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Technology Strategy Assessment: Findings from Storage Innovations 2030 Thermal Energy Storage

June 2023

Changing the World's Energy Future

Hill Balliet, Luke McLaughlin, Zhiwen Ma, Kyle Glusenkamp

Idaho National Laboratory

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Technology Strategy Assessment

Findings from Storage Innovations 2030

Thermal Energy Storage

July 2023

About Storage Innovations 2030

This technology strategy assessment on thermal energy storage, released to assess progress towards the Long-Duration Storage Shot, contains 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

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Table of Contents

About Storage Innovations 2030 i

Acknowledgments ii

Background 1

Thermal Energy Storage Use Cases 1

Thermal Energy Storage Types and Media 2

Technologies 4

Current and Prospective Deployment 5

Pathways to \$0.05/kWh_e – Bidirectional Electricity 6

Commercially Deployed TES 6

Emerging Bidirectional TES 10

Pathways to \$0.05/kWh_t – Heat Input and Output 13

R&D Opportunities – Industrial Process Heat 13

R&D Opportunities – Buildings 14

Appendix A: Innovation Matrix and Definitions 17

Appendix B: Industry Contributors 18

Appendix C: Innovation Coefficients 19

Appendix D: Descriptive Statistics for Individual Innovations 20

References 22

Background

The concept of thermal energy storage (TES) can be traced back to the early 19th century, with the invention of the ice box to prevent butter from melting (Thomas Moore, *An Essay on the Most Eligible Construction of Ice-Houses*, Baltimore: Bonsal and Niles, 1803). Modern TES development began with building heating and cooling and concentrated solar thermal technologies for power generation in the early 1900s and late 1970s, respectively [1]. TES systems provide many advantages compared with other long-duration energy storage (LDES) technologies, which include low costs, long operational lives, high energy density, synchronous power generation capability with inertia that inherently stabilizes the grid, and the ability to output both heat and electricity [2], [3], [4].

Thermal Energy Storage Use Cases

TES technologies can couple with most renewable energy systems, including wind, photovoltaic, and concentrated solar thermal energy, and can be used for heat-to-heat, heat-to-electricity, electricity-to-heat, and electricity-to-electricity (bidirectional electricity) applications [2], [5], [6]. The three types of TES that have heat as an input or output are grouped together for the purposes of this report. Retrofitting retired thermal power plants can be a potential cost-effective option for TES with electricity output because they both use a similar thermal-to-electricity type of conversion [7]. Additionally, TES can directly serve heat demand for buildings and industrial processes, displacing fossil fuels to achieve broad decarbonization.

Bidirectional Electricity

Figure 1 shows a bidirectional electricity TES (ETES) architecture that is emerging as a prime technology for LDES at a grid scale. The ETES technology can utilize existing TES technology infrastructures, has no geological limitations (such as mountains and water for pumped storage hydro, underground natural caverns for compressed air energy storage, etc.), and is capable of deployment anywhere in the United States and the world for broad uses. Particularly, ETES technology can be placed at retired fossil-fueled thermal power plants to reuse decommissioned assets, protect job security in associated communities, and provide resilient and high-inertia (i.e., spinning) power to the grid.

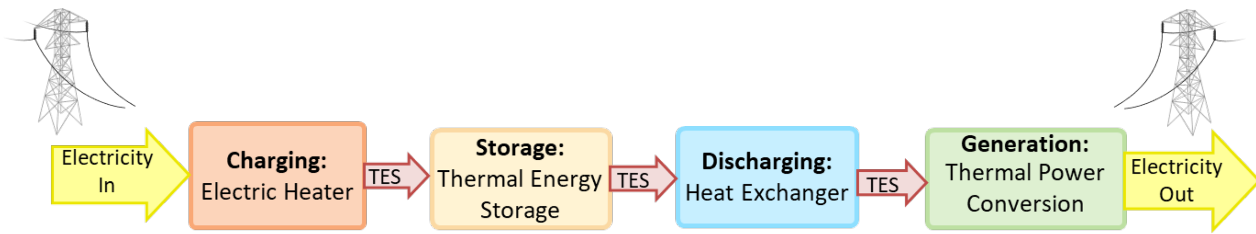

Figure 1. Stand-alone ETES application of electric-thermal energy storage independent from concentrating solar power

Heat Input and Output

There also are many ways to integrate TES within heat-to-electricity, heat-to-heat, and electricity-to-heat applications, such as those used in concentrating solar power (CSP), buildings, district heating, and industry process heat applications. These categories can be further classified for low- and high-temperature applications. High-temperature thermal energy storage (HTTES) heat-to-electricity TES applications are currently associated with CSP deployments for power generation. TES with CSP has been deployed in the Southwestern United States with rich solar resources and has proven its value to the electric grid. Electricity-to-heat and heat-to-heat HTTES applications present great potential for decarbonizing energy-intensive industrial process heat applications [8], [9], such as iron ore processing, iron smelting, cement production, glass manufacturing, mineral processing, and chemical production. Some industrial processes require process heat at temperatures > 1,400°C, so HTTES can be utilized to reduce fuel consumption in those processes through fuel, oxidizer, and process material pre-heating. Thermal energy storage for augmenting existing industrial process heat applications makes a much more attractive economic case because the energy penalty due to thermal-to-electric conversion is eliminated. Co-located applications of power production and heat also can add to the value stacking of integrating utility-scale TES; however, these scenarios are very case specific and not practically possible in many cases. These constraints are primarily attributed to the existing infrastructure being designed, developed, and constructed for many decades around the most economically feasible technologies, such as electricity and a selection of fossil fuels for heat input.

Low-temperature TES can be utilized for building and district heating and cooling, as well as some process heat applications in electricity-to-heat and heat-to-heat configurations. Lower temperature TES (LTTES) can be added to heat pump equipment (electric input), either directly interacting with the refrigerant in the condenser or evaporator, or through a secondary heat transfer fluid. It also can be integrated in the building envelope or within the ducts of the heating, ventilation, and air conditioning (HVAC) system. Cost-effective integration of TES into buildings adds significant cost, and it is one of the key barriers preventing the commercialization and deployment of TES. The optimal strategy for integrating TES with buildings has yet to be determined for various applications of TES. Nevertheless, thermal storage materials are far less costly per unit of energy stored than electricity storage materials. This means that thermal storage has the potential to reduce the cost to society of energy storage, as illustrated in Figure 2.

