies for subsurface evaluation of porous rock for storage. The timeline required to achieve the top 10% LCOS levels is estimated at 5 to 10 years.

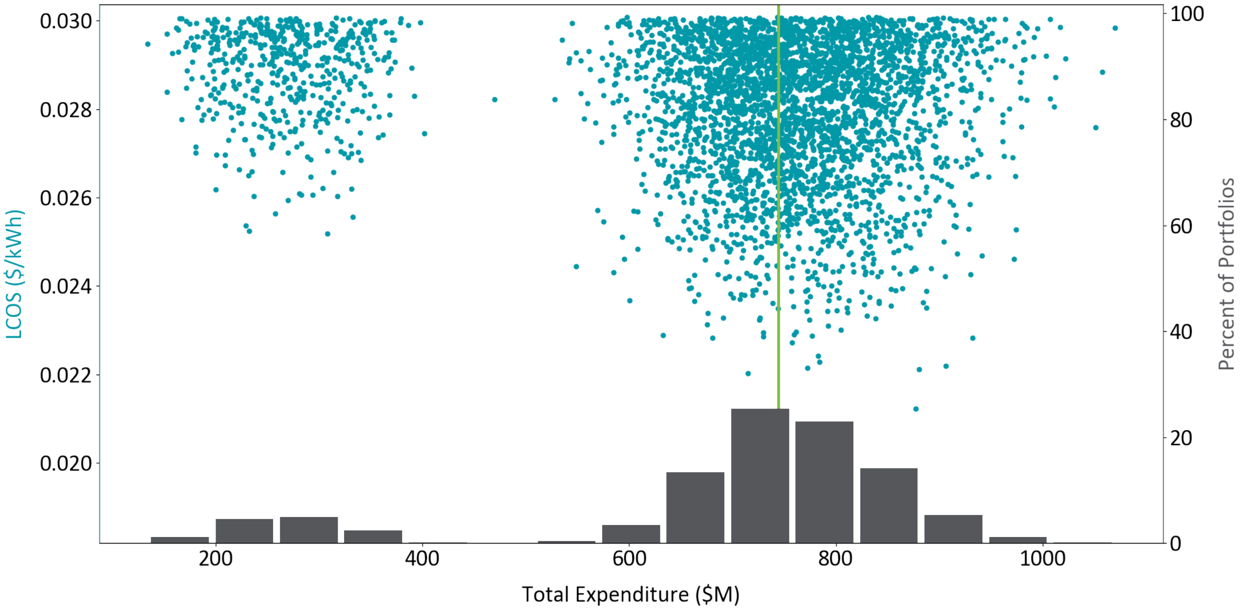

Figure 4. LCOS and estimated industry expenditures required for the top 10% of the portfolios

Note that the impact of each layered innovation is not additive. To account for this, the Monte Carlo model uses innovation coefficient matrices, which assign a value between 0 and 1 for each pair of innovations. These innovation coefficients indicate what fraction of savings potential for each innovation is independent of the other one. This way, a value of 1.0 represents two entirely independent innovations, where cost savings will stack linearly, and a value of 0.0 represents two entirely overlapping innovations, where only the more impactful innovation will have an effect on LCOS. Working with SMEs, the research teams established innovation coefficients that are used to measure the combined impact of multiple innovations.[a] Innovation coefficients for each innovation pairing are presented in Appendix C.

SMEs also were asked for their preferences regarding the investment mechanism for any intervention, selecting among National Laboratory research, research and development (R&D) grants, loans, and technical assistance. Table 3 presents the SME preferences for each mechanism. Cells with asterisks (*) represent the preferred mechanism. CAES SMEs overwhelmingly supported R&D grants as the preferred mechanism. National Laboratory research, typically with collaboration

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[a] To demonstrate how innovation coefficients work, the innovation coefficient for the combined investment in mechanical compression/expansion and hydraulic compression/expansion is 0, which means that the Monte Carlo simulation tool would not attribute any additional impact to the second innovation when added to the first. The reason is that investments in both technologies would not be additive or build on each other and would not benefit the same CAES system. The model would select the greatest impact between the two innovations and not consider both. The innovation coefficient for mechanical compression and system modeling and design/operation optimization is 1.0, meaning that both impacts would be fully realized because they could benefit the same CAES system and would not, in some way, cancel each other out.

by universities and industry, was favored for efforts involving modeling or basic research (e.g., supply chain analytics, alternative approaches to high-temperature thermal storage, advanced alloys). Loans were selected for some innovations involving industrial processes and demonstration projects that would require significant industry investment.

Table 3. SME preferences for investment mechanisms. (Technical Assistance includes advice or guidance on issues or goals, tools and maps, and training provided by government agencies or National Laboratories to support industry.)

Innovation	National Laboratory Research	R&D Grants	Loans	Technical Assistance
Supply Chain Analytics	80.0% *	0.0%	0.0%	20.0%
Mechanical Compression/Expansion	35.7%	50.0% *	7.1%	7.1%
Lower Temperature Turbines	12.5%	50.0% *	25.0%	12.5%
Compressed Air and Hydrogen Energy Storage Systems	12.5%	62.5% *	12.5%	12.5%
Hydraulic Compression/Expansion	28.6%	71.4% *	0.0%	0.0%
Technologies for Subsurface Evaluation of Porous Rock for Storage	33.3%	44.4% *	11.1%	11.1%
Alternative Approaches to High-Temperature Thermal Storage	44.4% *	44.4% *	0.0%	11.1%
Alternative Approaches to Storing Compressed Air	30.8%	46.2% *	7.7%	15.4%
Advanced Heat Exchanger Technologies	36.4%	45.5% *	18.2%	0.0%
Advanced Pressure Regulation Technologies	42.9%	57.1% *	0.0%	0.0%
Advanced Manufacturing Techniques	33.3% *	33.3% *	16.7%	16.7%
Advanced Alloys	50.0% *	37.5%	12.5%	0.0%
Novel Materials for Lining Wells for Storage	22.2%	33.3% *	33.3% *	11.1%
Organic Phase Change Materials	50.0% *	50.0% *	0.0%	0.0%
System Modeling and Design/Operation Optimization	33.3%	41.7% *	8.3%	16.7%
Demonstration Projects	14.3%	38.1% *	33.3%	14.3%

