Grid Energy Storage

Course No: R03-020
Credit: 3 PDH

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This course was adapted from the U.S. Department of Energy, Publication No. PNNL-33283 "2022 Grid Energy Storage Technology Cost and Performance Assessment" which is in the public domain.

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Abridgement

This document is an abridgement of the Department of Energy report on the status of current technologies for energy storage:

2022 Grid Energy Storage Technology Cost and Performance Assessment

This document is abridged by Vilayanur Viswanathan, Kendall Mongird, Ryan Franks, Xiaolin Li, Vincent Sprenkle (vincent.sprenkle@pnnl.gov), Pacific Northwest National Laboratory.

Richard Baxter, Mustang Prairie Energy

The abridgement is aimed at professional engineers who are interested in recent developments in the field but do not have the time to read the original 174-page report. The abridgement provides the major findings given in the original report: which technologies appear most promising, based on comparing estimates of power capacity, duration, and the levelized cost of storage. What the abridgement does not provide are the details about how the estimates have been calculated. Readers especially interested in a particular technology and seeking more details about how the Assessment study was conducted for this case can use the complete Assessment hyperlink above or the Reference section that is included in the abridgement.

For the benefit of readers who might not be familiar with some of the less well-known technologies, short descriptions have been provided.

Mark Rossow, PE, PhD

Acknowledgments

The Energy Storage Grand Challenge (ESGC) is a crosscutting effort managed by the Department of Energy's Research Technology Investment Committee. The project team would like to acknowledge the support, guidance, and management of Paul Spitsen from the DOE Office of Strategic Analysis, ESGC Policy and Valuation Track Lead and Eric Hsieh from the DOE Office of Electricity, ESGC Technology Development Track Lead in the development and execution of this assessment for the ESGC.

Other DOE contributors to acknowledge include Kara Podkaminer (Office of Strategic Analysis); Sunita Satyapal, Neha Rustagi, Ned Stetson and Eric Miller (Hydrogen and Fuel Cell Technologies); Sam Bockenhauer (Water Power Technologies); David Howell and Steven Boyd (Vehicle Technologies); Avi Shultz, Vijaykumar Rajgopal, Andru Prescod, Andrew Dawson (Solar Energy Technologies); Stephen Hendrickson (Office of Technology Transitions); Hugh Ho (Office of Strategic Planning and Policy); and Vinod Siberry (Office of Electricity). Input data for this work were derived from the energy storage pricing surveys supported by the DOE Office of Electricity Energy Storage Program under the guidance of Dr. Imre Gyuk.

Additional support for this effort was provided by Nate Blair, Chad Hunter, Vignesh Ramasamy, Chad Augustine, Greg Stark, Margaret Mann, Vicky Putsche, and David Feldman of the National Renewable Energy Laboratory; Vladimir Koritarov and Susan Babinec at Argonne National Laboratory; Brennan Smith at Oak Ridge National Laboratory; and Elsie Puig Santana, Tim Wolf, Andrea Starr, Shannon Bates, Matt Paiss, Charlie Vartanian, Daiwon Choi, Jan Haigh, and Mark Weimar at Pacific Northwest National Laboratory.

The authors also wish to acknowledge the significant contributions and insight provided by the industry partners referenced in the assessment.

Foreword to 2022 Report

The Department of Energy's (DOE) Energy Storage Grand Challenge (ESGC) is a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage. The program is organized around five crosscutting pillars (Technology Development, Manufacturing and Supply Chain, Technology Transitions, Policy and Valuation, and Workforce Development) that are critical to achieving the ESGC's 2030 goals. Foundational to these efforts is the need to fully understand the current cost structure of energy storage technologies and identify the research and development opportunities that can impact further cost reductions. The second edition of the Cost and Performance Assessment continues ESGC's efforts of providing a standardized approach to analyzing the cost elements of storage technologies, engaging industry to identify theses various cost elements, and projecting 2030 costs based on each technology's current state of development. This data-driven assessment of the current status of energy storage technologies is essential to track progress toward the goals described in the ESGC and inform the decision-making of a broad range of stakeholders.
As with last year, not all energy storage technologies are being addressed in the report due to the breadth of technologies available and their various stages of development. Future efforts will continue to expand the list of energy storage technologies covered while providing any significant updates to cost and performance data for previous technologies.

Note that since data for this report was obtained in the year 2021, the comparison charts have the year 2021 for current costs. Due to intra-annual uncertainty, the reported costs may have changed by the time this report was released. The cost estimates provided in the report are not intended to be exact numbers but reflect a representative cost based on ranges provided by various sources for the examined technologies.

The 2022 Cost and Performance Assessment includes five additional features comprising of additional technologies & durations, changes to methodology such as battery replacement & inclusion of decommissioning costs, and updating key performance metrics such as cycle & calendar life.

1. The 2020 Cost and Performance Assessment provided installed costs for six energy storage technologies: lithium-ion (Li-ion) batteries, lead-acid batteries, vanadium redox flow batteries, pumped storage hydro, compressed-air energy storage, and hydrogen energy storage. The assessment adds zinc batteries, thermal energy

storage, and gravitational energy storage.