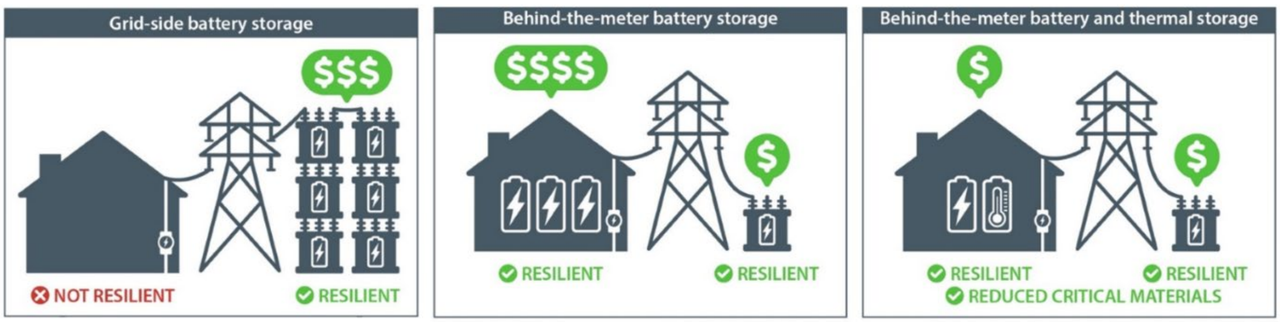

Figure 2. Three scenarios for future national-scale energy storage. (Left: Using only electricity-to-electricity (E-to-E), the grid side will require a very large investment. Middle: Moving E-to-E storage behind the meter will increase the cost but provide additional resilience to buildings. Right: Using thermal storage in buildings with E-to-E both in front and behind the meter may offer a pathway with the lowest overall cost to society.)

Thermal Energy Storage Types and Media

TES covers a broad range of energy formats by using a variety of storage media and energy conversion methods. Figure 3 introduces the major TES formats of sensible, latent, and thermochemical energy storage [10]. Large gaps still exist with latent (aside from water/ice) and thermochemical material choices, while sensible heat storage using liquids or solid particles has been deployed or is under pilot demonstration. The other main categorization of TES is high versus low temperature. HTTES technology is used for storing energy in the form of heat at temperatures above 300°C, which is suitable for power generation and some industrial processes [1], while LTTES is utilized for buildings, district heating, and other industrial process heat, such as food and beverage applications for drying and sterilization. Characterization of a TES system includes storage media, storage containment, and heat exchange/transfer (i.e., the ability of the TES system to support power generation or heat sources for efficient energy charging and discharging).

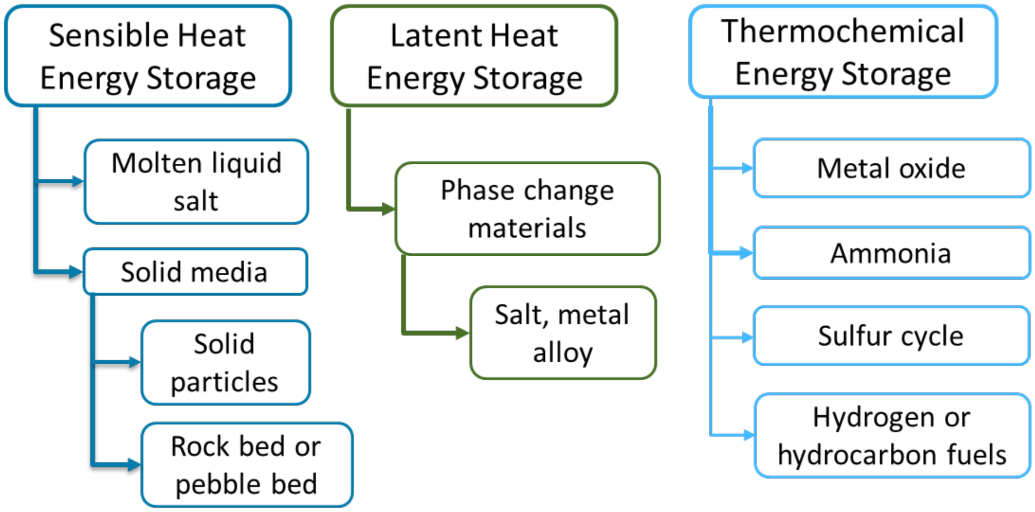

Figure 3. Types of thermal energy storage for power generation [10]

Sensible

Sensible heat storage is the most commercially deployed TES type and is applicable for both power generation and heating. In sensible heat, energy is stored by raising the temperature of a medium. The amount of energy stored is proportional to the physical properties of the storage material, including density, volume, specific heat, and temperature change of the storage material [11]. Molten nitrate salt (or solar salt, which is 60% $NaNO_3$ and 40% KNO_3, by weight) is commonly used as the thermal storage medium in commercial TES systems that store energy between 290°C and 600°C [12]. Molten salt as a storage medium has been applied in commercial CSP power plants since it was first demonstrated at Solar Energy Generating Systems plants in the 1990s [13]. Significant research outcomes regarding nitrate salt were obtained regarding the thermophysical properties, stability, and corrosion performance of alloys up to about 620°C, which represents an upper temperature limit for its practical use. TES in solid media, such as particles, concrete, and graphite, also has been developed or is under development and can be utilized at a very high temperature (> 1,000°C) [14], [15], [16], [17]. Figure 3 lists some TES media, including solid particles or rocks. Solid storage media obtained from nature can be abundant, low cost, and environmentally compatible. Ceramic- or sand-type solid particles as thermal storage media overcome the corrosion issues, the low-temperature freezing concerns of molten salt, and are attractive with high-temperature stability. Although some of the operating challenges experienced in the molten nitrate salt are mitigated by using a solid storage medium, new operational challenges arise when using solid media. This includes erosion in the application of moving sand-like particles and heat transfer fluid issues, such as contamination and low energy density in the case of a stationary porous solid media. Additionally, natural solid media storage includes the use of aquifers and consolidated or unconsolidated rocks found in the subsurface. This form of sensible storage takes advantage of large underground storage capacities, geothermal gradients, and natural thermal insulation.

Latent

TES can use latent heat associated with a phase change material (PCM), as shown in the middle column in Figure 1 [18]. Latent heat storage takes advantage of the relatively large amount of energy required to change the phase of the PCMs compared with raising its temperature. This increases energy density, with both latent and sensible heat contributing to the stored energy capacity. PCMs can be applied over a range of conditions, from low-temperature TES, such as building heating or cooling applications, to high-temperature TES for power generation or industrial process heat. HTTES PCM materials are less mature compared with sensible heat and have not been commercially deployed at a large power scale. LTTES PCM materials, such as water/ice, have existed for centuries, and new technologies, including bio-based, paraffin wax, and salt hydrate materials, are being developed for greater energy density and cyclability for promising building heating and cooling applications.

Thermochemical

The third TES option—thermochemical energy storage (TCES) [19]—offers high energy density by storing energy in reaction heat, such as in reduction/oxidation cycles. TCES can provide significant energy density and, thus, has a potential and unique opportunity for seasonal storage or to be transportable as a fuel. Energy quality, gauged by exergy, depends on the charging temperature with respect to the discharging temperature when driving a thermal power cycle or thermochemical processes for material production. Degradation in TCES media performance with long-term cycling is a key challenge in these systems.

Technologies

A broad array of high-temperature and low-temperature TES technologies are deployed in commercial settings and many technologies are under development. The general principles encompassing many technological variations are captured here, and it is noted that the described technologies can be deployed in bidirectional electricity or other heat configurations.