The share of innovations in the top 10% of the portfolios are presented in Figure 5. As discussed in the next section of this report and illustrated in Figure 4, the portfolios appear to fall into two tranches of investment levels, with a smaller share focused exclusively on mid- to high-impact innovations with lower investment requirements (e.g., system modeling and design/operation optimization, low-temperature turbines) and a large share achieving the deep discounts with some of the highest cost innovations, which would require significant industry engagement and collaboration, including demonstration projects and advanced manufacturing.

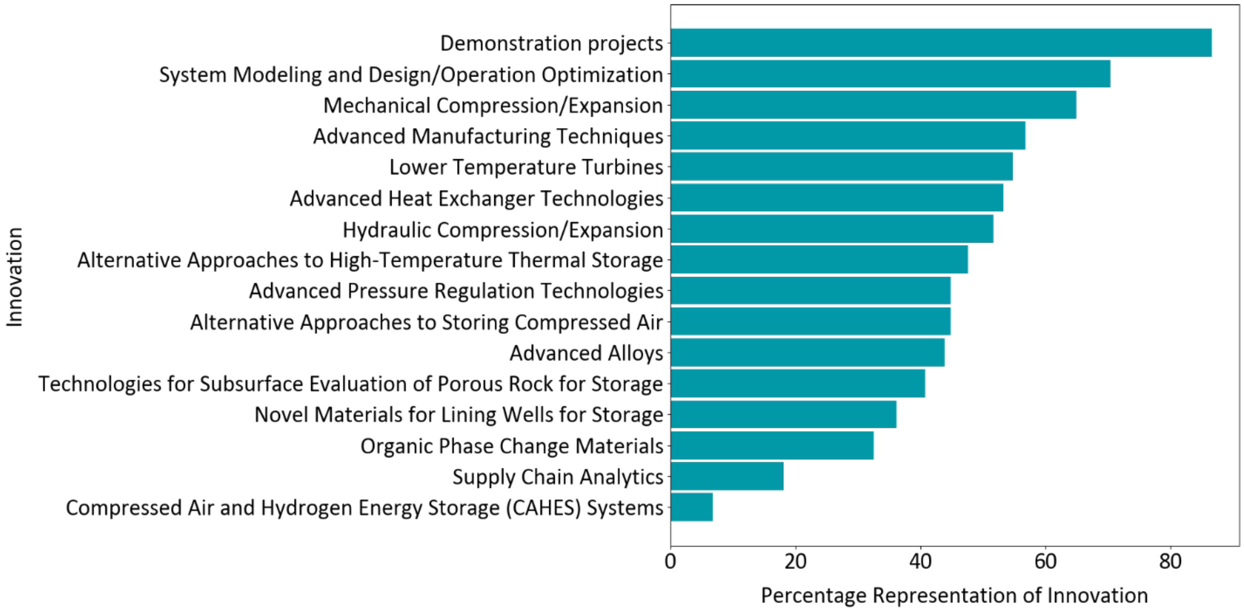

Figure 5. Innovation representation in the top 10% of the portfolios

Pre-Competitive R&D Opportunities

This section discusses the key challenges facing large-scale CAES adoption and explores how and what types of pre-competitive RD&D can further elevate the prospects of CAES, both technically and economically. Some key technical barriers with this technology include lower system efficiency, inconsistent benchmarking, and the characterization of available resources for compressed air storage. Following the discussion of the key challenges and RD&D opportunities, this section includes an evaluation of the RD&D pathways defined through industry contacts under the Framework Study.

Analytics

As an energy storage application, the first technical goal is to ensure energy conservation and high efficiency. That is, the goal is to have the energy that is discharged as electricity, after the storage interval, be as close to the total energy (electricity or in other forms, such as fuels) that entered the CAES plant. Other analytical efforts are designed to improve other performance metrics, including response times and energy densities, and reduce costs through enhanced siting, storage, availability of needed materials and components, and other key elements. Any process development or assessment of a technology has to begin with an understanding of, and agreement on, the metrics.

Round-Trip Efficiency

RTE is one of those quintessential metrics and is usually defined as the output electrical energy discharged after storage as a percentage of the incoming energy (electricity and any energy via fuel combustion). For grid storage, the important product or output is discharged electricity. The input or denominator in the definition of RTE should include all incoming energy forms that enter the plant (system) boundary, even if it is available at no cost.

The theoretical upper limit of RTE for CAES is defined by thermodynamics, while what is achievable is determined from the combination of each of the individual steps. For example, if the compressor and expander each operate at an efficiency of 80%, then the process efficiency cannot be greater than 64% (80% x 80%).

During discharge or compressed-air expansion, CAES systems choose various options to heat the air, such as the combustion of natural gas, hydrogen, electric heating with power from on-site, or nearby renewables. Per the definition of efficiency, their energy content should be included in the accounting of input energy.

The industrial participants at the Flight Paths listening session indicated that there is broad variability in their estimates of RTE, with some values exceeding the apparent thermodynamic limits. This underscores the importance of using a standardized RTE definition and is necessary for developers, investors, and analysts to have a clearer idea of the value of a proposed system and how it compares with competing storage technologies.

Product Cost

The cost of the product (i.e., the cost of electricity discharged through the plant gate) is calculated from the cost of the investment (capital expenditures) and operations (operating expenditures). Achieving high energy conservation (i.e., high RTE for a given plant cost) will invariably result in favorable values of the cost metrics that are normalized with respect to the power or energy sold, such as LCOS. Pre-competitive, collaborative R&D should begin with agreement on the definition of RTE and other relevant metrics and should be a priority for all energy storage options.