2. The 2020 Cost and Performance Assessment provided the levelized cost of energy. The 2022 Cost and Performance Assessment provides the levelized cost of storage (LCOS). The two metrics determine the average price that a unit of energy output would need to be sold at to cover all project costs inclusive of taxes, financing, operations and maintenance, and others. However, shifting toward LCOS as a separate metric allows for the inclusion of storage-specific components and terminology that can be more accurately defined when compared to the levelized cost of energy calculation. This includes the cost to charge the storage system as well as augmentation and replacement of the storage block and power equipment. The LCOS offers a way to comprehensively compare the true cost of owning and operating various storage assets and creates better alignment with the new Energy Storage Earthshot (https://www.energy.gov/eere/long-duration-storage-shot).
3. This report incorporates an increase in Li-ion iron phosphate and nickel manganese cobalt Li-ion cycle life and calendar life based on input from industry partners.
4. Recycling and decommissioning are included as additional costs for Li-ion, redox flow, and lead- acid technologies.
5. The 2020 Cost and Performance Assessment analyzed energy storage systems from 2 to 10 hours. The 2022 Cost and Performance Assessment analyzes storage system at additional 24- and 100-hour durations. In September 2021, DOE launched the Long-Duration Storage Shot which aims to reduce costs by 90% in storage systems that deliver over 10 hours of duration within one decade. The analysis of longer duration storage systems supports this effort.[1]

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[1] https://www.energy.gov/eere/long-duration-storage-shot

Executive Summary

As growth and evolution of the grid storage industry continues, it becomes increasingly important to examine the various technologies and compare their costs and performance on an equitable basis. As part of the Energy Storage Grand Challenge, Pacific Northwest National Laboratory is leading the development of a detailed cost and performance database for a variety of energy storage technologies that is easily accessible and referenceable for the entire energy storage stakeholder community. This work aims to: 1) update cost and performance values and provide current cost ranges; 2) increase fidelity of the individual cost categories comprising a technology; 3) provide cost ranges and estimates for storage cost projections in 2030; and 4) develop an online website to make energy storage cost and performance data easily accessible and updatable for the stakeholder community. This research effort will periodically update tracked performance metrics and cost estimates as the storage industry continues its rapid pace of technological advancement.

During the preparation of the Phase 2 report, global supply chain disruptions led to volatility in costs for many categories of goods, including materials and components for energy storage systems. The disruption to energy storage materials and components is the result of the confluence of two global factors, plus the nascent nature of some new technologies and vendors.

First, the COVID-19 pandemic initially slowed manufacturing and shipping as work was suspended and worker safety precautions and protocols were enacted. Subsequently, consumption patterns changed as consumers shifted expenditures from services to goods. The increased consumption of goods resulted in higher competition and prices for freight shipping, scarcity of shipping containers, and delays at marine, roadway, and railway freight ports and depots. This confluence of shock in and response to supply chain disruption is anticipated to continue in the near term, adding a degree of uncertainty and volatility to current and near-future costs for energy storage systems (Doll, 2021; Lee & Tian, 2021).

Note that since data for this report was obtained in the year 2021, the comparison charts have the year 2021 for current costs. In addition, the energy storage industry includes many new categories of technology, plus new intermediate companies in the supply chain for both new and established technologies. Supply chains become more resilient as the number of suppliers and users of a material or component increase and there is a transition from one-off or intermittent ordering to continuous ordering due to ongoing production. Some technologies and supply chain nodes in the energy storage system industry have not yet reached this turning point of commercial maturity, which results in further exacerbating supply chain disruptions and, in turn, increased near-term cost and cost volatility.

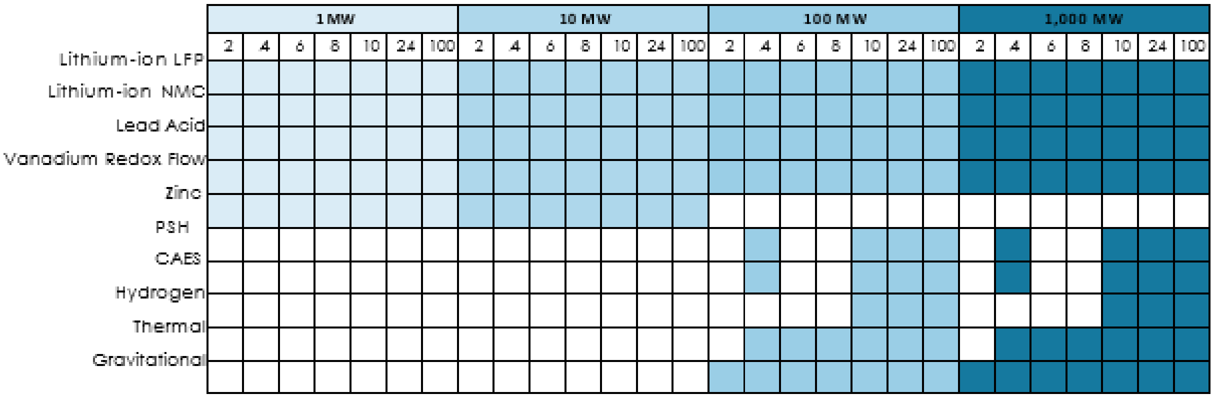
Phase 2 of this initiative includes cost and performance metrics for most commercially available energy storage technologies across various energy-to-power ratios:

- Lithium-ion (Li-ion): lithium iron phosphate (LFP) batteries
- Li-ion: Li-ion nickel manganese cobalt (NMC) batteries
- Lead-acid batteries
- Vanadium redox flow batteries (RFBs)
- Diabatic Compressed-air energy storage (CAES)
- Pumped storage hydropower (PSH)
- Hydrogen energy storage system (HESS) (bidirectional)
- Zinc-based batteries
- Gravity energy storage
- Thermal energy storage

Note that diabatic CAES and some of the thermal energy storage technologies considered are not zero emission technologies, since they use fuel such as natural gas in the discharge cycle. Additional storage technologies will be incorporated in later phases of this research effort to capture emerging storage technologies of interest to the Department of Energy and other stakeholders. In addition to current cost estimates and projections, the research team aimed to develop a cohesive framework to organize and aggregate the cost categories for energy storage systems (ESSs). This framework helps eliminate current inconsistencies associated with specific component costs (e.g., battery storage block vs. battery packs used in electric vehicles) and enables equitable comparisons between and among technologies, while using data from industry participants. The definitions and breakdown of these components has been reviewed by multiple energy storage experts in the technology developer community and national laboratories.

Cost and performance information was compiled for the defined categories and components based on conversations with technology developers and industry stakeholders, literature, commercial datasets, and reported storage costs for systems deployed across the United States. A range of detailed cost and performance estimates is presented for 2021 and projected out to 2030 for each technology. Current cost estimates provided in this report reflect the derived point estimate based on available data[2] from the reference sources listed above with estimated ranges for each studied technology. In addition to ESS installed costs, a levelized cost of storage (LCOS) value for each technology is also provided to better compare the complete cost of each ESS over its project life, inclusive of any major overhauls and replacements required to maintain operation. The LCOS measures the price that a unit of energy output from the storage asset would need to be sold at to cover all project costs inclusive of taxes, financing costs, operations and maintenance, and others. It offers a way to comprehensively compare the true cost of owning and operating various storage assets.

Each technology was modeled for a specific set of power and duration combinations, depicted in Figure 1. Batteries were modeled for all cost and power durations considered. Other technologies were modeled specifically in high-power and longer duration applications assumed to be representative of their likely use cases and enable comparisons between and among technologies. For example, PSH and CAES primarily serve longer durations, but a duration of 4 hours at power levels of 100 MW and 1,000 MW is included to provide a comparison point at a shorter duration with other technologies and capture uses in projects developed in the past. It is important to note that the cost and power combinations depicted in Figure 1 are not exhaustive of all use cases for each of the technologies modeled but were chosen to allow for consistent evaluations of LCOS across systems.



	1 MW							10 MW							100 MW							1,000 MW						
	2	4	6	8	10	24	100	2	4	6	8	10	24	100	2	4	6	8	10	24	100	2	4	6	8	10	24	100
Lithium-ion LFP	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Lithium-ion NMC	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Lead Acid	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Vanadium Redox Flow	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Zinc	■	■	■	■	■	■	■	■	■	■	■	■	■	■														
PSH																■			■	■	■		■			■	■	■
CAES																■			■	■	■		■			■	■	■
Hydrogen																			■	■	■					■	■	■
Thermal																■	■	■	■	■	■		■	■	■	■	■	■
Gravitational															■	■	■	■	■	■	■	■	■	■	■	■	■	■

Figure 1. Power Capacity (MW) and Energy Duration (hr) Coverage Table by Technology

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[2] Depending on technology and category, the derived point estimate corresponds to the average after removing outliers (Li-ion and zinc storage block, CAES, PSH), professional judgment (balance of system), single estimate (lead-acid module), or consensus values (power conversion system). Hence, whether the value is average, median, or point estimate depends on the cost category and technology. We have therefore used “derived point estimate” since no single word can describe what the estimates represent. Point estimates within this document refer to the value residing within the upper and lower bounds of the cost range as the most representative cost.

Key findings from this analysis include the following:

- PSH, the dominant grid storage technology, has a projected cost estimate of \$263/kWh for a 100 MW, 10-hour installed system. The most significant cost components are the reservoir (\$76/kWh) and powerhouse (\$742/kW). For a 24-hour system, the total installed cost is reduced to \$143/kWh.

- Battery grid storage solutions, which have seen significant growth in deployments in the past decade, have projected 2021 costs for fully installed 100 MW, 10-hour battery systems of: Li-ion LFP (\$356/kWh), Li-ion NMC (\$405/kWh), vanadium RFB (\$385/kWh), and lead-acid (\$409/kWh). Zinc-based systems are not available at the 100 MW scale; for a 10 MW, 10-hour system, the total installed cost for 2021 is \$449/kWh, putting it at a higher cost than the other systems at the same scale.

- Diabatic CAES is estimated to be the lowest cost storage technology on an installed cost basis at durations ≥ 4 hours (\$295/kWh for a 100 MW, 4-hour system, \$122/kWh for a 100 MW, 10-hour system). At 100 MW, 4 hours, LFP has the second lowest installed cost at \$385/kWh, followed by NMC (\$435/kWh) and lead-acid (\$447/kWh). At the 10-hour duration, PSH is projected to be the second lowest cost storage technology (\$263/kWh) at the same scale, followed by thermal and hydrogen. At 1,000 MW, while CAES retains its lowest cost status, thermal and gravitational storage move up in ranking, especially at 10-hour duration, with thermal nearly tied with PSH, followed by gravitational. For 1,000 MW, 100-hour duration, CAES is the lowest cost, closely followed by hydrogen, with PSH and thermal next, followed by gravitational, with batteries lagging far behind. Figures 2 and 3 show the total installed ESS costs by power capacity, duration, and technology for 2021 and 2030.