A majority of TES systems rely on a heat transfer fluid (HTF) to charge and discharge the energy storage system and can be categorized as single- or two-containment vessel systems [11]. Containment systems can include engineered structures, such as tanks, as well as natural geological features, such as an underground cavity or pit. For example, reservoir thermal energy storage utilizes subsurface geological features for storage, while traditional molten salt TES utilizes engineered tanks. The circulated HTF can have direct or indirect contact with the storage medium, or the HTF also can be the storage medium. Molten salt systems commonly utilize the salt as both the HTF and the storage medium. Single-containment vessel systems, or thermocline systems, rely on a temperature gradient across a storage material to store usable energy. To charge or discharge the system, a hot or cold HTF is pushed through the system, respectively [15], [17], [20]. The zone of varying temperature created during charge and discharge is a thermocline, and system performance is enhanced by having a sharp thermal gradient. Two-containment vessel systems utilize nominally isothermal hot and cold storage vessels to store energy proportional to the energy difference between the two tanks [21].

These technologies can be utilized in bidirectional electricity or other heat applications, depending on the energy input and output components used in the system. Innovative TES systems are utilizing novel charging and discharging methods to enable bidirectional electrical TES, improve system efficiency, and reduce system costs. Heat pumps and resistive heating are being developed for electrified system charging, while solar thermal, nuclear, or captured waste are being developed for heat-input applications. Thermophotovoltaics (TPVs) and advanced power cycles are being developed for high efficiency and low-cost system discharging. Heat pump-based systems can efficiently supply heat for a TES system by capturing energy from a thermal reservoir prior to heat addition, and these systems can operate in conjunction with single- or multiple-containment systems. Resistive TES charging can be accomplished with off-the-shelf cartridge heaters or resistive wire and can be used to directly or indirectly heat storage media to temperatures > 700°C [22]. For discharge, TPV technology converts heat into electricity using a combination of a thermal emitter and a photovoltaic cell and can operate at high temperatures to achieve high efficiency. Advanced power cycles, such as the recompression supercritical carbon dioxide Brayton cycle, can utilize a 750°C turbine inlet temperature to achieve thermal to electric efficiencies near 55% (nearly 10% better than the Rankine cycle) [23].

These novel charging and discharging technologies are in the early stages of development but show promise for future deployments in power generation and industrial processes. Although heat pumps are a mature technology, high-temperature applications above 300°C are not yet commercially available. Resistive heating also is a mature technology; however, high power capacity/temperature TES heating, specifically of a gaseous heat transfer fluid, needs to be demonstrated at a commercial scale. The TPV concept was established nearly 50 years ago and the latest development shows up to 40% conversion efficiency; however, the commercial production process has not yet been established. Advanced power cycles show more promise for achieving efficient energy discharge, with efficiencies near 55% [23].

Current and Prospective Deployment

Approximately 234 GWh of TES capacity were installed globally at the end of 2019 [24]. Nearly 85% of the installed TES systems account for building, district, and industrial process heating. HTTES systems have been historically deployed using molten salt as the energy storage medium with CSP technologies. In the United States, there are two molten salt CSP + TES deployments: (1) Solana Generating Station with a power capacity of 280 MW_e and 6 hours of storage, and (2) Crescent Dunes with a power capacity of 100 MW_e and 10 hours of storage. Many other CSP + TES systems have been deployed around the world [25], including Noor III in Morocco and Cerro Dominador in Chile.[a]

To improve TES system power generation efficiency and reduce costs, the Solar Energy Technologies Office's CSP Program in the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy (DOE), has focused technology development on Generation 3 CSP technology using solid particles as thermal storage media, rather than molten nitrate salt, and advanced power cycles for power generation [26]. The DOE CSP Program recently broke ground on a Generation 3 Particle Pilot Plant (G3P3) with 6 MWh of thermal energy storage at Sandia National Laboratories.[b] The G3P3 pilot will show storage dispatch temperatures greater than 700°C for integration with a supercritical carbon dioxide Brayton power cycle. The G3P3 system will demonstrate solid-particle TES with solar thermal input and efforts are ongoing at the National Renewable Energy Laboratory and Sandia National Laboratories to demonstrate this technology with electric particle heating for bidirectional electricity applications.

Storage Innovation Framework

While different types of TES have shown promise for bidirectional long-duration storage, the SI Framework, described in P. Balducci et al. [27], was only applied to two-tank TES with molten salt storage media and steam turbines. The data required to perform an analysis with the Framework are not available for lower technical readiness level technologies. It is noted that two-tank TES with molten salt has only been deployed in a heat-to-electricity configuration with solar thermal and nuclear heat input; however, it is considered for bidirectional applications here. The cost and performance values (Table 1) are derived exclusively from V. Viswanathan et al. (2022). Innovative types of thermal storage, such as moving or stationary solid-particle TES, are not at this technology readiness stage but show a high potential for meeting the needs of the clean energy transition, regardless of the results for molten salt [3], [15], [28] as defined for 100-MW, 10-hour molten salt storage with steam turbine system in 2030 with current levels of investment. These values result in a calculated levelized cost of storage (LCOS) of $0.134/kWh [27]. Innovative types of thermal storage, such as moving or stationary solid-particle TES, are not at this technology readiness stage

[a] https://solarpaces.nrel.gov/

[b] https://www.energy.gov/eere/articles/doe-breaks-ground-concentrating-solar-power-pilot-culminating-100-million-research

but show a high potential for meeting the needs of the clean energy transition, regardless of the results for molten salt [3], [15].

Table 1. Molten salt storage with steam turbine, cost, and performance (2030 estimates)

Parameter	Value	Description
Storage Block Calendar Life	35	Deployment life (years)
Power Electronics Cycle Life	9,125	Number of cycles before replacement of power equipment + balance of plant
Round-trip Efficiency (RTE)	44%	Base RTE
Storage Block Costs	88	Base storage block costs ($/kWh$_e$)
Balance of Plant Costs	16	Base balance of plant costs ($/kWh$_e$)
Controls and Communication Costs	1.50	Controls and communications costs ($/kW$_e$)
Power Equipment Costs	1645.7	Power equipment costs ($/kW$_e$)
System Integration Costs	30	System integration costs ($/kWh$_e$)
Project Development Costs	63.62	Project development costs ($/kWh$_e$)
Engineering, Procurement, and Construction (EPC) Costs	26.86	EPC costs ($/kWh$_e$)
Grid Integration Costs	12	Grid integration costs ($/kWh$_e$)
Fixed Operations and Maintenance (O&M) Costs	53.7	Base fixed O&M costs ($/kW$_e$-year)
Variable O&M Costs	0	Base variable O&M costs ($/kWh$_e$)

Pathways to $0.05/kWh$_e$ – Bidirectional Electricity

Commercially Deployed TES

Molten salt two-tank systems with a steam turbine were first considered for a pathway to $0.05/kWh$_e$ because of their existing use in commercial CSP and nuclear settings. The SI Framework was applied to the technology to systematically capture and synthesize the industry's sentiments about the future of the technology. 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. This Framework, although robust for molten salt TES technology, does not capture the impact of emerging TES technologies that show promise for achieving the $0.05/kWh$_e$ DOE goal in a bidirectional electricity application.

A large group of 23 subject matter experts (SMEs) were identified and contacted. These SMEs represented 20 organizations, ranging from industry groups to vendors and universities. The Framework Team conducted interviews, soliciting information regarding pathways to innovation and the associated cost reductions and performance improvements. The innovations defined by the SMEs are presented in Table 2. Definitions of each innovation are presented in Appendix A.