SMEs participating in the Framework Study defined several opportunities to reduce product costs through the use of advanced analytics:

- Enhance system modeling and design optimization through the use of artificial intelligence/machine learning to study digital twins in simulated economic operations, using the findings as a feedback loop to system design.
- Develop standardized testing and measurement procedures, perhaps through the development of an industry standard protocol to create consistent performance measurement, including RTE.
- Design management and control systems for optimally siting CAES and integrating/managing multiple CAES systems located in a single region or balancing area.
- Reduce risk in the supply of critical long-duration energy storage CAES systems (e.g., rotating equipment, thermal energy storage materials).

The impacts of these analytical activities on CAES cost and performance are explored later in this section.

Other advanced analytical approaches, including the development of digital twins for predictive maintenance, could be used to predict the need for repairs to reduce downtime and the associated costs.

Techno-Economic Analysis

Potential developers, investors, and energy analysts seek information about the value of a project. Such information is generated with techno-economic analysis of a concept where the process is defined, the components are sized, the performance (e.g., energy, power, load response, efficiency, storage duration, greenhouse gas emissions) is rated, and cost metrics (e.g., capital cost, operating cost, LCOS, levelized cost of energy) are calculated. A model representing a CAES process can identify the limiting step (e.g., energy efficiency, capital cost, labor, response time) and follow that with RD&D investments to mitigate or improve that performance metric with new materials, operating conditions, or devices. An analytical approach with techno-economic analysis complements concept development and subsequent scale-up. Such analysis can help (1) set achievable targets; (2) identify bottlenecks that limit the performance and cost and guide RD&D priorities; (3) assess the cost versus benefit of alternative options in the process; (4) size components to match market availability and options for modular designs; and (5) identify favorable operating domains by balancing power, energy, and competitive advantage with respect to alternative storage options. These analyses can serve as valuable tools in size (capacity) versus cost discussions between a developer and component (e.g., compressor, turbine) suppliers.

Balancing Power and Energy

Higher power (in megawatts) charge and discharge rates require large compressors and expanders. The volumetric capacity of these units is correlated to the square of the cylinder diameter. Large turbines are available with capacities of hundreds of megawatts [8], with fan diameters of 3 meters or more [9]. While large units are cost-effective, the size and number of each functional component need to be matched to avoid operating at loads far from the design loads, while allowing redundancy for maintenance downtime. Energy storage capacity (in megawatt-hours), on the other hand, is determined by the amount of air (and thermal energy) that can be stored. Higher pressure and volume (and temperature of the TES media) equate to more energy storage capacity. A high energy-to-power ratio enables longer charge and discharge periods. The incremental cost of a larger underground reservoir, therefore, is lower than that of multiple storage tanks.

Technology Components

This section reviews the broad areas that can support key technology areas, such as compressed-air storage volume, thermal energy storage and management strategies, and integration of the process steps with on-site and nearby energy providers and consumers.

Characterization of Storage Resources

Underground reservoirs (abandoned mines, oil or gas fields, aquifers, and caverns) may enable very large volumes of storage. Their value depends on their proximity to power sources, their suitability,[b] their acquisition cost, and the permitting time needed. Repurposed idle pipeline networks represent another great resource for CAES systems. Leveraging these storage volumes can potentially save significant capital costs and enable the commercial success of such ventures. Developing a database of such resources and their characteristics (e.g., location, volume, porosity, permeability [10]) will be invaluable to CAES developers seeking to match their preferred locations with reservoirs (terrestrial or underwater coastal) nearby.

Framework Study SMEs also identified technologies for subsurface evaluation of porous rock for storage as an important innovation. Multiple innovations are required for evaluating the viability of subsurface rock for air storage, including geophysical density measurements for accurate assessment of storage capacity; rapid pressure testing technologies for confirming reservoir deliverability; rapid, low-cost tubular lining for storage; effective isolation technologies to isolate hydrocarbon layers from aquifer layers; monitoring and surveillance technologies to confirm well integrity and ensure the elimination of fugitive emissions; and workflows for rapidly assessing the feasibility of idle oil and gas well sites for storage.

Aboveground storage with tanks requires a footprint with real estate implications. Some footprint requirements can be mitigated with vertical tanks with high length-to-diameter (L/D) ratios. A high L/D allows thinner walls for a given pressure rating. Applications that have adopted idled natural gas

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[b] The DOE National Energy Technology Laboratory recommends > 10% porosity, > 500 mD [10].

pipelines for CAES storage take advantage of the high L/D and pre-permitted access and use. Repurposed pipelines can greatly reduce the capital cost of a plant.

Thermal Energy Storage

A key need for CAES systems is to integrate the thermal energy between the compression and the expansion steps. Because the charge and discharge are asynchronous, an efficient heat exchange system and a thermal energy storage medium are both needed. Options for the latter range from selecting the medium (sensible heat in liquids or solids, phase change material), which, in turn, is guided by, for example, the temperature range of the medium, the option of using and selecting a heat exchange fluid, containment of the medium and its energy loss rate, and so on. A comprehensive study of these options and their tradeoffs can help developers select the most appropriate combination for the needs and constraints of a given plant. SMEs participating in the Framework Study also called for the development of alternative approaches to high-temperature thermal storage. Other innovations include the design of low-cost thermal storage techniques (e.g., concrete, molten silicon, alumina spheres) that provide high capacity at a minimum cost and improved water-based storage with insulated tanks that enable longer duration heat storage.

