Technology Strategy Assessment

Findings from Storage Innovations 2030
Bidirectional Hydrogen Storage
July 2023

About Storage Innovations 2030

This technology strategy assessment on bidirectional hydrogen storage, 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 from a 2020 Li-ion baseline 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.

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Background

Since Henry Cavendish showed that hydrogen is an element in 1766, several approaches have been developed for the production of hydrogen. The most common are associated with the production and conversion of hydrocarbon-based fuels. Coal gasification, steam methane reforming, and other reformation processes provide the majority of current hydrogen production due to the relatively low cost of hydrogen produced through these processes.

More than 95% of hydrogen production is used for industrial processes rather than energy storage [1]. To facilitate affordable decarbonization of these industrial processes and advance the use of hydrogen to address other difficult-to-decarbonize sectors (such as power generation and heavy-duty transportation), DOE launched the Hydrogen Shot as part of the Energy Earthshots Initiative [2]. The goal of the Hydrogen Shot is to reduce the cost of clean hydrogen by 80% to $1/kg of clean hydrogen production within one decade (known as the "1 1 1" goal). This is distinct from the Long-Duration Storage Shot, which is the primary focus of this report; however, it is intrinsically linked to bidirectional hydrogen storage [3].

Several important chemical synthesis processes are dependent upon hydrogen, and the production and use of hydrogen is generally driven by its connection to one of these markets. For example, ammonia is one of the most highly produced chemicals in the world and it depends chiefly on hydrogen. Ammonia is primarily used for agricultural fertilizer and is considered to be largely responsible for a doubling of agricultural production per unit of land over the last century [4]. Another of hydrogen's primary uses is as a catalyst in petroleum refining during the desulfurization process. Beyond chemical production, hydrogen is used as a reductant in the production of steel and has been demonstrated as a substitute for metallurgical coal in the production of raw iron. It is even used in the hydrogenation reaction for food products to create more shelf-stable semi-solid fats.

However, while hydrogen is produced on the order of 100 million metric tons/year globally to feed these industries, more than 95% of hydrogen is produced from hydrocarbons that emit CO_2 during the process [5]. Conversely, electrolysis is a process by which electricity is used to separate hydrogen and oxygen in water molecules, usually across a membrane. Hydrogen production via electrolysis lowers the carbon intensity of produced hydrogen when coupled with low-carbon electricity. Currently, global electrolysis capacity is on the order of 1 GW, which equates to about 500 metric tons/day of hydrogen production, and it is expanding rapidly in planned deployments over the next few years [6]. To support large-scale industrial decarbonization, capacity will likely need to increase by two to three orders of magnitude.

Electrolysis technology is broadly separated into groups that are defined by the electrolyte used, with further subdivision based on the operating characteristics. The majority of commercial electrolyzer systems are based around three main technology groups: liquid alkaline, proton exchange membrane, and solid oxide. Liquid Alkaline (LA) electrolysis is the oldest, most mature, and least expensive technology, with 400 plants in operation as early as 1902 [7]. Recently, updated designs have been developed that have renewed industry interest in LA electrolysis. Its hydrogen output is lower relative to the size of the system due to a low current density [8]. LA electrolysis utilizes a liquid potassium hydroxide solution as the electrolyte. Proton exchange membrane (PEM) electrolysis (also known as polymer electrolyte membrane electrolysis), described in 1960, relies on an acid-impregnated polymer membrane as the electrolyte and typically offers three to six times higher hydrogen production per unit cell area than LA electrolysis [9]. Solid oxide electrolysis, or high-temperature electrolysis, utilizes a ceramic electrolyte and operates on steam rather than liquid water, enabling electrical efficiencies of more than 90%, which is up from 60% with PEM [10], [11]. Two pre-commercial electrolyzer technologies to note are alkaline exchange membrane (AEM) and

proton-conducting solid oxide electrolysis cell (p-SOEC). AEM potentially has the advantages of both LA and PEM technologies in that it is able to use low-cost materials (such as non-platinum-group metal catalysts) like LA but with the ability to operate at higher output pressures with a smaller footprint like PEM. Proton-conducting SOEC is similar to commercial SOEC, which uses an oxide-conducting ceramic; however, it uses a proton-conducting ceramic that has the potential to operate at lower temperatures and has lower capital costs. Each of these technologies is experiencing a rapid improvement in performance and a reduction in installed cost, and each appears to be well suited to specific applications.

Besides differences in the type of electrolyzer used, the main difference in the architecture of bidirectional hydrogen systems is how the hydrogen is stored. Currently, the most cost-effective way to store large amounts of hydrogen gas is underground, such as in large salt caverns that have been hollowed out [12]. These salt caverns are geographically concentrated in small portions of the United States and are not generally near large metropolitan areas; however, other subsurface architectures are being investigated to expand this reach [13]. A more widely deployable option is aboveground pressurized tanks. These systems are about 10 times as expensive because of the materials and safety margins required to hold hydrogen at high pressures. A third option is using materials-based storage, such as liquid organic hydrogen carriers. By reversibly attaching the produced hydrogen to other molecules, it can be stored at near atmospheric pressure and room temperature. This has the potential to reduce the material cost of storage but may result in a reduction in the efficiency of the process because there are both hydrogen uptake and release processes. While materials-based storage has not been used extensively for large-scale hydrogen storage in the past, there is currently significant activity regarding developing materials and processes for use in large-scale hydrogen storage applications.