Table 2. List of innovations by category (descriptions are found in Appendix A)

Innovation Category	Innovation
Supply chain	Domestication of supply chains
Technology components	Heat-to-electricity conversion improvements
	Electricity-to-heat conversion improvements
	Component standardization
	Single-tank storage
Advanced materials development	Mass production and automation
Deployment	Deployment policies
	Large-scale demonstration
	Small-scale demonstration
	Deployment efficiency
End of life	Salt recycling

Input from SMEs was used to define the requirements and timelines for investment, potential impacts on performance (e.g., round-trip efficiency, cycle life), and the cost (e.g., storage block, balance of plant, operations and maintenance) impacts of 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 achievable outcomes by 2030 with regard to LCOS.

Figure 4 also shows the prevalence of each innovation in portfolios that ranked among the top 10% of the most effective portfolios. The LCOS range with the highest concentration of simulated outcomes is in the \$0.12 to \$0.14/kWh$_e$ range (Figure 5). However, some portfolios substantially reduce LCOS, with the highest impact portfolios (top 10%) resulting in an LCOS of between \$0.107 and \$0.116/kWh, denoted by the marked region.

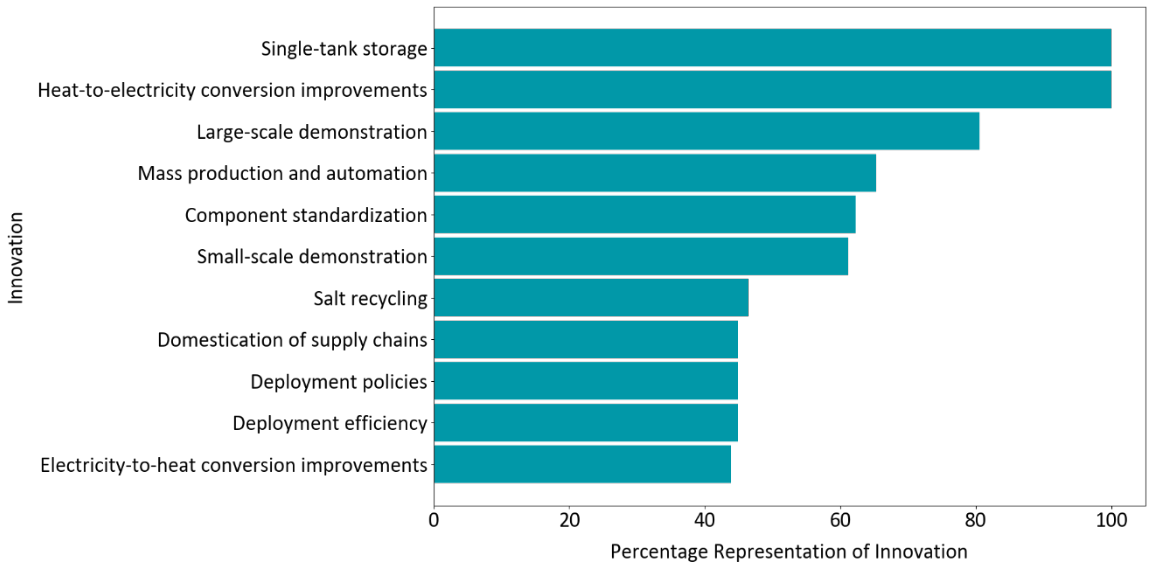

Figure 4. Representation of innovations in portfolios performing in the top 10%

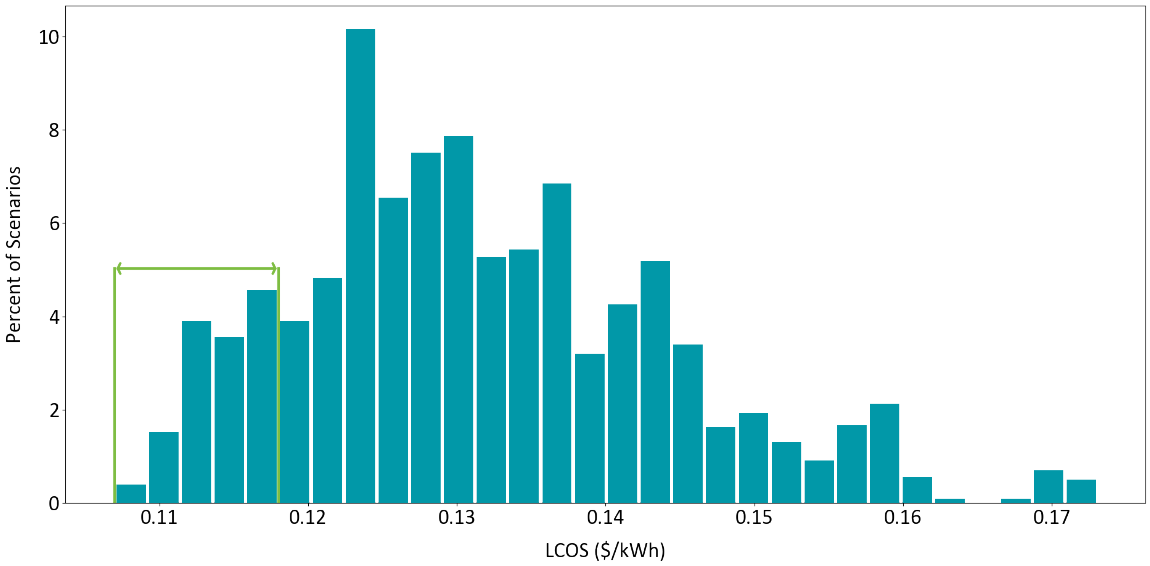

Figure 5. Portfolio frequency distribution across LCOS. The green rectangle indicates the bins containing the top 10% of the portfolios.

The results of the Monte Carlo simulation for the portfolios that fall within the top 10% in terms of LCOS impact are presented in Figure 6. The vertical line indicates that the mean portfolio's cost is $759 million. The x-axis values represent the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements. Total expenditure levels with the highest portfolio densities in the top 10% are in the $700 million to $900 million range, and the timeline required to achieve these LCOS levels is estimated at 6 to 8 years.