Process Integration

Chemical plants increase the utilization of their resources by integrating multiple units and processes. Adiabatic and isothermal CAES systems attempt to store and exchange thermal energy between charge and discharge. A significant fraction of that energy cannot be recouped economically due to low temperature (or quality) and has to be wasted. Depending on the temperature, this energy can potentially be used to generate steam, hot water, or space heating for the CAES facilities or nearby buildings and processes. Similarly, the air at the turbine exit is at sufficient pressure that it may be useable in other low-pressure applications in nearby facilities (e.g., a compressed-air network in the plant or nearby industry, forges, and furnaces). Reducing waste energy can improve the efficiency of the process and reduce plant operating costs. Yet another example is to continue to use compressors to support a carbon dioxide capture plant. Carbon dioxide can be a potential working fluid in a closed-loop CAES-like system, with coupling to carbon capture and supercritical carbon dioxide power conversion. Analysis and integration of the waste streams and idled equipment with on-site or nearby applications will help make a stronger case for their commercial success.

Advanced Materials Development

Energy Density

Depending on the type of process, the energy density of CAES systems can range from 3 to 24 kWh/m^3. The energy density of CAES systems exceed pumped storage hydropower densities of 0.5 to 1.5 kWh/m^3, is lower than vanadium redox flow battery densities of 10 to 70 kWh/m^3, and is much lower than lithium-ion systems, which register energy densities ranging from 150 to 500 kWh/m^3 [11]. The largest component in such systems is the storage medium for the compressed air. This means that higher pressure storage enables reduced volume and higher energy density. Identifying underground reservoirs (e.g., with color-coded maps) and their temperature-pressure capacity, along with feasibility strategies to increase their tolerance, will help increase the energy density. The most common rock cavern lining method being explored consists of an inner steel shell and an outer reinforced concrete shell. With the goal of enhancing energy density while avoiding leakage, failure, or loss of tightness of the sealing membrane, new methods (e.g., shallow lined rock cavern tunnels or concrete liners with a fiber-reinforced plastic sealing layer) have been demonstrated and tested in pilot projects or investigated with computational models [12], [13]. For aboveground storage, larger single enclosures with larger surface areas require stronger or thicker walls. Choosing materials with high tensile strength and tolerance to pressure cycles is an area for tradeoff studies between cost and containment volume. If applications are constrained with regard to footprint rather than volume, one option is to array the vertical cylinders. A systematic study to review these and other strategies with regard to tradeoff scenarios can lead to improved energy density [14].

Durable Materials

The major components—the compressor, expander, heat exchangers, thermal energy storage medium, and storage containers—experience cycles of temperature and pressure. The combination of pressure and temperature causes fatigue and cycling processes accelerate their failure and replacement. The development of novel materials and operational strategies (e.g., temperature control, reducing pressure swings using containers rated for different pressures) may be able to extend their durability. Such research would benefit other applications that rely on these components (e.g., jet engines, power plants). Other materials-related innovations defined in the Framework Study included advanced alloys designed to be more cost-effective, more corrosion-resistant, and more capable of bearing high pressures and the development of organic phase change materials that can be tailored to the temperature range for heat transfer in a CAES system.

Deployment

Demonstration Plants

Research, development, demonstration, and deployment are necessary steps for CAES, or any new technology, to mature. While CAES systems may be set up with major components available “off the shelf,” revisions based on new options and experience in order to fine-tune the process design lead to performance improvements, while the demand for similar components energizes the supply side and leads to cost reduction. Framework Study SMEs stressed the importance of demonstration projects incorporating novel CAES strategies, including novel system types (e.g., isothermal, adiabatic) and approaches to storage (e.g., pipeline storage, storage in drained saline aquifers, storage in underwater pressure vessels). Analytic support could be supplied by National Laboratories to determine RTE under various use cases and to conduct techno-economic studies, lifecycle cost studies, and valuation assessments.

Co-Location

The location of CAES plants seeks to balance demand, opportunity, and cost. Ideally, a CAES plant will be located close to (1) a power generation facility (limited transmission losses, establishing a mutually beneficial relationship); (2) a geologically suitable reservoir (avoiding the construction and maintenance of storage tanks and reducing footprint requirements); (3) a reservoir for storage of the thermal energy; (4) facilities or buildings that have a demand for steam, hot water, hot air, or pressurized air; and (5) a community with the needed workforce. A pre-competitive study to identify areas where several of these combinations are available may facilitate the greater development of CAES.

Standardization

In general, fewer larger components benefit from economies of scale, which enables a reduction in the unitized cost of supporting subcomponents. Current generations of compressors, turbines, pressure vessels, and other components are sized based on the demands of other applications (e.g., gas turbine plants, jet engines). Today, there appears to be CAES systems that range from early Technology Readiness Level to operational plants. With each successful venture, repetitions may follow but on different scales. Pre-competitive agreements to standardize key component sizing may help suppliers design and build plants in larger numbers so that plants of different scales can set up and expand capacity. This will help the component manufacturers increase their production volume and reduce their costs, while CAES plants can expand their capacities in modular steps. Advanced manufacturing techniques that include automation, waste reduction, and the integration of best practices from existing manufacturing modalities could yield significant cost reductions according to the SMEs interviewed for the Framework Study, as could more flexible robotic welding in the manufacturing of pressure vessels and pipes.

Component Sizing

The component market offers compressors, expanders, turbines, heat exchangers, and gas storage volumes of different capacities. A given plant needs to balance the speeds of rotating equipment and optimize their sizing for cost. Speed reducers often are used to balance the rotation speeds of turbines and synchronous generators [15]. If multiple plants can use hardware coordinated for specific capacities, their cost can be reduced through mass production.

Regulatory and Fiscal Policies

CAES system development requires extensive permitting from various government agencies. The permitting process invariably takes time and adds uncertainty. Industrial proponents of CAES have identified this process as a significant challenge. Policies laying out the ground rules for energy storage applications and their permitting process can reduce the lead time and reduce the cost of these plants and their product, which is stored and discharged electric energy. For example, the state of Kansas has facilitated these processes with their Compressed Air Energy Storage Act [16], effective since 2009. A study that reports on promising locations, permitting processes and challenges, and mitigating solutions would help developers navigate these issues during the planning phase.