- Regarding projected 2030 installed ESS costs, for 100 MW, 4-hour systems, LFP (\$291/kWh) and CAES (\$295/kWh) installed costs are nearly the same, whereas CAES is significantly lower at 10 hours due to low cavern cost. At durations greater than 10 hours, HESS installed cost is just below CAES for both 100 MW and 1,000 MW systems. At 100 MW, 100 hours, CAES and HESS systems are estimated at \$18/kWh and \$15/kWh, respectively followed by thermal and PSH, at \$73/kWh and \$83/kWh, respectively, with battery costs much higher just as in 2021.

- Diabatic CAES provides the lowest LCOS at durations ≥ 4 hours mainly due to the lower unit energy cost for caverns. At 1,000 MW, 10 hours, the LCOS for CAES is \$0.10/kWh followed closely by PSH (\$0.11/kWh) and gravitational (\$0.13/kWh), with lead-acid and hydrogen at the high end at \$0.33/kWh and \$0.35/kWh, respectively. HESS offers the highest LCOS at 10 hours due to its higher power equipment cost and lower round-trip efficiency but gets more competitive at higher durations due to low cavern cost.

- As duration increases, the LCOS for all technologies decreases to a minimum at 10 hours followed by an increase at higher durations because their annual discharge energy throughput is limited by the number of cycles they can perform in a year (less than one cycle per day for the 24- and 100-hour durations). For technologies with a lower unit energy cost for the storage block (SB) (CAES, PSH, hydrogen, thermal), the LCOS increase at high durations is less than for batteries, which have higher unit energy cost for the SB. Since calendar life is limiting for 100- hour duration, choice of lead-acid batteries with lower cycle life and lower SB capital cost, is expected to lower the LCOS at high durations.

Major findings from this analysis are shown in Figures 2 and 3. Values presented show the derived point estimates for total installed ESS cost (\$/kWh) by technology, power capacity (MW), and duration (hr)[3]. Figure 2 provides estimates for 2021, while ES-3 shows estimates for 2030. LCOS estimates for 100 MW and 1,000 MW systems across all durations are shown in Figure 4. This chart, along with comparisons across additional power capacities is provided in the Levelized Cost of Storage section.

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[3] The total installed cost divided by rated energy gives \$/kWh, while the total installed cost divided by rated power gives \$/kW for the system