Electrolysis-produced hydrogen offers an unusual opportunity for energy storage applications. Unlike more conventional energy storage approaches, such as batteries, which operate entirely within electrical markets, hydrogen is a valuable product beyond the electric market and can be directed to the most lucrative use. Hydrogen also can be directly converted back to electricity using either a fuel cell or turbine, or it can be sold to other markets, such as chemical synthesis, steel production, or even export. In this way, excess electricity can be upgraded to the most valuable product. Finally, its use can be actively managed between multiple off-takers; for example, local hydrogen storage can provide a specific amount of stored electricity and any excess can be exported to ammonia production. This flexibility is amplified by the fact that hydrogen storage has fully decoupled power and energy components, which allows for affordable scaling options. Together, this allows a substantial amount of creativity to enable the economic utilization of variable power resources while supporting decarbonization of the industry (Figure 1).
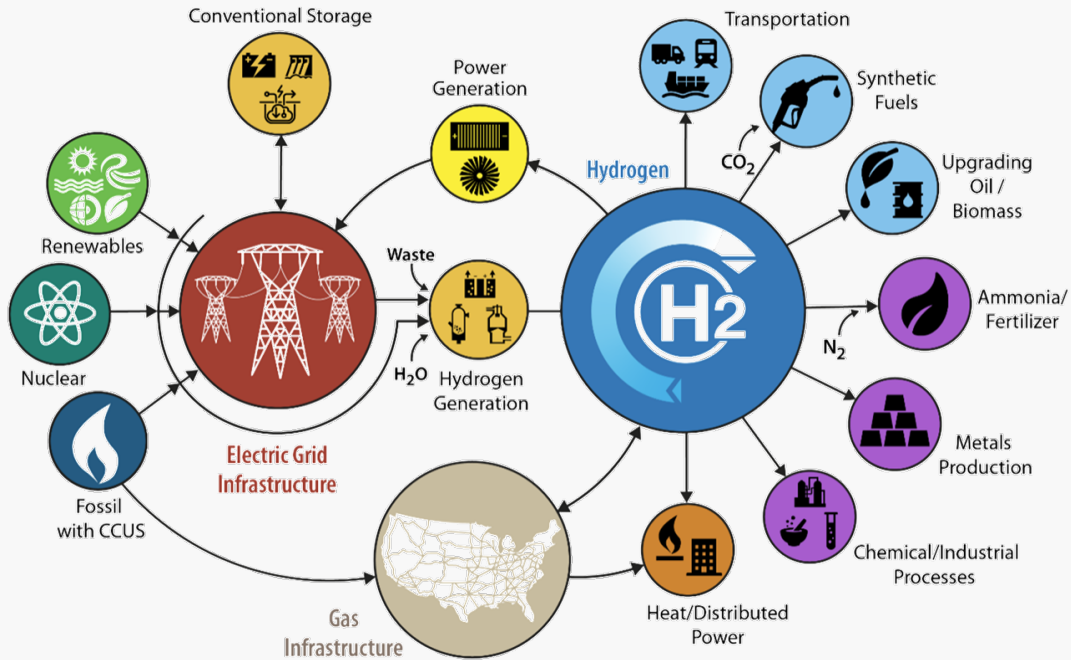
Figure 1. Illustration of the multi-market role of hydrogen in the clean energy transition [14]. The two markets are for hydrogen and electricity, with market drivers shown for hydrogen.

Step 1 of the Framework Study is to assess the research and development (R&D) trajectory status quo for a given technology, or to project performance and cost parameters out to 2030, given no marginal increase in DOE R&D 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 from the 2022 Grid Energy Storage Technology Cost and Performance Assessment, as defined for 100-MW, 10-hour bidirectional salt cavern storage [15]. Cost estimates for hydrogen production also have been produced by DOE; however, they are not designed for a bidirectional system [16]. The components of the bidirectional hydrogen system comprising discrete electrolyzer and fuel cell components are shown in Figure 2. The storage block value for pressurized surface tanks is derived from interviews with industry subject matter experts (SMEs). Note that capital cost values differ in terms of their units of measurement, with some (e.g., controls and communication, power equipment) tied to the power capacity of the system, and others (e.g., storage block capital costs) tied to energy capacity. The cost and performance metrics in Table 1 result in a calculated levelized cost of storage (LCOS) of $0.24/kWh for tank storage and $0.13/kWh for cavern storage [17]. Current scale-ups in manufacturing capacity are rapidly driving equipment costs down to levels that would support the Hydrogen Shot goal of $1/kg of hydrogen production. This also will support the Long-Duration Storage Shot goal of $0.05/kWh because equipment costs are a significant factor in LCOS. Also note that this report assumes that electricity will be available for hydrogen production at $0.025/kWh, in line with other programs in DOE [15], [18].
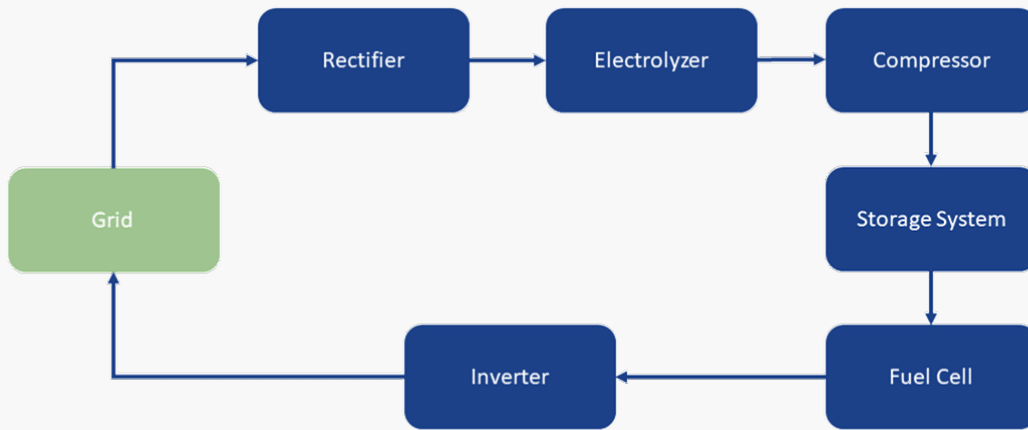
Figure 2. Flow diagram of the components of a bidirectional hydrogen storage plant

Table 1.The cost and performance of hydrogen energy storage in pressurized surface tanks and salt caverns (2030 estimates). Details about assumptions and cost can be found in the 2022 Grid Energy Storage Technology Cost and Performance Assessment [15].