The Impact of Investment in CAES

The Framework Study identified several high-impact RD&D pathways, many of which have already been discussed in this section. The impacts on investments in specific technologies, as defined based on SME input, are presented in Table 4. Some technologies presented in Table 4 (e.g., compressed air and hydrogen energy storage systems, lower temperature turbines) have upside potential; however, significant RD&D investment would be required to realize the cost reductions estimated by the industry. There also are several innovations that would have a moderate impact at fairly low investment levels, including system modeling and design/operation optimization, supply chain analytics, and advanced heat exchanger technologies.

Investments

CAES is dissimilar to other energy storage technologies, although it does share a feature with pumped storage hydropower: it comprises a series of subsystems, which include mature technologies, such as compressors, expanders, turbines, and heat exchangers. Therefore, no single investment would be expected to drive large cost reductions; this is evident in Table 4, with no single investment expected to reduce capital costs by more than 18% by 2030. CAES represents a very small market for many of the technologies that it requires, including heat exchanges, turbines, and compressors. Therefore, the incentive for industry to address these technological shortcomings is lower than for other energy storage technologies. CAES also consists of multiple technologies (e.g., diabatic, adiabatic, isothermal) and some innovations are exclusive to a single technology, thus dampening the combined effects.

Table 4. The impacts of proposed R&D investment levels, mean investment levels, and timelines

Innovation	Turbine, Compressor, EPC, and Cavern Storage (%)	Cycle Life Improvement (%)	Round-trip Efficiency Impact (%)	Mean Investment Requirement (in million $)	Mean Timeline (years)
Supply Chain Analytics	-7.7%	6.0%	3.0%	1.8	1.6
Mechanical Compression/ Expansion	-17.7%	26.7%	5.8%	23.9	4.0
Lower Temperature Turbines	-13.0%	5.0%	6.5%	25.5	4.0
Compressed Air and Hydrogen Energy Storage Systems	-16.9%	13.3%	10.0%	76.1	5.2
Hydraulic Compression/Expansion	-4.7%	9.0%	15.0%	31.8	4.0
Technologies for Subsurface Evaluation of Porous Rock for Storage	-6.2%	5.0%	0.0%	41.8	3.3
Alternative Approaches to High-Temperature Thermal Storage	-5.1%	0.0%	7.7%	24.1	4.8
Alternative Approaches to Storing Compressed Air	-5.4%	5.0%	2.5%	52.7	4.3
Advanced Heat Exchanger Technologies	-9.7%	13.5%	5.8%	18.4	3.9
Advanced Pressure Regulation Technologies	-7.1%	5.0%	3.5%	14.0	4.3
Advanced Manufacturing Techniques	-15.7%	12.5%	0.0%	12.3	3.4
Advanced Alloys	-1.9%	13.3%	3.5%	26.2	3.0
Novel Materials for Lining Wells for Storage	-1.3%	33.3%	1.3%	21.2	3.2
Organic Phase Change Materials	0.0%	0.0%	3.5%	8.2	3.8
System Modeling and Design/ Operation Optimization	-7.5%	6.7%	9.2%	6.9	2.8
Demonstration Projects	-13.1%	8.3%	8.5%	252.0	4.7

The recommended investment level and timeline for each innovation also are identified in Table 4. Most investment levels are in the $10 million to $30 million range and require investments over 3 to 5 years. Compressed air and hydrogen energy storage systems and demonstration projects require significant investments and industry collaboration. Advanced manufacturing techniques may be required to further reduce costs and, while demonstration projects represent a significant opportunity for cost reduction and may be required to field-test and validate many of the other innovations, the cost of doing so could be significant.

Additional Opportunities and Discussion

This section explores several additional opportunities for reducing costs, improving performance, and enhancing the prospects for successful deployment through collaboration among industry, policymakers, and local communities and by integration with renewable energy generation plants.

Reservoir Suitability

The presence of flammable gases in underground caverns poses the risk of explosion. The presence of other gases that might require emissions management imposes additional costs. Non-reservoir-based options also are being considered by industry, including using underground pipelines or aboveground pressure vessels for energy storage.

Successful Demonstrations

Demonstrations of viability, such as the ability to generate revenue, or a history of safe operations will help increase buy-in from the community and investors.

Community Development

Recognizable community benefits, such as engagement with residents, the growth of support services, schools, and hospitals, will help establish how energy storage can complement and enhance societal benefits. Environmental justice areas can benefit from these energy storage initiatives, especially if these energy storage facilities can fill in for job losses because of discontinued coal mines and power plants. CAES systems also can help support off-grid/remote communities where access to electricity is limited. The White House Environmental Justice Advisory Council has issued draft recommendations to “develop onsite solar, storage and other renewable energy and energy efficiency projects” [17].

Workforce

The workforce necessary for operating CAES plants is not considered to be a critical need today. However, skilled personnel and managers are likely to be attracted to locations with good infrastructure and facilities. Sustainable CAES plants will require a workforce, an energy source (power plant), and a demand source (other industry or villages and cities). The plant location has to match all of these, along with myriad other considerations.

Investment Incentives

Several states have set targets (e.g., California, Massachusetts, Nevada, New Jersey, New York, Oregon) for energy storage capacities, while others (e.g., California, Massachusetts, New York) have offered incentives for energy storage programs [16]. Kansas has a CAES Act (Kansas HB 2369), which became effective in 2009 [18], [19].

System Cost

CAES systems are relatively easy to set up given that the manufacturing of most of the hardware components is quite mature. However, these systems are most profitable in large capacities, which require significant capital investment. System construction costs led to the suspension of a 270-MW CAES project in Ohio in 2013 [15].

Cheaper construction materials and mass-produced components can greatly lower the capital requirement. The constraint in materials development or selection is the required durability through the combination of high temperature and pressure and the stress of cyclical operations. With increasing deployment and standardization of some components, the cost can be brought down through mass production.