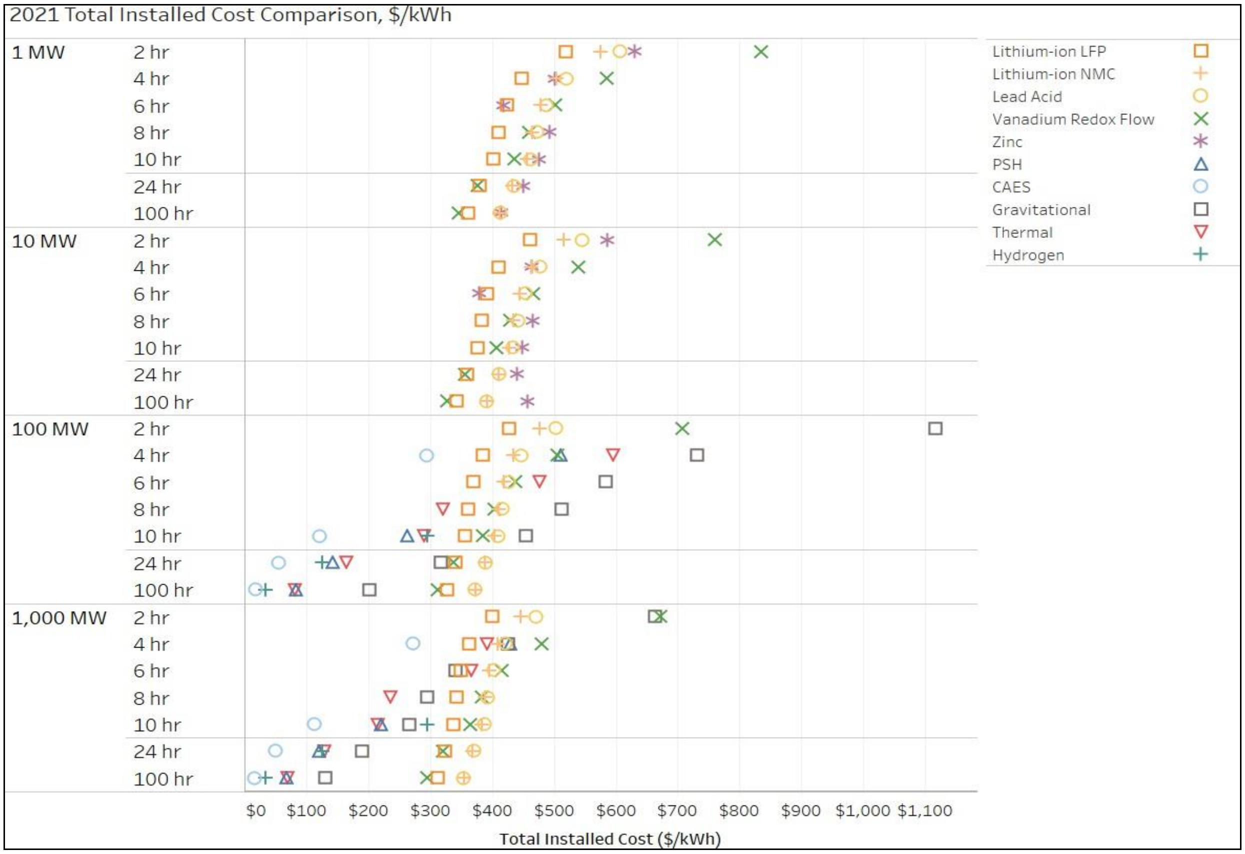


Figure 2. Comparison of Total Installed ESS Cost Estimates by Technology, 2021 Values

Figure 3. Comparison of LCOS ($/kWh) by Technology, Power Capacity, and Duration

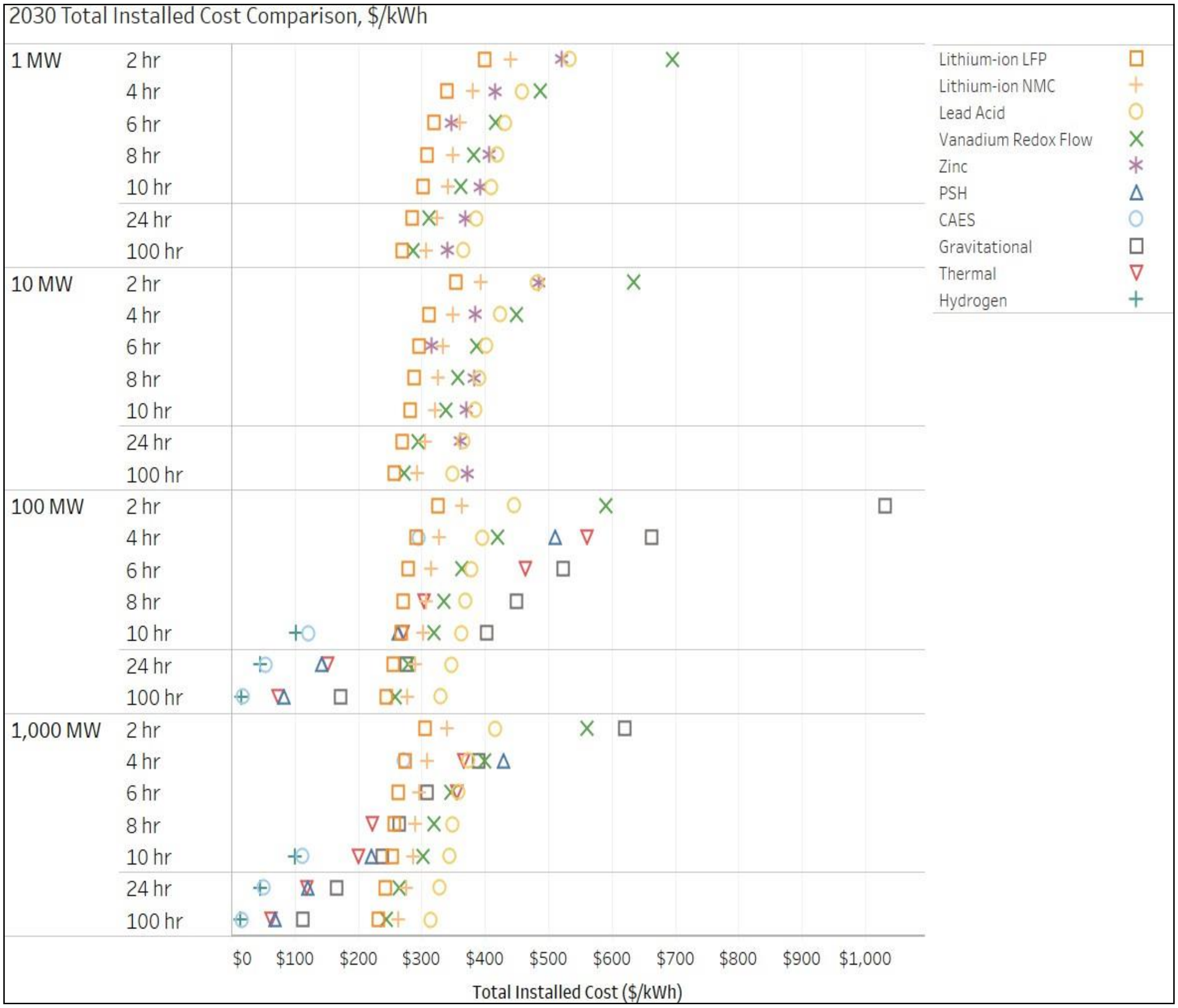


Figure 4. Comparison of Total Installed ESS Cost Point Estimates by Technology, 2030 Values