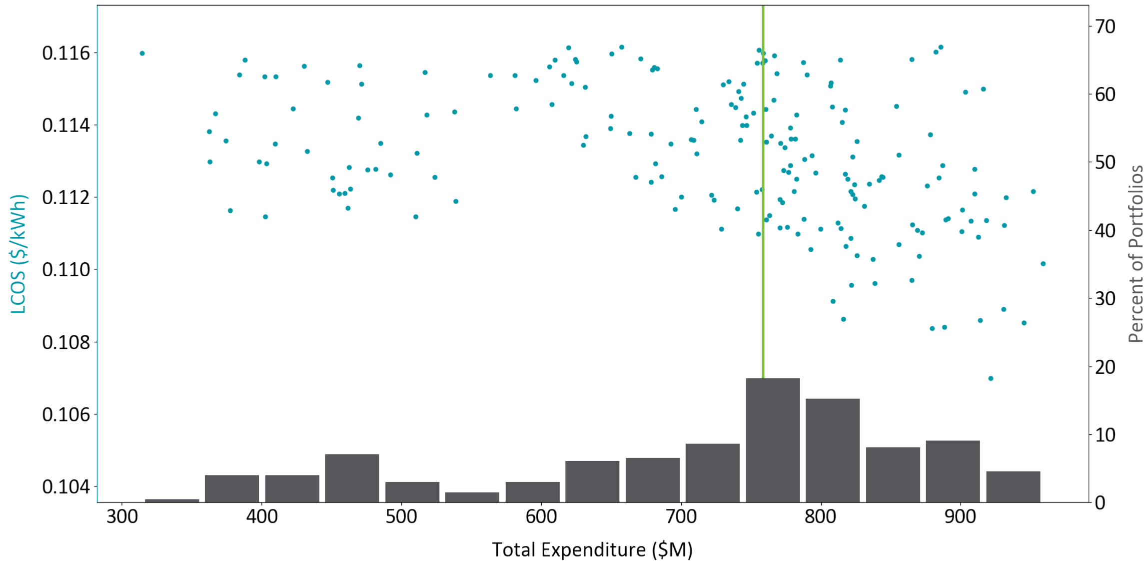

Figure 6. LCOS and industry expenditures for the top 10% of the portfolios

Note that the impact of each layered innovation is not necessarily additive. The impact of each additional innovation is weighted using logic to determine the combined impact. Combinations of investments can be in conflict with or related to alternative technical solutions, thus diminishing their combined impact. Innovation coefficients, which scale the combined impact, for each pair of innovations are presented in Appendix C. These innovation coefficients account for any overlapping or incompatibility of pairs of innovations.

SMEs also were asked for their preferences regarding the investment mechanism, selecting among National Laboratories research, R&D grants, loans, and technical assistance. Table 3 presents the SME preferences for each mechanism. R&D grants were generally seen to be important across all innovations, while technical assistance was considered to be less important.

Table 3. SMEs' preferences for investment mechanisms. Cells with asterisks (*) represent more preferred mechanisms. Cells with daggers (†) represent the second most preferred mechanism. (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
Domestication of supply chains	0%	0%	0%	17% *
Heat-to-electricity conversion improvements	50% *	17% †	17% †	0%
Electricity-to-heat conversion improvements	17% †	33% *	0%	0%
Component standardization	33% *	33% *	17% †	17% †
Single-tank storage	33% *	50% *	33% †	0%
Mass production and automation	0%	67% *	50% *	0%
Deployment policies	50% *	33% †	0%	0%
Large-scale demonstration	33% †	67% *	50% *	17% †
Small-scale demonstration	50% †	83% *	17%	0%
Deployment efficiency	0%	33% *	33% *	33% *
Salt recycling	33% *	33% *	17% †	17% †

R&D Opportunities for Bidirectional Molten Salt

Table 4 shows the rest of the results from the SME discussions. As presented in Table 4, single-tank storage consistently yields metrics in the top tier (notated with asterisks [*]) and the mid-tier (notated with daggers [†]). Round-trip efficiency and storage block cost improvements have the greatest impact on LCOS for molten salt thermal storage; however, few innovations improve round-trip efficiency. Turbines that convert heat to electricity are well studied and have been commercially deployed at coal and natural gas power plants long enough to reach full maturity. This means that it is unlikely that any innovation will improve their efficiency. Avoiding the loss of efficiency from electricity generation is one of the reasons that process heat applications have attracted significant interest from the thermal storage industry. More detailed data, including minimum and maximum values and standard deviations for each metric, are presented in Appendix D.

Table 4. The impacts of proposed R&D investment levels and timelines. All numbers are derived from SME discussions. Cells with asterisks (*) are top-tier effects and cells with daggers (†) are mid-tier effects.

Innovation	Storage Block Cost Impact (%)	Cycle Life Improvement (%)	Round-trip Efficiency Impact (% points)	Mean Investment Requirement (million $)	Mean Timeline (in years)
Domestication of supply chains	0	0	0	55 †	2 *
Heat-to-electricity conversion improvements	0	0	7.5 *	18.3 *	3.1 *
Electricity-to-heat conversion improvements	0	20 *	0	85	3.5 †
Component standardization	-5	1.7	0	39.2 †	3 *
Single-tank storage	-44 *	7.5 †	1.5 †	24.1 *	4.5
Mass production and automation	-25 †	1.7	0	59.4 †	3.8 †
Deployment policies	-2.5	0	0	18 *	3 *
Large-scale demonstration	-22 †	5 †	1.5 †	350.6	5.9
Small-scale demonstration	-16 †	5 †	1.5 †	101.5	4.2 †
Deployment efficiency	-7.5	2.5	0	13.5 *	4.3 †
Salt recycling	-3.3	0	0	11.8 *	5.3

While these results show that industry has not coalesced around a pathway for molten salt to reach \$0.05/kWh$_e$, it is important to note that there are other types of thermal energy storage that have shown promise for bulk grid storage. These emerging technologies are described in the following section.

Emerging Bidirectional TES

Several emerging solid and liquid media TES technologies show great potential for meeting future TES cost and performance requirements. A moving-particle solid storage system uses internally insulated silos to store particles and relies on the force of gravity to move high-temperature storage material through heaters, moving bed or fluidized bed heat exchangers, and between-storage vessels to minimize parasitic power inputs [16], [29]. Moving-particle TES can be charged with heat pump or resistive electrical input (as well as solar thermal, nuclear, or waste heat input) and can be discharged with existing or advanced power cycles to replace traditional thermoelectric generating stations. Moving-particle TES with refractory-insulated concrete silos and a low storage cost material, such as silica sand with a cost of ~\$30 to \$40/ton, has the potential for installed costs near \$2/kWh$_t$ and an LCOS of \$0.05/kWh$_e$ [3], [30]. Stationary solid media, or packed-bed, storage also uses low-cost storage media and can utilize terrestrial repositories for months of energy storage [15]. Packed-bed TES, or Terrestrial Heat Repository for Months of Storage (THERMS), relies on the movement of a gaseous heat transfer fluid rather than solid media to charge and discharge the storage system [15]. Like moving-particle TES, packed-bed TES can be charged electrically (or with heat) and be deployed with existing or advanced power cycles for power generation. Although recent increases in labor and material costs due to the COVID-19 pandemic have made it difficult to reach DOE cost targets, innovative TES deployments may leverage existing thermal power generation and the infrastructure of gas- or coal-fired plants to minimize the capital investment for an economic path to integrate TES into the electric grid. For example, packed-bed TES can achieve an LCOS < \$0.10/kWh$_e$ when used to retrofit a thermoelectric generating station [31].

The electricity purchase price, round-trip efficiency, capital cost, service life, number of annual cycles, and storage duration of TES systems all influence the LCOS of existing and emerging TES technologies. Technologies seeking to meet the DOE cost targets must reduce costs by addressing each of these parameters. Figure 7(a) presents the results of a sensitivity study that identified the economic impact that each parameter has on TES LCOS, using low, target, and high values [3]. Figure 7(b) lists the assumptions used for other cost and performance metrics. The results show what parameter costs are required to meet the \$0.05/kWh$_e$ LCOS goal using the ARPA-E DAYS (Advanced Research Projects Agency–Energy Duration Addition to Electricity Storage) formula, and it shows which cost parameters are most important to address [3].