Long-Term Contracts

CAES systems require significant capital and personnel investment at start-up; however, these systems can be operated over decades, which is much longer than typical lifetimes of electrochemical storage systems. Long-term contracts with power generators and power purchase agreements that account for the very long operational lifetime of CAES would facilitate the prospects for investment. Feedback from industry participants in the Flight Paths listening session identified the importance of long-term power purchase agreements and government policies to assure investors and insurance companies that CAES systems are viable, have manageable risks, and are well suited for long-term financing.

Appendix A: Industry Contributors

Table A.1. List of SMEs contributing to the Framework analysis

Participant	Institution
Donald Paul	University of Southern California
Iraj Ershaghi	University of Southern California
Ramachandra Shenoy	Themes LLC
Ashok Krishna	Themes LLC
Ben Hoffman	Themes LLC
Masood Parvania	University of Utah
Joe Spease	WindSoHy, LLC
John Yan	Talos Industries
Chris Connors	Breeze Inc.
Deni Wiart	Breeze Inc.
Michael Orsha	Breeze Inc.
Robert Bailie	Siemens Energy, Inc.
Jason Kerth	Siemens Energy, Inc.
Jack Farley	Apex Compressed Air Energy Storage, LLC
Stephen Naeve	Apex Compressed Air Energy Storage, LLC
Tri Luu	Hydrostor Inc.
Andrew McGillis	Hydrostor Inc.
Mark Howitt	Storelectric Limited
Seamus Garvey	Nottingham University
Eric Loth	University of Virginia
Pirouz Kahvepour	University of California at Los Angeles
Perry Li	University of Minnesota
Benjamin Bollinger	Malta, Inc.

Appendix B: Innovation Matrix and Definitions

Table B.1. List of innovations by innovation category. Some innovations apply to cavern storage and tank storage; however, some only apply to tank storage.

Innovation Category	Innovation
Supply chain	Supply Chain Analytics
Technology components	Mechanical Compression/Expansion
	Lower Temperature Turbines
	Compressed-Air and Hydrogen Energy Storage Systems
	Hydraulic Compression/Expansion
	Technologies for Subsurface Evaluation of Porous Rock for Storage
	Alternative Approaches to High-Temperature Thermal Storage
	Alternative Approaches to Storing Compressed Air
	Advanced Heat Exchanger Technologies
	Advanced Pressure Regulation Technologies
Manufacturing	Advanced Manufacturing Techniques
Advanced materials development	Advanced Alloys
	Novel Materials for Lining Wells for Storage
	Organic Phase Change Materials
Deployment	System Modeling and Design/Operation Optimization
	Demonstration Projects

Supply chain analytics: Reduce risk in the supply of critical long-duration energy storage CAES systems (e.g., rotating equipment, thermal energy storage materials).

Mechanical Compression/Expansion: Advance technology for compressors, expanders, and reciprocating mechanical pistons with high efficiency and heat tolerance.

Lower Temperature Turbines: Develop turbines that operate at a lower temperature to minimize reheating of air prior to expansion in the turbine to power a generator or to supplement energy output following the high-temperature turbine stage.

Compressed Air and Hydrogen Energy Storage (CAHES) Systems: Invest in the components (e.g., hydrogen generator; hydrogen and oxygen compressors; air, hydrogen, oxygen, and water tanks; exhaust and air expanders; all heat exchangers and CO_2 compressors and pumps) and systems required to support CAHES development.

Hydraulic Compression/Expansion: Develop liquid piston-based isothermal CAES, including (1) fast-acting valves (large air and water valves required at scale that need to withstand wear and tear with opening and closing frequently in short cycles, (2) pumps as turbines (reversible hydraulic pumps that can act as turbines to reduce the capital expenditures), (3) hydraulic turbines with variable liquid pressures (novel hydraulic turbines that can operate at high efficiency when facing falling heads by allowing nozzles to increase flow as pressures fall), and (4) valve seats (materials that will reduce wear and tear in fast-acting valves).

Technologies for Subsurface Evaluation of Porous Rock for Storage: Address the multiple innovations required for evaluating the viability of subsurface rock for air storage, including geophysical density measurements for accurate assessment of storage capacity; rapid pressure testing technologies for confirming reservoir deliverability; rapid, low-cost tubular lining for storage; effective isolation technologies to isolate hydrocarbon layers from aquifer layers; monitoring and surveillance technologies to confirm well integrity; ensuring the elimination of fugitive emissions; and workflows for rapidly assessing the feasibility of idle oil and gas well sites for storage.

Alternative Approaches to High-Temperature Thermal Storage: Design low-cost thermal storage techniques (e.g., concrete, molten silicon, alumina spheres) that provide high capacity at a minimum cost and improved water-based storage with insulated tanks that enable longer duration heat storage.

Alternative Approaches to Storing Compressed Air: Conduct research into expanding storage media beyond domal salt, including abandoned pipelines, drained saline aquifers, underwater pressure vessels, and aboveground tanks.

Advanced Heat Exchanger Technologies: Develop advanced heat exchanger technologies for managing pressure drops and improving the efficiency of heat exchange.

Advanced Pressure Regulation Technologies: Conduct component design improvements (e.g., turbines and valves that can work with variable pressure) to minimize losses due to pressure regulation.

Advanced Manufacturing: Implement automation, waste reduction approaches, and adapt existing infrastructure integration of best practices from existing manufacturing modalities. Develop more flexible robotic welding in the manufacturing of pressure vessels and pipes.

Advanced Alloys: Develop more cost-effective and corrosion-resistant alloys capable of bearing high pressures.

Novel Materials for Lining Wells for Storage: Lower cost, corrosion-resistant materials for well liners for the injection/production of compressed working fluids into porous rock.

Organic Phase Change Materials: Develop compounds that can be tailored to the temperature range for heat transfer in a CAES system.