Acronyms

AC	alternating current
Ah	ampere-hour
BESS	battery energy storage system
BMS	battery management system
BOP	balance of plant
BOS	balance of system
C&C	controls and communication
CAES	compressed-air energy storage
CFF	construction finance factor
CRF	capital recovery factor
CSP	concentrating solar power
DC	direct current
DOD	depth of discharge
DOE	U.S. Department of Energy
EIC	electricals, instrumentation, and controls
EPC	engineering, procurement, and construction
ESGC	Energy Storage Grand Challenge
ESS	energy storage system
HESS	hydrogen energy storage system
HEX	heat exchanger
HVAC	heating, ventilation, and air conditioning
kWe	kilowatt electric
kWh	kilowatt-hour
kWhe	kilowatt-hour electric
kWht	kilowatt-hour thermal
LAES	liquid air energy storage
LCOS	levelized cost of storage
LFP	lithium-ion iron phosphate
Li-ion	lithium-ion
MACRS	modified accelerated cost recovery system

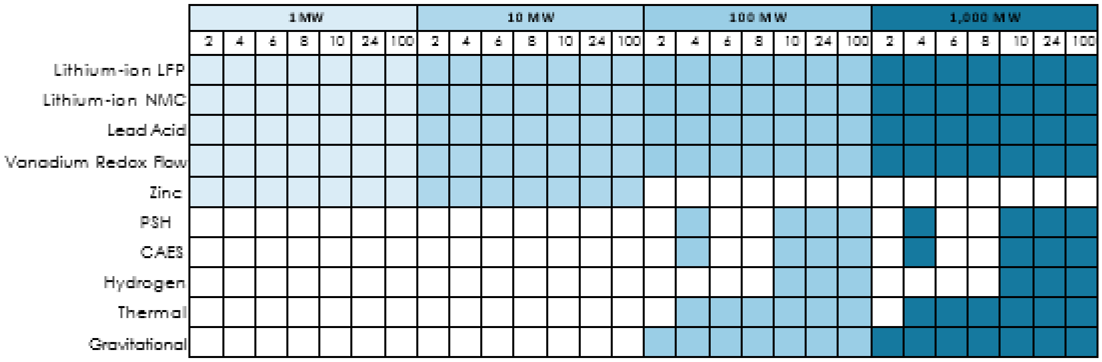
MWh	megawatt-hour
MWt	megawatt thermal
NEMA	National Electrical Manufacturers Association
NI-ZN	nickel-zinc
NMC	nickel manganese cobalt
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OEM	original equipment manufacturer
PCS	power conversion system
PEM	polymer electrolyte membrane
PHES	pumped heat energy storage
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydro
RFB	redox flow battery
RTE	round-trip efficiency
SB	storage block
SBOS	storage balance of system
SOC	state of charge
TRL	technology readiness level
USP	uninterruptable power source
WACC	weighted average cost of capital

Introduction

Energy storage and its impact on the grid and transportation sectors have expanded globally in recent years as storage costs continue to fall and new opportunities are defined across a variety of industry sectors and applications. Electrification of the transportation sector is being driven by the availability of lower cost, higher performance lithium-ion (Li-ion) batteries for electric vehicles and is being actively tracked and advanced by the Department of Energy's (DOE's) Energy Efficiency and Renewable Energy Vehicle Technologies Office and other commercial entities. Grid-scale energy storage, however, lacks the stringent power and weight constraints of electric vehicles, enabling a multitude of storage technologies to compete to provide current and emerging grid flexibility services.

As growth and evolution of the grid storage industry continues, it becomes increasingly important to examine the various technologies and compare their costs and performance on an equitable basis. As part of the Energy Storage Grand Challenge (ESGC), Pacific Northwest National Laboratory (PNNL) is leading the development of a detailed cost and performance database for a variety of energy storage technologies that is easily accessible and referenceable for the entire energy stakeholder community. This work is based on previous storage cost and performance research at PNNL funded by DOE's HydroWIRES Initiative (Mongird et al., 2019). This work aims to: 1) provide a detailed analysis of the all- in costs for energy storage technologies, from basic components to connecting the system to the grid; 2) update and increase fidelity of the individual cost elements comprising a technology; 3) provide cost ranges and estimates for storage cost projections in 2030; and 4) develop an online website to make energy storage cost and performance metrics easily accessible and updatable for the stakeholder community. This research effort will periodically update tracked performance metrics and cost estimates as the storage industry continues its rapid pace of technological advances. Due to intra-annual uncertainty, the reported costs may have changed by the time this report was released. The cost estimates provided in the report are not intended to be exact numbers but reflect a representative cost based on ranges provided by various sources for the examined technologies.

The analysis was done for energy storage systems (ESSs) across various power levels and energy-to- power ratios. The power and energy duration combinations for each technology provided in the 2022 report are shown in Figure 5. The power and duration choices reflect a combination of their current and potential future applications, and also include selections to enable comparisons between categories. For example, pumped storage hydro (PSH) and compressed-air energy storage (CAES) primarily serve longer durations, but a duration of 4 hours at power levels of 100 MW and 1,000 MW are included to provide a comparison point at a shorter duration with other technologies and capture uses in projects developed in the past.