Parameter	Value	Description
Hydrogen conversion system life	30	Deployment life (years)
Storage tank cycle life	3,650	Number of cycles before replacement of the storage tank system
Round-trip efficiency (RTE)	31%	Base RTE for a system with 73% electrolyzer efficiency and 51% fuel cell efficiency
Storage block costs (tank storage)	72.8	Base storage block costs for pressurized tank storage systems ($/kWh)
Storage block costs (salt cavern storage)	6	Base storage block costs for salt cavern storage systems ($/kWh)
Balance of plant costs	79.4	Base balance of plant costs, including fuel cell, electrolyzer, and compressor ($/kWh)
Controls and communication costs	1.06	Controls and communication costs ($/kW)
Power equipment costs	123	Power equipment costs, including inverter and rectifier ($/kW)
System integration costs	0	System integration costs ($/kWh)
Project development costs	50	Project development costs ($/kWh)
Engineering, procurement, and construction (EPC) costs	27.52	EPC costs ($/kWh)
Grid integration costs	16.3	Grid integration costs ($/kWh)
Fixed operations and maintenance (O&M) costs	14.3	Base fixed O&M costs ($/kW-year)
Variable O&M costs	0.0005125	Base variable O&M costs ($/kWh)

Pathways to $0.05/kWh

The framework used here to describe the cost and technology pathways for bidirectional hydrogen storage is a systematic methodology for capturing and synthesizing an industry's sentiments about the future of its technology. Storage in surface tanks is used as the baseline because it is deployable anywhere; however, the results for salt cavern storage are presented for comparison. While many of these results involve quantitative estimates of parameters and LCOS, it is important to remember that they represent subjective perspectives from the industry. A group of 17 SMEs were identified and contacted. These SMEs represented 17 organizations, ranging from industry groups to vendors

and universities. The Framework Team conducted interviews, soliciting information regarding pathways to innovation and associated cost reductions and performance improvements. The innovations defined by the SMEs are presented in Table 2. The definitions of each innovation are presented in Appendix A.

Table 2. 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	Applicable Technology
Critical mineral sourcing	Critical mineral discoveries	Cavern and tank
Supply chain	Domestication of the supply chain	Cavern and tank
Technology components	Hydrogen to electricity advancements	Cavern and tank
	Hydrogen carrier advancements	Tank
	Storage tank materials	Tank
	Smart tanks	Tank
Manufacturing	Scale and automation	Cavern and tank
Deployment	Deployment studies	Cavern and tank
	Demonstration	Cavern and tank
	Liquid hydrogen carriers	Tank
	Hybridization with renewables	Cavern and tank
End of life	Recycling components	Cavern and tank