System Modeling and Design/Operation Optimization: Enhance system modeling and design optimization through the use of artificial intelligence/machine learning to study digital twins in simulated economic operations, using the findings as a feedback loop to system design. Develop standardized testing and measurement procedures, perhaps through the development of an industry standard protocol to create consistent performance measurement, including RTE. Design management and control systems for optimally siting CAES and integrating/managing multiple CAES systems located in a single region or balancing area.

Demonstration Projects: Demonstrate projects incorporating novel CAES strategies, including novel system types (e.g., isothermal, adiabatic) and approaches to storage (e.g., pipeline storage, storage in drained saline aquifers, storage in underwater pressure vessels). Analytic support supplied by National Laboratories to determine RTE under various use cases and conduct techno-economic studies, lifecycle cost studies, and valuation assessments.

Appendix C: Innovation Coefficients

Table C.1. Innovation coefficients

Innovation	Supply Chain Analytics	Mechanical Compression/Expansion	Lower Temperature Turbines	Compressed Air and Hydrogen Energy Storage (CAHES) Systems	Hydraulic Compression/Expansion	Technologies for Subsurface Evaluation of Porous Rock for Storage	Alternative Approaches to High-Temperature Thermal Storage	Alternative Approaches to Storing Compressed Air	Advanced Heat Exchanger Technologies	Advanced Pressure Regulation Technologies	Advanced Manufacturing Techniques	Advanced Alloy	Novel Materials for Lining Wells for Storage	Organic Phase Change Materials	System Modeling and Design/Operation Optimization	Demonstration Projects
Supply Chain Analytics	–	0.10	0.10	0.20	0.10	1.00	0.50	1.00	0.20	0.20	0.50	0.50	0.30	0.20	1.00	1.00
Mechanical Compression/Expansion	0.10	–	1.00	0.25	0.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	0.30	1.00	1.00
Lower Temperature Turbines	0.10	1.00	–	0.25	1.00	1.00	0.50	0.50	0.50	1.00	1.00	1.00	1.00	0.30	1.00	1.00
Compressed Air and Hydrogen Energy Storage Systems	0.20	0.25	0.25	–	0.00	1.00	0.00	1.00	0.00	0.00	0.50	0.50	1.00	0.00	1.00	1.00
Hydraulic Compression/Expansion	0.10	0.00	1.00	0.00	–	1.00	0.30	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technologies for Subsurface Evaluation of Porous Rock for Storage	1.00	1.00	1.00	1.00	1.00	–	1.00	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Alternative Approaches to High-Temperature Thermal Storage	0.50	1.00	0.50	0.00	0.30	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Alternative Approaches to Storing Compressed Air	1.00	1.00	0.50	1.00	1.00	0.75	1.00	–	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00
Advanced Heat Exchanger Technologies	0.20	1.00	0.50	0.00	0.50	1.00	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Advanced Pressure Regulation Technologies	0.20	0.50	1.00	0.00	1.00	1.00	1.00	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00
Advanced Manufacturing Techniques	0.50	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00
Advanced Alloys	0.50	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	–	1.00	0.00	1.00	1.00
Novel Materials for Lining Wells for Storage	0.30	1.00	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	–	1.00	1.00	1.00
Organic Phase Change Materials	0.20	0.30	0.30	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	–	1.00	1.00
System Modeling and Design/Operation Optimization	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	–	0.75
Demonstration Projects	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.75	–

Appendix D: Descriptive Statistics for Individual Innovations

Table D.1. Descriptive statistics for individual innovations

Innovation_ cat	Innovation	Invest_ low	Invest _ high	Invest _ mean	Invest _ std	Timeline_ low	Timeline_ high	Timeline_ mean	Timeline_ std	sbc_ low	sbc_ high	sbc_ mean	sbc_ std	cyc_ low	cyc_ high	cyc_ mean	cyc_ std
Supply Chain	Supply Chain Analytics	0.50	5.00	1.78	1.38	0.50	3.00	1.61	0.87	(0.02)	(0.10)	(0.08)	0.03	0.02	0.10	0.06	0.04
Technology Components	Mechanical Compression/Expansion	2.00	100.00	23.93	33.09	2.00	10.00	3.97	2.12	(0.02)	(0.66)	(0.18)	0.22	0.05	0.50	0.27	0.18
	Lower Temperature Turbines	1.00	100.00	25.50	34.17	2.00	7.00	4.00	1.83	(0.05)	(0.19)	(0.13)	0.06	0.05	0.05	0.05	–
	Compressed Air and Hydrogen Energy Storage Systems	1.00	300.00	76.09	93.73	1.00	20.00	5.23	5.21	(0.10)	(0.24)	(0.17)	0.07	0.05	0.25	0.13	0.08
	Hydraulic Compression/Expansion	2.00	100.00	31.80	36.62	2.00	7.00	4.00	1.55	0.09	(0.19)	(0.05)	0.12	0.02	0.20	0.09	0.08
	Technologies for Subsurface Evaluation of Porous Rock for Storage	0.50	200.00	41.83	62.92	1.00	5.00	3.33	1.56	(0.01)	(0.12)	(0.06)	0.06	–	0.10	0.05	0.05
	Alternative Approaches to High-Temperature Thermal Storage	1.00	100.00	24.13	29.79	2.00	10.00	4.75	2.29	–	(0.10)	(0.05)	0.05	–	–	–	–
	Alternative Approaches to Storing Compressed Air	1.00	400.00	52.73	113.13	2.00	10.00	4.33	2.31	0.01	(0.12)	(0.05)	0.06	–	0.10	0.05	0.05
	Advanced Heat Exchanger Technologies	1.00	100.00	18.43	26.13	1.00	8.00	3.86	1.85	(0.05)	(0.19)	(0.10)	0.06	0.02	0.25	0.14	0.12
	Advanced Pressure Regulation Technologies	2.00	50.00	14.00	15.90	2.00	10.00	4.25	2.44	(0.05)	(0.09)	(0.07)	0.02	0.05	0.05	0.05	–
Manufacturing	Advanced Manufacturing Techniques	1.00	50.00	12.29	16.51	1.00	5.00	3.43	1.50	(0.09)	(0.19)	(0.16)	0.04	–	0.25	0.13	0.13
Advanced Materials Development	Advanced Alloys	1.00	100.00	26.22	39.81	–	5.00	3.00	1.65	(0.02)	(0.02)	(0.02)	–	0.05	0.25	0.13	0.08
	Novel Materials for Lining Wells for Storage	1.00	100.00	21.20	29.66	1.00	5.00	3.17	1.52	(0.00)	(0.03)	(0.01)	0.01	–	1.00	0.33	0.47
	Organic Phase Change Materials	3.00	20.00	8.17	5.70	2.00	5.00	3.83	1.21	–	–	–	–	–	–	–	–
Deployment	System Modeling and Design/Operation Optimization	0.50	25.00	6.88	7.32	0.50	5.00	2.79	1.57	–	(0.10)	(0.08)	0.04	–	0.10	0.07	0.05
	Demonstration Projects	2.00	2,000.00	252.00	515.41	0.50	10.00	4.70	2.86	(0.10)	(0.22)	(0.13)	0.06	0.05	0.10	0.08	0.02