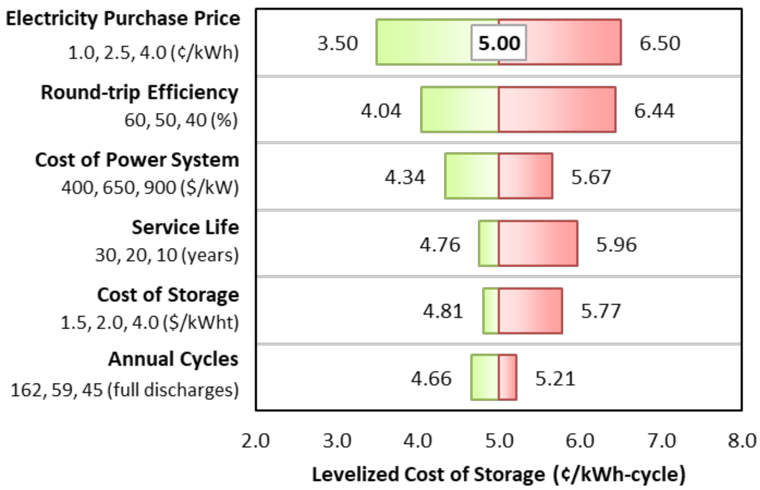

Figure 7(a). Techno-economic scenarios for achieving the \$0.05/kWh$_e$ LCOS goal using the ARPA-E DAYS formula [3]

Parameter	Value
Duration (hours)	100
Capacity (MW)	400
O&M (\$/kW$_e$/year)	0.00171
Controls and communications	0
System Integration	0
Project Development	0
EPC	0
Nominal discount rate	10%

Figure 7(b). Table of assumptions for cost and performance metrics not listed in 7(a)

R&D Opportunities for Emerging Bidirectional TES

Highest impact opportunities: High-temperature TES, with a focus on single- and two-containment vessel solid media storage, provides an opportunity to advance bidirectional electricity TES. In a bidirectional electricity setting, these materials increase energy density, increase power cycle efficiency, and ultimately reduce the cost and carbon footprint of energy delivered from HTTES. Furthermore, these materials enable heating with an electrically heated HTF, direct ohmic heating, or electrically induced radiative heating. A high impact can be achieved through the development of HTTES storage and charging/discharging systems. Additionally, HTTES with solar thermal or nuclear input and reservoir thermal energy storage systems show promise for power generation applications despite utilizing heat for energy input rather than electricity.

Examples of Promising Innovations:

- Ceramic and earth-based storage materials (e.g., rocks and sand) having a low cost and high stability at high temperatures (> 1,000°C)
- Advanced single- and two-tank TES designs: Moving-particle and packed-bed TES
- Next-generation molten salt technology reaching higher operating temperatures with lower cost salts
- Advanced power cycles: Recompression supercritical carbon dioxide Brayton cycle and combined cycles

Identification of areas of need: The Flight Paths listening sessions have informed the technical and non-technical aspects of TES technologies, particularly ETES, that need further development to de-risk commercial investment and accelerate widespread deployment of TES technologies for bidirectional electricity energy storage applications.

Technical Areas of Need:

- **High power capacity electrical heaters:** Electrical heating of gaseous, fluid, and solid energy storage media has been identified as a necessary development for low-cost and reliable deployment of high-temperature TES technologies. Low power capacity heating of TES media has been demonstrated; however, high power heating poses technical challenges that need to be addressed to achieve high efficiency and dependable ETES systems. High power heating, which is necessary for rapid charging when intermittent renewable electricity is available, induces large thermal gradients and thermomechanical stress within heating elements that can lead to premature failure. Corrosion of high-power heater elements also must be assessed when heaters are used in applications with exposure to oxygen or reactive media.
- **Reliability, resiliency, and control assessments via the demonstration of an integrated TES system:** Testing high-temperature solid media TES systems under realistic conditions (i.e., grid connections and intermittent renewable energy charging) was identified as a critical path for identifying systems that can deliver reliable and uninterrupted power to the grid under sustained, rapid response, and other adverse operating conditions. To ensure that bidirectional electricity HTTES can provide stable and predictable power to the grid, it is important to assess system performance when there are variations in demand, storage temperature, charging intervals, and storage holding durations. TES systems must be able to meet the system ramp rates necessary to dispatch power when needed to meet grid demand. System gain settings, dead band, and other grid-connection parameters must be better understood prior to implementation in a commercial setting.
- **High-temperature media handling:** The controllability and flowability of particles are important. Innovative solutions should be investigated to convey and monitor the movement of hot particles. The transportation of high-temperature heat transfer and storage media requires affordable, long-lived materials and equipment rated for high temperatures. Existing materials and equipment, such as high-temperature alloys, pumps, lifts, and so forth, must be further developed for higher temperatures and improved operational lives. U.S. supply chains for such components must be further established to increase availability and reduce costs and reliance on international markets.
- **Solid media abrasion assessment:** High-temperature solid media experiencing thermal and physical transportation cycles must be further characterized. Studies have validated the durability of solid media under static thermal cycling; however, the effect of solid media transportation on solid media and system containment degradation is not well characterized.

Non-Technical Areas of Need:

- **Availability of test beds/facilities:** Test beds and facilities are crucial for evaluating and de-risking new technologies prior to commercial deployment. These facilities provide a controlled environment for assessing performance, reliability, and safety under realistic operating conditions. Test beds minimize risk by allowing for the identification of technical, operational, and safety issues before being deployed at a large scale with large capital risk. Performance assessment also is necessary to identify operational and technical areas of improvement to drive down costs and increase power output. Test beds also are needed to enable the completion of regulatory compliance assessments. Companies may need to ensure that their products meet compliance requirements and relevant standards.

Pathways to \$0.05/kWh$_t$ – Heat Input and Output

Due to the versatility of TES, efforts have been undertaken and are ongoing to determine the pathway to an equivalent \$0.05/kWh$_e$ for electricity-to-heat, heat-to-electricity, and heat-to-heat TES applications [32]. The cited efforts have demonstrated that the electricity-to-electricity framework of LCOS can be adapted for a variety of TES use cases. This work does not present a pathway analysis but rather a methodology for measuring LCOS when heat is an input or output.

R&D Opportunities – Industrial Process Heat

TES for industrial process heat applications can use sensible heat storage at various temperatures for different applications [33]. While other LDES technologies are restricted to electrical-to-heat conversions for process heat applications, HTTES can be charged with heat or electrical input and deliver high-temperature heat directly to the process due to the thermal nature of the energy storage.

Highest Impact Opportunities

Solid storage media high-temperature TES technologies have an opportunity for the highest impact in advancing TES for industrial process heat decarbonization due to their wide range of temperature applicability. When the end use of the energy is for thermal loads, storing thermal energy rather than electrochemical can be more cost effective [34].

Examples of Promising Innovations

- High-temperature (> 1,000°C) solid media TES using low-cost and naturally abundant material
- Single- or multi-containment systems that are designed for direct integration into industrial processes
- Storage-to-process heat exchangers rated for high temperatures (> 600°C)

Identification of Areas of Need

The Flight Paths industry listening sessions have informed the technical and non-technical aspects of TES technologies that need further development to widely decarbonize industrial process heat.