Input from SMEs was used to define investment requirements, timelines for investment, potential impacts on performance (e.g., RTE, cycle life), and the impact of cost (e.g., storage block, balance of plant, O&M) for each innovation. The Monte Carlo simulation tool then combined each innovation with one to seven other innovations and based on the range of impacts estimated by industry, the tool produced the distribution of potentially achievable outcomes by 2030 with respect to LCOS. Going forward, these groups of innovations are referred to as *portfolios*. Figure 3 shows the prevalence of each innovation in portfolios that ranked among the top 10% for LCOS reduction. The LCOS range with the highest concentration of simulated outcomes is in the $0.17 to $0.21/kWh range (Figure 4). However, some portfolios reduce LCOS further, with the highest impact portfolios (the top 10%) resulting in an LCOS of between $0.15 and $0.17/kWh, as denoted by the marked region. It is important to note that LCOS is likely not the best metric to measure the economic viability of bidirectional hydrogen because of its multi-market nature, shown in Figure 1. More discussion on this point can be found in the section titled "The Role of Bidirectional Hydrogen Storage."
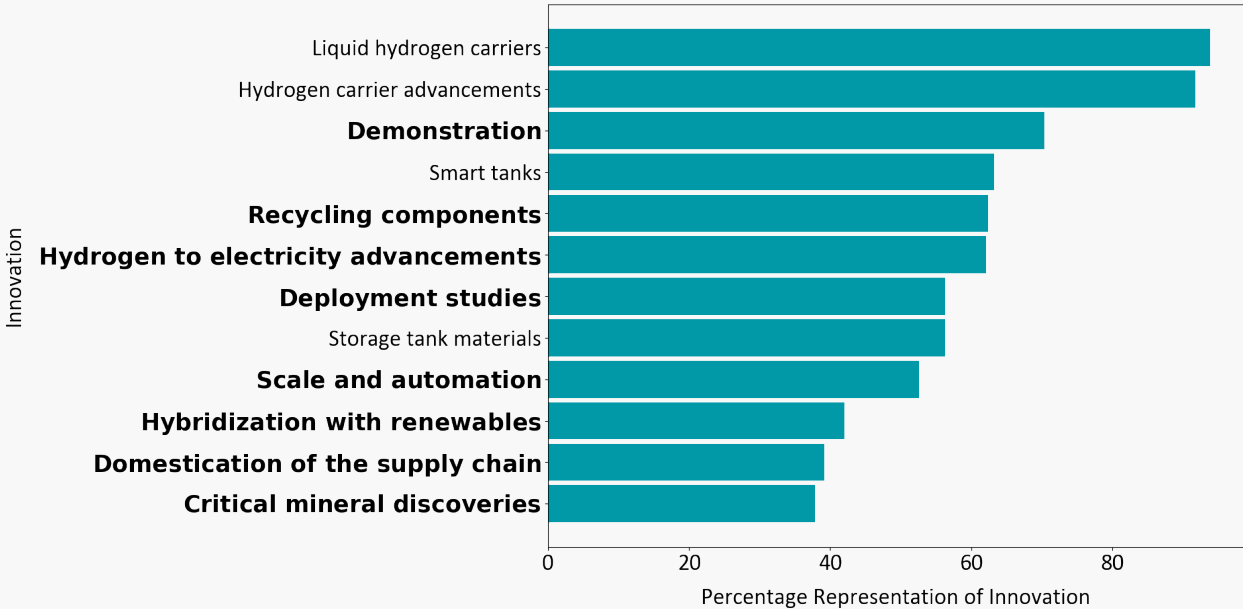
Figure 3. The percentage of portfolios in the top 10% (resulting in the lowest LCOS) that include each innovation. Bolded innovations apply to both tank and cavern storage, while the other innovations only apply to tank storage.
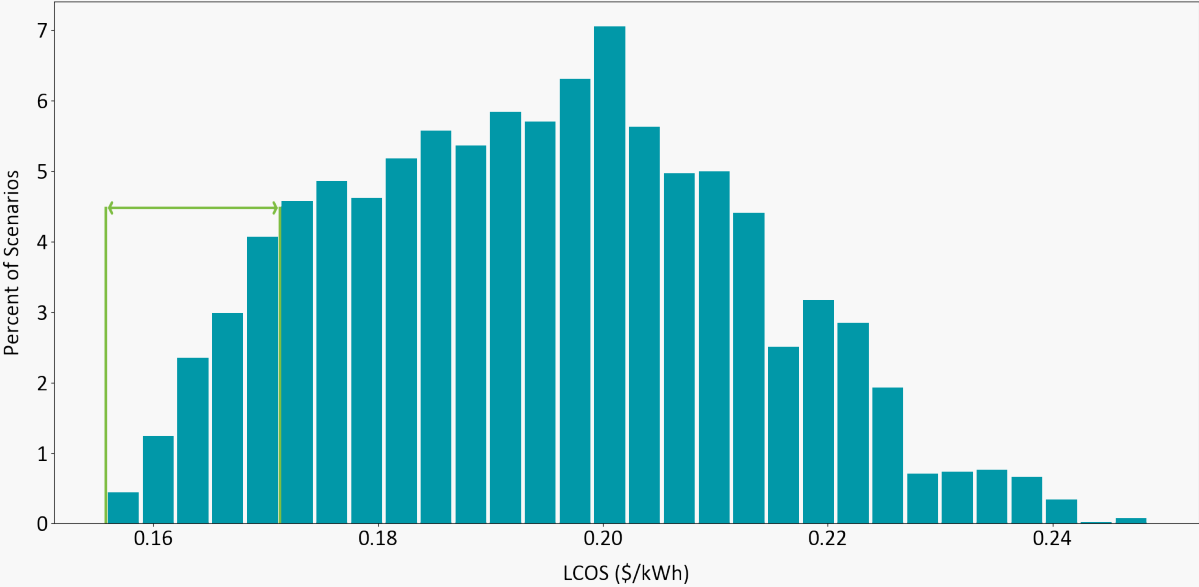
Figure 4. Distribution of mean LCOS for each portfolio based on the impact of the portfolio's innovations. The green rectangle marks the bins containing the top 10% of the portfolios.

The results of the Monte Carlo simulation for those portfolios that fall within the top 10% in terms of LCOS impact are presented in Figure 5. The vertical line indicates that the mean portfolio's cost is $491 million. The dollar values across the x-axis represent the marginal investment over business as usual levels required to achieve the corresponding LCOS improvements. Total expenditure levels with the highest portfolio densities in the top 10% are split into three distinct groups, and the timeline required to achieve these LCOS levels is estimated at 7 to 12 years. These separate investment