sbc = storage block cost, cyc = lifetime cycles

Note that storage block costs are a proxy for 94% of total system costs, whereas balance of plant, which serves as a proxy for the cost of cavern storage, is roughly 6% of total system costs.

Innovation_ cat	Innovation	rte_ low	rte_ high	rte_ mean	rte_ std	bpc_ low	bpc_ high	bpc_ mean	bpc_ std	fom_ low	fom_ high	fom_ mean	fom_ std	vom_ low	vom_ high	vom_ mean	vom_ std
Supply Chain	Supply Chain Analytics	0.03	0.03	0.03	–	(0.05)	(0.25)	(0.15)	0.10	(0.05)	(0.10)	(0.08)	0.03	(0.05)	(0.05)	(0.05)	–
Technology Components	Mechanical Compression/Expansion	0.05	0.10	0.06	0.02	(0.05)	(0.10)	(0.09)	0.02	0.10	(0.05)	0.03	0.08	0.50	(0.05)	0.23	0.28
	Lower Temperature Turbines	0.03	0.10	0.07	0.04	(0.05)	(0.20)	(0.13)	0.08	(0.05)	(0.05)	(0.05)	–	(0.05)	(0.05)	(0.05)	–
	Compressed Air and Hydrogen Energy Storage Systems	0.05	0.15	0.10	0.04	(0.10)	(0.25)	(0.20)	0.07	(0.10)	(0.25)	(0.18)	0.08	(0.10)	(0.25)	(0.18)	0.08
	Hydraulic Compression/Expansion	0.05	0.30	0.15	0.11	(0.02)	(0.02)	(0.02)	–	(0.04)	(0.10)	(0.07)	0.03	(0.04)	(0.10)	(0.07)	0.03
	Technologies for Subsurface Evaluation of Porous Rock for Storage	–	–	–	–	–	(0.50)	(0.25)	0.25	–	–	–	–	–	–	–	–
	Alternative Approaches to High-Temperature Thermal Storage	0.05	0.10	0.08	0.02	0.20	(0.30)	(0.10)	0.22	0.10	(0.20)	(0.02)	0.13	0.05	0.05	0.05	–
	Alternative Approaches to Storing Compressed Air	–	0.05	0.03	0.03	(0.10)	(0.10)	(0.10)	–	–	(0.10)	(0.05)	0.05	–	(0.10)	(0.05)	0.05
	Advanced Heat Exchanger Technologies	0.04	0.10	0.06	0.02	(0.10)	(0.10)	(0.10)	–	(0.05)	(0.05)	(0.05)	–	(0.05)	(0.05)	(0.05)	–
	Advanced Pressure Regulation Technologies	0.02	0.05	0.04	0.02	(0.05)	(0.10)	(0.08)	0.03	(0.04)	(0.04)	(0.04)	–	(0.04)	(0.04)	(0.04)	–
Manufacturing	Advanced Manufacturing Techniques	–	–	–	–	(0.10)	(0.25)	(0.18)	0.08	(0.10)	(0.10)	(0.10)	–	(0.10)	(0.10)	(0.10)	–
Advanced Materials Development	Advanced Alloys	0.02	0.05	0.04	0.02	(0.02)	(0.50)	(0.26)	0.20	(0.02)	(0.02)	(0.02)	–	(0.02)	(0.02)	(0.02)	–
	Novel Materials for Lining Wells for Storage	–	0.02	0.01	0.01	(0.50)	(0.50)	(0.50)	–	0.05	–	0.03	0.03	0.05	(0.50)	(0.15)	0.25
	Organic Phase Change Materials	0.02	0.05	0.04	0.02	(0.10)	(0.10)	(0.10)	–	(0.05)	(0.05)	(0.05)	–	(0.05)	(0.05)	(0.05)	–
Deployment	System Modeling and Design/Operation Optimization	0.05	0.10	0.09	0.02	(0.10)	(0.20)	(0.15)	0.05	(0.10)	(0.20)	(0.13)	0.05	(0.10)	(0.10)	(0.10)	0.00
	Demonstration Projects	0.04	0.20	0.09	0.07	(0.10)	(0.20)	(0.15)	0.05	0.20	(0.10)	(0.03)	0.13	0.20	(0.10)	–	0.14

rte = round-trip efficiency, bpc = balance of plant cost, fom = fixed operations and maintenance, vom = variable operations and maintenance

Note that storage block costs are a proxy for 94% of total system costs, whereas balance of plant, which serves as a proxy for the cost of cavern storage, is roughly 6% of total system costs.

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