Technical Areas of Need

- **Efficiency of heat transfer to the industrial process:** The delivery of high-temperature heat to industrial processes needs to be improved to increase system efficiency and reduce the volumetric footprint. Innovative TES-to-process heat exchangers should be developed. Auxiliary components, including valves and ducting, should be improved for TES + process heat deployments.
- **Consistency of delivered heat temperature:** Delivery of heat at a constant power and temperature is important for many industrial processes. The development of control strategies and hardware to maintain a consistent delivery temperature to industrial processes needs further development. As thermal reserves are depleted, control strategy and delivery techniques must be improved for commercial deployment.

- **Design for assembly, maintenance, and operation:** The design of the integration of a new energy source in the form of a TES unit with an existing process needs to utilize existing technologies and supply chains as much as possible. In order to better leverage the capabilities of the existing technologies, it is important to identify and use such tools for integrating a TES unit.
- **Simplification of process integration:** The integration of the new process with the existing process must be simplified to minimize change to the existing infrastructure and subsequently the infrastructure upgrade costs.

Non-Technical Areas of Need

- **Supply chains for high-temperature components:** Since the COVID-19 pandemic, supply chains for high-temperature materials and components needed for high-temperature TES systems have been disrupted. The improved availability of these materials and components are needed for cost-effective deployment of TES systems for industrial process heat decarbonization.
- **The use of locally available materials and existing supply chains:** Using locally available natural resources, in most cases, leads to solutions that maximize cost effectiveness and are not too dependent upon external (potentially volatile) supply chains. Supply chains that are supporting the existing energy industry and providing the equipment, materials, and technology solutions should be incorporated in the new technology integration to reduce the time to commercial deployment.

R&D Opportunities – Buildings

Thermal energy storage in buildings can be used to adjust the timing of electricity demand to better match intermittent supply and to satisfy distribution constraints. TES for building heating and cooling applications predominantly utilizes sensible and latent heat technologies at low temperatures (i.e., near room temperature). Most building applications are electricity-to-heat form of storage.

Next-generation TES materials, new integration strategies, improved system design and operation, and advancements in codes and standards for behind-the-meter storage can foster sustainable, scalable, affordable, and equitable solutions to meet building sector energy and climate goals. In the long term, TES is expected to have lower total installed costs compared with electricity-to-electricity storage, particularly in applications where ambient temperatures allow for larger heat-pump coefficient of performance ratios between charging and discharging periods.

The U.S. DOE Building Technologies Office is developing a roadmap for thermal storage in buildings to support U.S. decarbonization efforts. Methods for evaluating the benefit in terms of cost per kWh_e have been developed [31] and thermal storage in buildings represents a promising pathway to achieving less than $0.05/$kWh_e$.

Highest Impact Opportunities

The U.S. building stock is comprised of 126 million commercial and residential buildings, totaling 329 billion square feet of floorspace [35]. About 74% of U.S. total electricity is consumed in buildings [36] and more than 50% of the consumed electricity is for meeting thermal demands in the building, such as space heating, space cooling, water heating, and refrigeration [37]. Thus, applying TES in buildings could address a major portion of the national storage requirements. TES could directly help reduce the need for electric grid reinforcement resulting from electrification of space heating, especially in cold climates. TES also can reduce summer peak demand while meeting the increasing cooling demand. By integrating TES in buildings, the behind-the-meter demands of electricity in buildings can be flexible, which could increase the utilization of renewable generation and shift electricity demand to periods of high solar power generation. Decentralized TES in buildings also could reduce grid dependency and enhance the security of the energy supply in buildings in areas where the grid is weak or unreliable [24]. This is particularly important for buildings in coastal areas with critical equipment (e.g., hospitals in New York City).

Applying TES in existing buildings, especially all-electric buildings where electricity is consumed for thermal demands, could have the greatest impacts. Areas with a high energy burden, such as low-income areas with electric baseboard heating, should be prioritized for TES to reduce energy costs and the requirement for upgrading electrical panels [38].

Examples of Promising Innovations

- Low-cost, high-performance PCMs that have improved thermal properties and corrosion resistance could reduce the size and cost, improve efficiency, and increase the charging/discharging rates of TES.
- Plug-play TES with advanced control that can be integrated with existing building energy systems with minimal incremental cost.
- Communication platforms to enroll customers, assess their storage capabilities, and remotely control the charge/discharge of distributed energy storage systems based on grid signals to enable large-scale deployment [39]. Through these platforms, transactive control between the grid and the aggregator can be performed and the needed demand-side management can be conducted through controls at a building level [40].

Identification of Areas of Need

As indicated in the DOE Flight Paths industry listening sessions, a comprehensive analysis of value proposition for integrating TES in buildings is needed to show the value to stakeholders, including building owners/occupants, builders, HVAC equipment manufacturers, and utilities. To realize the value of TES solutions, they must be more cost effective than the alternatives (e.g., electrochemical batteries). Achieving this requires the cost of TES equipment and integration with building needs to be reduced and the performance (and the added value) needs to be further improved and demonstrated under real-world operating conditions. The areas of need are categorized below in technical and non-technical areas.

Technical Areas of Need

- **Low-cost and high-performance TES and its integration with a building's energy systems:** To minimize the installation cost and time on-site, TES could be integrated within HVAC equipment at the factory or be easily connected in the field (e.g., by an HVAC technician/plumber). Additionally, the size and weight of TES need to be minimized, especially for low-income, multifamily buildings.
- **Intelligent controls for improving performance and easing implementation:** The advanced supervisory control algorithms that optimize the operation of HVAC and storage based on grid signals still require engineering expertise and a long time to set up and tune for each building. These challenges need to be addressed to make equipment-integrated TES more scalable and cost effective.
- **Simulation and design tools to facilitate design optimization of TES systems:** Traditional modeling tools for HVAC design do not consider building-integrated TES. Reliable and easy-to-use modeling tools are needed to allow engineers to design and optimize TES design, system integration, and controls for building-integrated TES.
- **Communication platforms to enable the aggregation of distributed TES to actively respond to the demand management of electric grids:** To scale up the impact of TES,

communication platforms and transactive control algorithms are needed to enroll customers, assess their storage capabilities, and remotely control the charge/discharge of distributed TES based on grid signals.

Non-Technical Areas of Need

- **Supporting utility tariffs and incentives:** The lack of utility incentives is the top barrier for TES deployment [38]. Building owners are unlikely to invest capital in TES without incentives; however, without user data from buildings, utilities are not convinced that they should subsidize or incentivize. It was important to identify and demonstrate the use cases (e.g., building type and end use served) for which TES has a clear and quantifiable value to utilities.
- **Including TES in building codes and standards:** Current building energy code cost-effectiveness analyses do not capture the value of TES, which may increase total energy usage, but better utilize resources to reduce energy costs and emissions. Market adoption of TES could be incentivized by receiving credit and recognition in the building codes and standards. To properly evaluate the contribution of load shifting and the resulting emissions reduction by using TES, the real-time data of greenhouse gas emissions from the grid need to be captured and shared on a more incremental basis.