groupings likely arise from the presence of "critical mineral discoveries" and "domestication of the supply chain" in the portfolios because they were reported to have no effect on cost or performance but have significant impacts on the required cost. This could result in a number of portfolios with the same impact on cost but significantly different capital requirements. A similar investment and timeline distribution is seen for hydrogen with cavern storage; however, LCOS improves to $0.113 to $0.116/kWh. The top 20% of the portfolios are shown for salt cavern storage instead of the top 10% because there are fewer combinations of innovations.
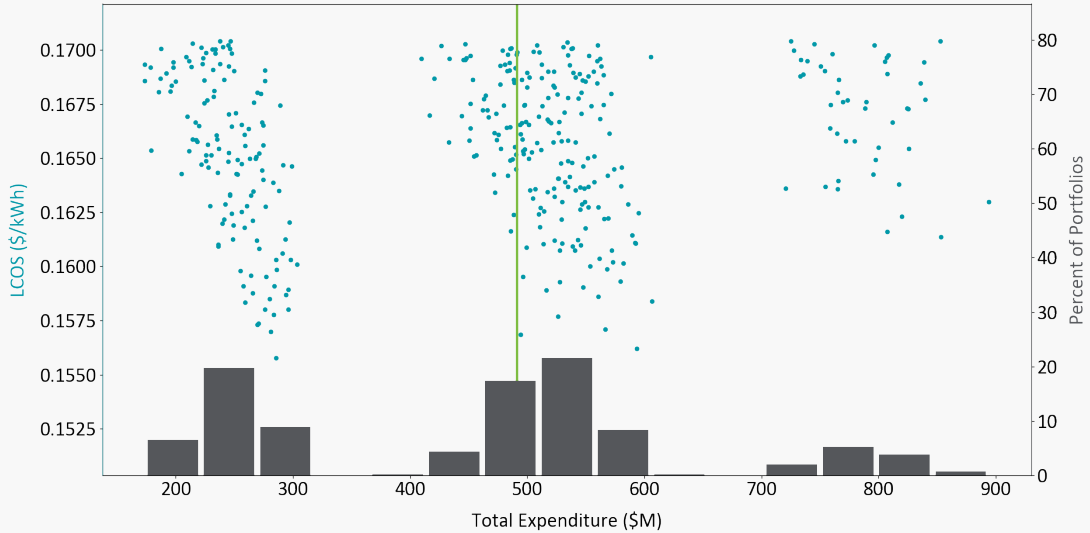
Figure 5. LCOS and expenditures for the top 10% of the portfolios for hydrogen with surface tank storage. The axis on the left labels the scatter plot of expected LCOS for each portfolio versus total expenditure, while the axis on the right labels the histogram of expenditures. This means that the histogram shows the distribution of the dots on the scatter plot. The vertical line marks the median expenditure.
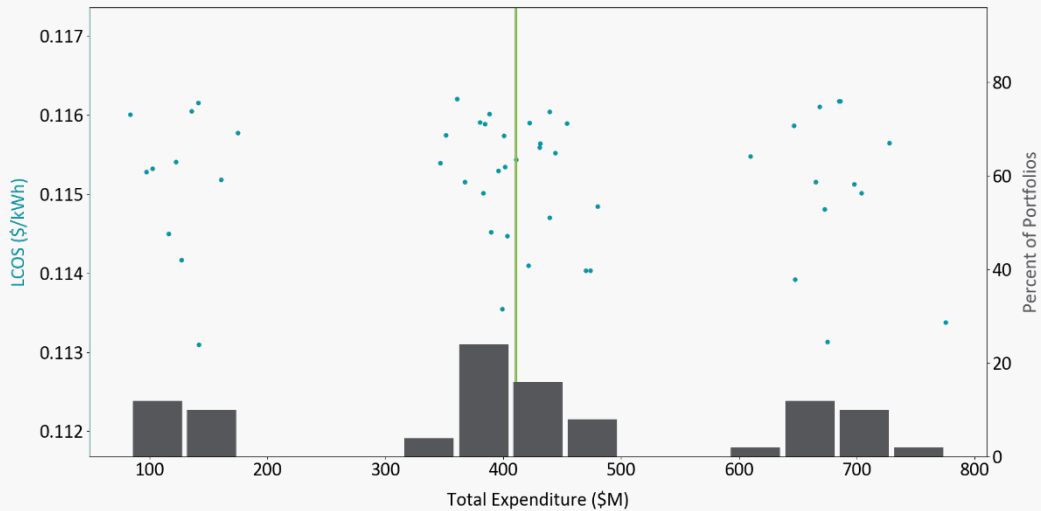
Figure 6. LCOS and expenditures for the top 20% of the portfolios for hydrogen with salt cavern storage. The axis on the left labels the scatter plot of expected LCOS for each portfolio versus total expenditure, while the axis on the right labels the histogram of expenditures. This means that the histogram shows the distribution of the dots on the scatter plot. The vertical line marks the median expenditure.

Note that the impact of each layered innovation is not necessarily additive. The impact of each additional innovation is weighed using logic to determine the combined impact. Combinations of

investments can be mutually exclusive or overlapping, thus diminishing their combined impact. Innovation coefficients, which scale the combined impact for each innovation pairing, are presented in Appendix C.

SMEs also were asked for their preferences regarding the investment mechanism, selecting among National Laboratory investments, grants, loans, and technical assistance. Table 3 presents the percentage of respondents who expressed support for each mechanism. Not all respondents selected investment mechanisms for each innovation. Grants were generally seen to be important across all innovations, while technical assistance was considered to be less important.

Table 3. SME preferences for investment mechanisms. Cells with asterisks (*) are the more preferred 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
Critical mineral discoveries	50% *	50% *	0%	0%
Domestication of the supply chain	33% *	33% *	33% *	0%
Hydrogen to electricity advancements	0%	67% *	0%	33%
Hydrogen carrier advancements	20%	40% *	40% *	0%
Storage tank materials	0%	50% *	50% *	0%
Smart tanks	20%	40% *	20%	20%
Scale and automation	25% *	25% *	25% *	25% *
Deployment studies	67% *	33%	0%	0%
Demonstration	0%	50% *	50% *	0%
Liquid hydrogen carriers	17%	33% *	33% *	17%
Hybridization with renewables	33% *	33% *	33% *	0%
Recycling components	40% *	40% *	20%	0%

R&D Opportunities

As presented in Table 4, hydrogen carriers and hydrogen carrier advancements consistently yield metrics in the top tier and mid tier. None of the innovations were reported to have cycle life impacts, which is likely because hydrogen storage is shelf-life limited rather than limited by the cycle life. The recommended investment levels and timeline by innovation also are identified in Table 4. Most expenditures are in the $10 million to $40 million range and require investments over 5 to 10 years.