	1 MW							10 MW							100 MW							1,000 MW						
	2	4	6	8	10	24	100	2	4	6	8	10	24	100	2	4	6	8	10	24	100	2	4	6	8	10	24	100
Lithium-ion LFP	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Lithium-ion NMC	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Lead Acid	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Vanadium Redox Flow	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Zinc	■	■	■	■	■	■	■	■	■	■	■	■	■	■														
PSH																■			■	■	■		■			■	■	■
CAES																■			■	■	■		■			■	■	■
Hydrogen																			■	■	■					■	■	■
Thermal																■	■	■	■	■	■		■	■	■	■	■	■
Gravitational															■	■	■	■	■	■	■	■	■	■	■	■	■	■

Figure 5. Power Capacity (MW) and Energy Duration (hr) Coverage Table by Technology

Phase 2 of this initiative includes cost and performance metrics for the following energy storage technologies across the energy-to-power ratios indicated above:

- Li-ion: Li-ion iron phosphate (LFP) batteries
- Li-ion: Li-ion nickel manganese cobalt (NMC) batteries
- Lead-acid batteries
- Vanadium redox flow batteries (RFBs)
- Diabatic CAES
- PSH
- Hydrogen energy storage system (HESS) (bidirectional)
- Zinc-based batteries
- Gravity energy storage
- Thermal energy storage

Additional storage technologies will be incorporated in future phases to capture newer technologies of interest to DOE and other stakeholders.

In addition to cost estimates and projections, this work aims to develop a cohesive framework to organize and aggregate cost and performance metrics for ESSs. An ESS may include numerous stakeholders including intermediate sellers and buyers (e.g., vendors, distributors, resellers, developers, financial interests, electric service provider, and operators). Cost metrics are approached from the viewpoint of the final downstream entity in the energy storage project, ultimately representing the final project cost. This framework helps eliminate current inconsistencies associated with specific cost categories (e.g., energy storage racks vs. energy storage modules). Over the past year, this framework has been socialized with industry and the research community with only minor revisions.

Cost and performance information was compiled for the defined categories and components based on conversations with developers and industry stakeholders, literature, commercial datasets, and real- world storage costs for systems deployed across the United States. A range of detailed cost and performance estimates are presented for 2021 and projected out to 2030 for each technology.

The current cost estimates provided in this report reflect the derived point estimate based on available data from the reference sources listed above with estimated ranges for each studied technology. In addition to ESS installed costs, a $/kWh levelized cost of storage (LCOS) value for each technology is also provided to better compare the complete cost of each ESS over the duration of its project life, inclusive of any major overhauls and replacements required to maintain operation. The LCOS measures the cost that a unit of energy output from the storage asset would need to be sold at to cover all project costs inclusive of taxes, financing, operations and maintenance, and others. It offers a way to comprehensively compare the true cost of owning and operating various storage assets.

Cycle life is one of the most important metrics that determines LCOS, particularly for battery technologies. Specification sheets from developers show Li-ion cycle life data obtained at 1C charge and discharge rates. Hence, about 10 cycles per day are possible corresponding to test duration of 3 years for 10,950 cycles. Additionally, the cycle life is estimated by extrapolating data obtained for a limited number of cycles in the 1000-4500 cycles range, restricting test duration further to 0.25-1 year. Hence, calendar life limitation doesn't come into play for reported cycle life data. However, during operation, most warranties limit the user to one full 100% depth of discharge (DOD) equivalent cycle per day.

Therefore, for batteries to reach the same number of 10,500 reported cycles, they would have to cycle 10 times longer, or 30 years, which is much greater than the calendar life for Li-ion batteries. This would require derating the cycle life reported in specification sheets.

For lead-acid batteries, cycling is not done at such high rates. The cycle life is sufficiently small so that even at one cycle per day, the battery life is limited to 3-4 years of operation, where calendar aging doesn't have a significant impact. Plus, the duration for each cycle at 80% DOD is approximately 20 hours for an 8-hour discharge rate, close to one cycle per day. The smallest discharge duration considered is 2 hours at 50% DOD, which requires 6 hours per cycle (4 cycles per day). Testing in the laboratory would be completed in one year (for 1460 cycles) as opposed to the 2 years it would take based on the warranty conditions not to exceed one 100% equivalent DOD cycle per day. Hence, the calendar life related aging is not expected to have a big impact for lead-acid batteries.

In the field while providing various grid services, energy storage systems do not continuously charge or discharge. At times they remain idle if there are no grid services that offer sufficient value for the system to operate thus reducing the capacity factor[4] (Hunter et al., In Press; Hunter et al., 2021). The capacity factor depends on the following variables:

- Type and penetration of renewables in the region
- Annual load and generation profiles for the region
- Allowable annual energy throughout for the ESS
- Duration of the ESS (Energy to power ratio)
- Round trip efficiency (RTE)

Regions with high wind penetration may require the ESS to charge at night, while regions with high solar PV penetration will require the ESS to charge during the day. The region-specific annual load and generation profiles further affect the charge and discharge periods and durations. The charge duration will depend on the hours of over-generation, the charge efficiency and the rated energy capacity of the storage system. The discharge duration depends on the periods of under-generation and the rated energy capacity. For storage systems with separate charge and discharge powertrains, there is flexibility of oversizing the charge powertrain to capture excess renewable energy in less time. Due to the complexity associated with region-specific load and generation profiles, this study has developed a simplified approach to estimate charge and discharge capacity factors as described below.