TES can be realized technically; however, economic competitiveness is challenging when low-cost, easy-access natural gas and coal resources are available. Combining low-cost TES technologies and renewable inputs to provide a continuous supply of electricity or heat can become economical with improved funding, policy mechanisms, and the development of regulatory frameworks and standards. TES technologies, when combined with renewable energy input, can be deployed in both bidirectional electricity and heat input and output configurations to help decarbonize broad energy sectors that rely on fossil fuels in power generation, buildings, and industry processes. The cost reduction in renewable generation associated with the low-cost TES will be a deployment route for end-user acceptance.

Appendix A: Innovation Matrix and Definitions

Table A.1. Innovation Matrix and Definitions

Innovation Category	Innovation
Supply chain	Domestication of supply chains
Technology components	Heat-to-electricity conversion improvements
	Electricity-to-heat conversion improvements
	Component standardization
	Single-tank storage
Advanced materials development	Mass production and automation
Deployment	Deployment policies
	Large-scale demonstration
	Small-scale demonstration
	Deployment efficiency
End of life	Salt recycling

Domestication of supply chains: Developing a supply chain for balance of plant components used by thermal storage devices and salt within the United States.

Heat-to-electricity conversion improvements: Improving and incorporating positive displacement generation, low-pressure turbines, and thermophotovoltaics.

Electricity-to-heat conversion improvements: Improving the performance of the device that converts electricity to heat for storage.

Component standardization: Standardizing and modularizing components in thermal storage systems to improve compatibility and competition.

Single-tank storage: Developing single-tank thermocline storage to replace dual-tank thermal storage.

Mass production and automation: Mass producing and automating the manufacturing of high- and medium-temperature heat exchangers, thermophotovoltaics, electrolyzers, and fuel cells.

Deployment policies: Advanced studies on market policies and regulations to improve the deployment of thermal storage in the grid.

Large-scale demonstration: Demonstrating pilot thermal storage systems above 100 MW.

Small-scale demonstration: Demonstrating pilot thermal storage systems below 1 MW.

Deployment efficiency: Investing in techniques and technologies to increase deployment efficiency.

Salt recycling: Improving the efficiency of the supply chain for salt recycling.

Appendix B: Industry Contributors

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

Participant	Institution
Sumanjeet Kaur	Lawrence Berkeley National Laboratory
Steve Bisset	Terrajoule Energy, Inc.
Frederic Bourgault	New Leaf Management Ltd
Philip Brennan	Echogen Power Systems, Inc.
Bruce Anderson	247Solar, Inc.
Benjamin Hoffman	Themes LLC
Justin Briggs	Antora Energy
Bill Conlon	Pintail Power
Ravi Prasher	Bloom Energy/University of California, Berkeley
Thomas Bauer	German Aerospace Center
Hanna Breunig	Lawrence Berkeley National Laboratory
Rami Saeed	Idaho National Laboratory

Appendix C: Innovation Coefficients

Table C.1. Innovation coefficients

Innovation	Domestication of supply chains	Heat-to-electricity conversion improvements	Electricity-to-heat conversion improvements	Component standardization	Single-tank storage	Mass production and automation	Deployment policies	Large-scale demonstration	Small-scale demonstration	Deployment efficiency	Salt recycling
Domestication of supply chains	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50
Heat-to-electricity conversion improvements	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Electricity-to-heat conversion improvements	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Component standardization	1.00	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Single-tank storage	1.00	1.00	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00
Mass production and automation	1.00	1.00	1.00	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00
Deployment policies	1.00	1.00	1.00	1.00	1.00	1.00	–	1.00	1.00	0.50	1.00
Large-scale demonstration	1.00	1.00	1.00	1.00	1.00	1.00	1.00	–	0.50	0.50	1.00
Small-scale demonstration	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	–	0.50	1.00
Deployment efficiency	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	–	1.00
Salt recycling	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	–

Appendix D: Descriptive Statistics for Individual Innovations

Table D.1. Descriptive statistics for individual innovations

Innovation_cat	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
Supply chain	Domestication of supply chains	10.00	100.00	55.00	63.64	1.00	3.00	2.00	1.41	-0.05	0.00	-0.03	0.04	0.00	0.05	0.03	0.04
Technology components	Heat-to-electricity conversion improvements	1.00	100.00	18.25	33.23	2.00	5.00	3.13	0.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Electricity-to-heat conversion improvements	40.00	150.00	85.00	50.66	1.00	5.00	3.50	1.73	0.00	0.00	0.00	0.00	0.00	0.30	0.15	0.21
	Component standardization	20.00	75.00	39.17	21.08	1.00	5.00	3.00	1.26	-0.50	-0.05	-0.21	0.20	0.00	0.05	0.02	0.03
	Single-tank storage	1.00	100.00	24.13	34.64	3.00	8.00	4.50	2.35	-0.75	-0.20	-0.44	0.19	0.00	0.20	0.08	0.10
Advanced materials development	Mass production and automation	10.00	200.00	59.38	63.66	2.00	7.00	3.75	1.75	-0.75	0.00	-0.25	0.43	0.00	0.05	0.02	0.03
Deployment	Deployment policies	5.00	50.00	18.00	17.44	2.00	5.00	3.00	1.55	-0.05	0.00	-0.03	0.04	0.00	0.00	0.00	0.00
	Large-scale demonstration	100.00	1000.00	350.63	310.10	3.00	10.00	5.88	2.85	-0.50	-0.05	-0.22	0.25	0.00	0.10	0.05	0.07
	Small-scale demonstration	5.00	500.00	101.50	152.99	2.00	10.00	4.20	2.39	-0.40	0.00	-0.16	0.18	0.00	0.10	0.05	0.07
	Deployment efficiency	1.00	35.00	13.50	13.47	2.00	10.00	4.33	3.14	-0.10	-0.05	-0.08	0.04	0.00	0.05	0.03	0.04
End of life	Salt recycling	2.00	30.00	11.75	12.61	3.00	10.00	5.25	3.30	-0.10	0.00	-0.03	0.06	0.00	0.00	0.00	0.00

sbc = storage block cost, cyc = lifetime cycles

Table D.2. Descriptive statistics for individual innovations

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	Domestication of supply chains	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.05	0.00	-0.03	0.04	-0.05	0.00	-0.03	0.04
Technology components	Heat-to-electricity conversion improvements	0.05	0.10	0.08	0.03	-0.20	-0.05	-0.13	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Electricity-to-heat conversion improvements	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
	Component standardization	0.00	0.00	0.00	0.00	-0.20	-0.05	-0.12	0.08	-0.20	-0.05	-0.12	0.08	-0.20	-0.05	-0.12	0.08
	Single-tank storage	-0.03	0.10	0.02	0.03	0.00	0.00	0.00	0.00	-0.90	0.00	-0.40	0.46	-1.00	0.00	-0.43	0.51
Advanced materials development	Mass production and automation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.05	0.00	-0.02	0.03	-0.05	0.00	-0.02	0.03
Deployment	Deployment policies	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
	Large-scale demonstration	0.00	0.03	0.02	0.02	-0.10	-0.05	-0.08	0.04	-0.90	-0.15	-0.53	0.53	-1.00	0.00	-0.50	0.71
	Small-scale demonstration	0.00	0.03	0.02	0.02	-0.05	0.00	-0.03	0.04	-0.90	-0.15	-0.53	0.53	-1.00	0.00	-0.50	0.71
	Deployment efficiency	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
End of life	Salt recycling	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

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

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