The Framework Team recognizes that some estimates are aggressive and optimistic; however, they remain worthy of attention because they demonstrate a strong directional cue from the industry that these innovations show great promise and have broad-based industry support. The identification of new sources of critical minerals, domestication of the supply chain, and hybridization with renewables generation were not viewed as promising for cost and performance improvements by the industry. While many of the interviewed SMEs spoke to the importance of developing a supply chain in the United States, follow-up responses indicate that the cost benefits of avoiding tariffs, increased competition, and a more streamlined purchasing process would be balanced by the increased cost of labor. Similarly, SMEs talked about the importance of finding new sources for critical minerals; however, follow-up responses indicate that the industry is skeptical that any new sources will be sufficiently abundant to significantly impact the cost. The geopolitical implications of new sources for critical minerals are more likely to drive this type of investment than cost reduction

goals. More detailed data, including minimum and maximum values and standard deviations for each metric, are presented in Appendix D.

Table 4. Mean impacts of proposed R&D, investment levels, and timelines, reported by SMEs. Cells with asterisks (*) are top-tier effects and cells with daggers (†) are mid-tier effects.

Innovation	Storage Block Cost Impact (%)	Balance of Plant Cost Impact (%)	Round-trip Efficiency Impact (%)	Mean Investment Requirement (million $)	Mean Timeline (years)
Critical mineral discoveries	0	0	0	225	10
Domestication of the supply chain	0	0	0	300	10
Hydrogen to electricity advancements	0	-30 *	-3	26 †	4.9 †
Hydrogen carrier advancements	-26 *	-30 *	5 *	40 †	4.9 †
Storage tank materials	-8 †	0	0	15 *	3.0 *
Smart tanks	-18 †	0	0	17 *	2.5 *
Scale and automation	-8 †	-10 †	0	35 †	6.0
Deployment studies	-10 †	-10 †	0	21 †	4.8 †
Demonstration	-15 †	-20 †	0	50	3.5 *
Liquid hydrogen carriers	-73 *	0	-1	73	4.8 †
Hybridization with renewables generation	-4	0	0	11 *	5.8
Recycling components	-9 †	-30 *	0	7 *	6.3

Of the identified innovations, those with impacts on storage block and balance of plant cost improvements have the greatest impact on LCOS for bidirectional hydrogen storage. Most of the innovations reported for electrolyzer and fuel cell improvements were focused on reducing cost, sometimes at a slight expense to efficiency. For turbine-fired hydrogen to electricity consumption, this trend continued, and round-trip efficiency (RTE) was expected to moderately decrease.

Comparing the results from surface tank (Figure 5) and salt cavern storage (Figure 6) shows the importance of reducing storage block costs for deploying bidirectional hydrogen storage in regions that do not have salt caverns. Even more telling is that the base LCOS for surface tank storage is $0.24/kWh, while the base LCOS for salt cavern storage is $0.13/kWh. This results in nearly a halving of LCOS and brings bidirectional hydrogen storage into a more competitive range with existing energy storage devices. From Table 1, the balance of plant costs contribute a similar cost to the project, so significant reductions in the storage block cost and hydrogen-electricity conversion systems are likely to be the main drivers of LCOS reduction.

The most promising way to make significant reductions to the capital cost of the broadly deployable bidirectional hydrogen storage that was identified by SMEs is through liquid hydrogen carriers. While respondents noted that liquid hydrogen carriers would significantly reduce the storage block cost, there was relatively significant uncertainty about the exact percentage. There was even more uncertainty about how much larger the operations and maintenance costs would be for liquid hydrogen carrier-based systems, which means that the model incorporated the significant uncertainties in those two impacts. This is likely related to the relative immaturity of the technology. Many types of hydrogen carriers are currently being investigated, with different recyclability, efficiency, and cost of the carrier. Some of the most promising innovations are with direct hydrogen carriers, where the molecule is directly synthesized rather than going through hydrolysis to isolate hydrogen gas and then adding it to a carrier model. Other directions for research include identifying hydrogen carriers that release the hydrogen at lower temperatures.

Even with significant reductions in capital cost, the RTE of bidirectional hydrogen storage remains a significant barrier to reaching $0.05/kWh. Currently, RTE is 31%, which means that $0.055/kWh of

LCOS is from efficiency losses (assuming charging at $0.025/kWh). Efficiency would need to reach 33.3% for losses to equal $0.05/kWh and would have to hit 50% to leave $0.025/kWh in headroom for capital and fixed operational costs. Based on Framework feedback, the industry has not coalesced around a pathway to achieve significant efficiency improvements. Still, this is an active area of research and there are many organizations looking for innovative ways to improve electrolyzer and fuel cell efficiency. For example, interviewees spoke about a range of commercially established electrolyzers, such as PEM and AEM electrolyzers; however, not all architectures that are being researched were captured. A recent paper describing one such architecture claims significant improvements in efficiency, which could help overcome this barrier if successfully commercialized [19].

Another innovation that may help overcome the RTE barrier is high-temperature electrolysis. There was insufficient input from industry to include this innovation in the Monte Carlo simulation; however, research has shown promise for this technology, especially when co-located with a source of heat, such as nuclear or concentrated solar power. Electrolysis becomes more electrically efficient as temperature increases, so high-temperature, electrolysis-based storage systems could have RTEs around 44% or higher [20]. Another area of active research, which did not get enough industry response, is unitized reversible fuel cells. These configurations are being investigated to reduce capital costs and improve RTE in energy storage applications, and DOE has set a goal of 55% and 60% efficiency by 2030 for low- and high-temperature applications, respectively [21].

The Role of Bidirectional Hydrogen Storage

Reaching $0.05/kWh will be a major milestone for the financial viability of storage devices that generate value through regular, predictable arbitrage. Storage devices play an important role in integrating more variable renewable generation onto the grid, and many energy storage technologies focus on this use case as a way to keep their capacity factors high. Bidirectional hydrogen storage is in a somewhat unique position among long-duration energy storage technologies in that it can store energy from the grid and deliver it to two different markets, depending on the demand for hydrogen and electricity. For most energy storage devices, being locked into the electricity market means that if daily energy price spreads do not regularly exceed the LCOS of the device for periods as long as its rated duration, the capacity factor may be too low for economic viability. Therefore, bidirectional hydrogen storage has an advantage in situations where the price spread is less frequently or predictably large. In these cases, the system could sell excess hydrogen directly to its growing market. As such, it is likely to play a different role than batteries and $0.05/kWh is not the most appropriate metric for determining whether bidirectional hydrogen storage can be economically viable for facilitating the clean energy transition. This is because while the bidirectional role of hydrogen storage is most sensitive to the relative spread of electricity prices, measured by LCOS, the hydrogen production role is sensitive to absolute prices. In this role, where hydrogen is the primary output of the system, the availability of cheap energy would be a primary driver of profitability and may outweigh some of the effects of capital cost reduction. In the long term, new economic metrics may be needed for multi-market assets like bidirectional hydrogen.

Bidirectional hydrogen storage may be better suited for providing resilience and reliability services, which is another critical role in enabling higher penetrations of renewable generation. A system could be set up to normally produce hydrogen for direct consumption but dynamically provide firm capacity and regulation when prices are high enough. For example, during the Texas power outages in 2021, the price cap was set at $9/kWh [22]. While a surface tank storage system with an LCOS of $0.24/kWh may not have been profitable on a daily arbitrage basis, it would have provided significant value during that event. As penetrations of wind and solar increase on the grid, the impact of

extended periods of low solar and wind production will also increase [23]. Low generation events will drive a need for firm capacity at irregular intervals. Bidirectional hydrogen storage would be well suited for this role because it can primarily provide hydrogen as a product during times with lower net load and switch to electricity production when it is most valuable. As such, a system that can produce hydrogen at the Hydrogen Shot goal of $1/kg is likely to be economically viable for playing a role in bidirectional energy storage, even if storage block costs remain high.

Within the role of providing probabilistic, high-value reliability and resilience services, there are two value drivers that maximize the economic viability of hydrogen storage. These are the local resources and the discharge duration. Because storage block cost is one of the primary drivers of LCOS, this type of bidirectional hydrogen storage would be most effective where salt cavern storage is available. The storage block cost would be very low relative to the cost of the balance of plant, so it would not need to be amortized across as many cycles in order to be profitable. The balance of plant costs would be largely paid for through direct hydrogen production. Additionally, because the cost of hydrogen production is largely driven by electricity prices, the availability of cheap, abundant power or potential power will be important. While these value drivers are inherently geographically limited and do not necessarily align with load center locations, high energy use companies, such as data center owners, often site their businesses based on electricity prices and reliability. The discharge duration also will be an important value driver for hydrogen. Because power and energy capacity are decoupled for bidirectional hydrogen storage, its economic viability increases relative to other options as its storage duration increases. For example, even with only electricity as an output, bidirectional hydrogen storage is likely to be the most economically viable technology for seasonal storage with durations over 700 hours [24]. As such, hydrogen storage is expected to expand to 682 GW if fossil plants are eliminated from the grid [25].

Appendix A: Innovation Matrix and Definitions

Table A.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	Applicable Technology
Critical mineral sourcing	Critical mineral discoveries	Cavern and tank
Supply chain	Domestication of the supply chain	Cavern and tank
Technology components	Hydrogen to electricity advancements	Cavern and tank
	Hydrogen carrier advancements	Tank
	Storage tank materials	Tank
	Smart tanks	Tank
Manufacturing	Scale and automation	Cavern and tank
Deployment	Deployment studies	Cavern and tank
	Demonstration	Cavern and tank
	Liquid hydrogen carriers	Tank
	Hybridization with renewables	Cavern and tank
End of life	Recycling components	Cavern and tank

Critical mineral discoveries: The discovery of new sources for the platinum and iridium needed by electrolyzers.

Domestication of the supply chain: The development of a supply chain for the components used by hydrogen storage devices within the United States.

Hydrogen to electricity advancements: Advances in and implementation of polyethelene, nickel, silicone, and steel electrolyzers; PEM electrolyzers; AEM electrolyzers; and hydrogen combustion.

Hydrogen carrier advancements: Advances in direct hydrogen carriers or low-temperature hydrogen carriers beyond currently commercialized hydrogen carrier technologies.

Storage tank materials: The incorporation of carbon fiber and thermoplastics into storage tanks.

Smart tanks: Storage tanks that monitor their own health using internet-connected sensors. This could reduce the margin of safety required for tanks.

Scale and automation: The mass production and automation of manufacturing for electrolyzers, fuel cells, and storage tanks.

Deployment studies: Advanced studies on market policies and regulations, such as safety factors and permitting, to improve the deployment of hydrogen storage on the grid. Includes studies in techniques and technologies to increase deployment efficiency.

Demonstration: The demonstration of pilot hydrogen storage systems to de-risk the technology.

Liquid hydrogen carriers: Hydrogen is attached on a carrier molecule, such as ammonia, methylcyclohexane, or formic acid, in order to store it as a stable liquid around room temperature.

Hybridization with renewables: The deployment of projects with hydrogen storage co-located and co-optimized with hydropower, onshore/offshore wind, marine energy, or solar power.

Recycling components: Improvements in electrolyzer, fuel cell, and storage tank recycling.

Appendix B: Industry Contributors

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

Participant	Institution
Adam Weber	Lawrence Berkeley National Laboratory
Hanna Breunig	Lawrence Berkeley National Laboratory
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Jane Allo	ElektrikGreen
Jeff Hyungrak Chung	HyAxiom
Gerald DeCuollo	TreadStone Technologies
Claire Behar	Hy Stor Energy
Andrew Coors	Steelhead Composites
Thomas Autrey	Pacific Northwest National Laboratory
Scott Jorgensen	Hyrax Intercontinental LLC
Todd Brix	OCOchem

Appendix C: Innovation Coefficients

Table C.1. Innovation coefficients

Innovation	Critical mineral discoveries	Domestication of the supply chain	Hydrogen to electricity advancements	Hydrogen carrier advancements	Storage tank materials	Smart tanks	Scale and automation	Deployment studies	Demonstration	Liquid hydrogen carriers	Hybridization with renewables	Recycling components
Critical mineral discoveries	–	1.00	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.30
Domestication of the supply chain	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50
Hydrogen to electricity advancements	0.50	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Hydrogen carrier advancements	0.50	1.00	1.00	–	–	–	0.50	1.00	1.00	1.00	1.00	0.30
Storage tank materials	1.00	1.00	1.00	–	–	1.00	1.00	1.00	1.00	–	1.00	0.50
Smart tanks	1.00	1.00	1.00	–	1.00	–	1.00	1.00	1.00	–	1.00	0.80
Scale and automation	1.00	1.00	1.00	0.50	1.00	1.00	–	1.00	1.00	0.75	1.00	1.00
Deployment studies	1.00	1.00	1.00	1.00	1.00	1.00	1.00	–	0.50	0.50	1.00	1.00
Demonstration	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	–	1.00	1.00	1.00
Liquid hydrogen carriers	1.00	1.00	1.00	1.00	–	–	0.75	0.50	1.00	–	1.00	0.75
Hybridization with renewables	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	–	1.00
Recycling components	0.30	0.50	1.00	0.30	0.50	0.80	1.00	1.00	1.00	0.75	1.00	–

Appendix D: Descriptive Statistics for Individual Innovations

Table D.1. Descriptive statistics for individual innovations

Innovation	Expense low	Expense high	Expense mean	Expense 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
Critical mineral discoveries	50	500	225.0	202.1	5	15	10.0	7.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Domestication of the supply chain	100	500	300.0	282.8	5	15	10.0	7.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen to electricity advancements	0.5	80	26.0	32.4	2	10	4.9	2.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen carrier advancements	2	125	39.6	41.4	2	10	4.9	2.9	-0.50	-0.10	-0.26	0.15	0.00	0.00	0.00	0.00
Storage tank materials	5	25	15.0	14.1	2	4	3.0	1.4	-0.10	-0.05	-0.08	0.04	0.00	0.00	0.00	0.00
Smart tanks	3	26	17.3	10.7	1	5	2.5	1.9	-0.40	-0.05	-0.18	0.19	0.00	0.00	0.00	0.00
Scale and automation	20	50	35.0	21.2	4	8	6.0	2.8	-0.10	-0.05	-0.08	0.04	0.00	0.00	0.00	0.00
Deployment studies	5	50	20.8	17.7	2	10	4.8	2.9	-0.15	-0.05	-0.10	0.05	0.00	0.00	0.00	0.00
Demonstration	20	100	50.0	35.6	2	5	3.5	2.1	-0.20	-0.10	-0.15	0.07	0.00	0.00	0.00	0.00
Liquid hydrogen carriers	20	125	72.5	42.9	3	10	4.75	3.6	-0.95	-0.50	-0.73	0.23	0.00	0.00	0.00	0.00
Hybridization with renewables	1	30	11.3	13.0	3	10	5.8	3.0	-0.05	-0.03	-0.04	0.01	0.00	0.00	0.00	0.00
Recycling components	2	25	6.8	7.6	2	10	6.3	3.5	-0.25	0.00	-0.09	0.12	0.00	0.00	0.00	0.00

sbc = storage block cost, cyc = lifetime cycles

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
Critical mineral discoveries	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Domestication of the supply chain	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen to electricity advancements	-0.15	0.02	-0.03	0.10	-0.67	-0.05	-0.27	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen carrier advancements	0.00	0.15	0.05	0.09	-0.60	0.00	-0.28	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage tank materials	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Smart tanks	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scale and automation	0.00	0.00	0.00	0.00	-0.10	-0.05	-0.08	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Deployment studies	0.00	0.00	0.00	0.00	-0.15	-0.05	-0.10	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Demonstration	0.00	0.00	0.00	0.00	-0.20	-0.10	-0.15	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liquid hydrogen carriers	-0.04	0.00	-0.01	0.02	0.00	0.00	0.00	0.00	0.00	19.20	9.60	13.58	0.00	0.00	0.00	0.00
Hybridization with renewables	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Recycling components	0.00	0.00	0.00	0.00	-0.60	0.00	-0.25	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

rte = round-trip efficiency, bpc = balance of plant cost, fom = fixed operations and maintenance (O&M), vom = variable O&M

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