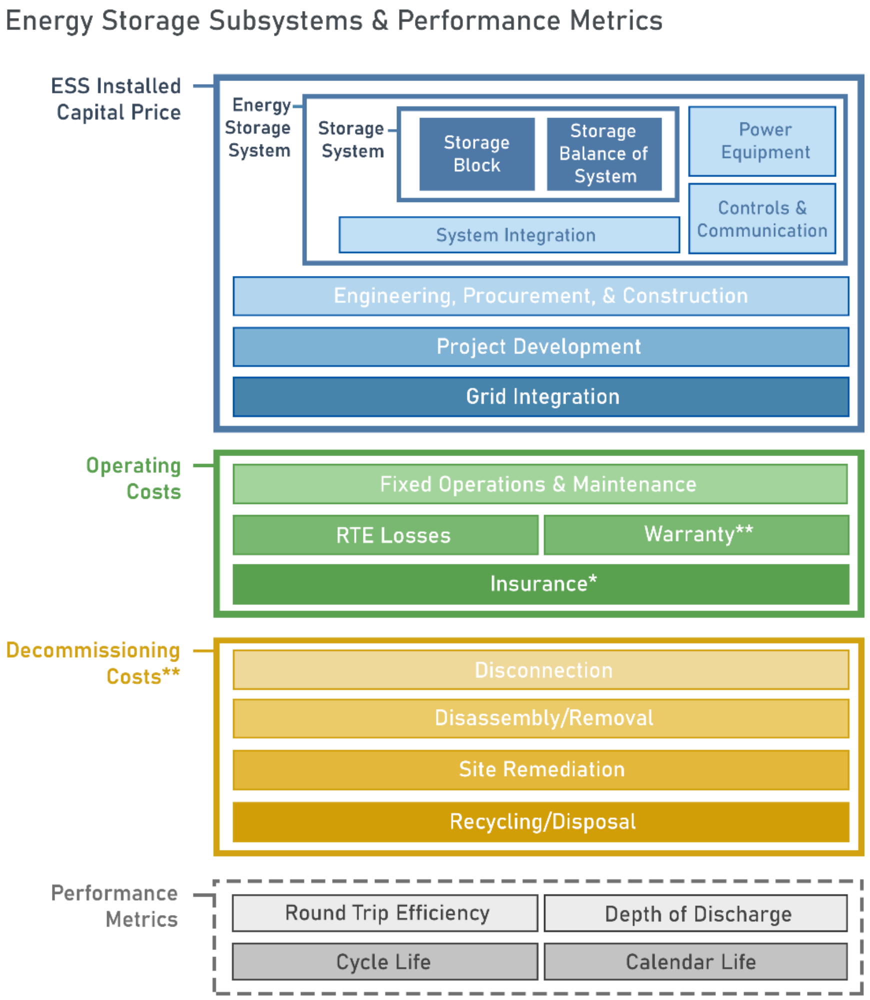
The allowable annual cumulative discharge energy is limited to 365 discharges at 100% DOD (or one full discharge per day). At the 80% DOD used in this analysis, the maximum number of cycles allowed per day is 1/0.8 or 1.25 cycles. The total time needed to complete each cycle depends on the ESS duration and RTE. For example, for a 2-h ESS with 0.8 RTE, the ESS operates for 4.5 hours each cycle (2 hours discharge, 2.5 hours charge), or 5.6 hours in a day (4.5 hours/cycle x 1.25 cycles/day). This corresponds to a capacity factor of 23% for charge and discharge combined. For a 10-hour storage system with the same RTE, the ESS operates for 22.5 hours in each cycle, for a combined capacity factor of 94%.

[4] Capacity factor is the ratio of the total time the storage system is engaged over the actual available time. Capacity factor for charge is the percent of time the ESS is being charged, while the capacity factor for discharge is the percent of time the ESS is being discharged.

Terminology

Organization and Categorization of Cost and Performance Categories

For the 2020 report, the research team compiled information on various cost components for a range of energy storage technologies and produced a cohesive breakdown of items that is consistent and tractable across multiple storage types. Figure 6 displays an updated schematic of the cost and performance categorization that resulted from that effort.



* Estimates for these components are not included at this time in technology-specific findings

** Estimates for these components are available for a limited subset of storage technologies at this time

Figure 6. ESSs and Performance Metrics

It should be noted that this schematic has been designed to capture a practical level of granularity for the costs of ESS. For a battery energy storage system (BESS), the storage block (SB) corresponds to battery modules and racks, flow battery stacks, electrolyte, and tanks, while the storage balance of system (SBOS) consists of containers; heating, ventilation, and air conditioning (HVAC); safety disconnects; fire extinguishers; and pumps, valves, and pipes. For other technologies, like PSH and CAES plants, these cost elements (SB and SBOS) are aggregated to capture the costs associated with reservoirs and caverns, respectively. For PSH and CAES systems, additional cost elements such as power equipment, controls and communication (C&C), and system integration corresponding to electromechanical equipment/powertrain and powerhouse/power island construction are aggregated. While engineering, procurement and construction (EPC) and project development costs are typically included in CAES system costs, these are captured in a catch-all contingency fee cost component for PSH. For HESS, the SB is represented by the electrolyzer, stationary fuel cell, and cavern, while the balance of system (BOS) is represented by the compressor, humidifiers, and air and fuel delivery system. A table of how the cost components compare (following the diagram for total installed cost in Figure 6 is shown in Figure 7. with further resolution of subcomponents of each energy storage subsystem or cost component.[5]

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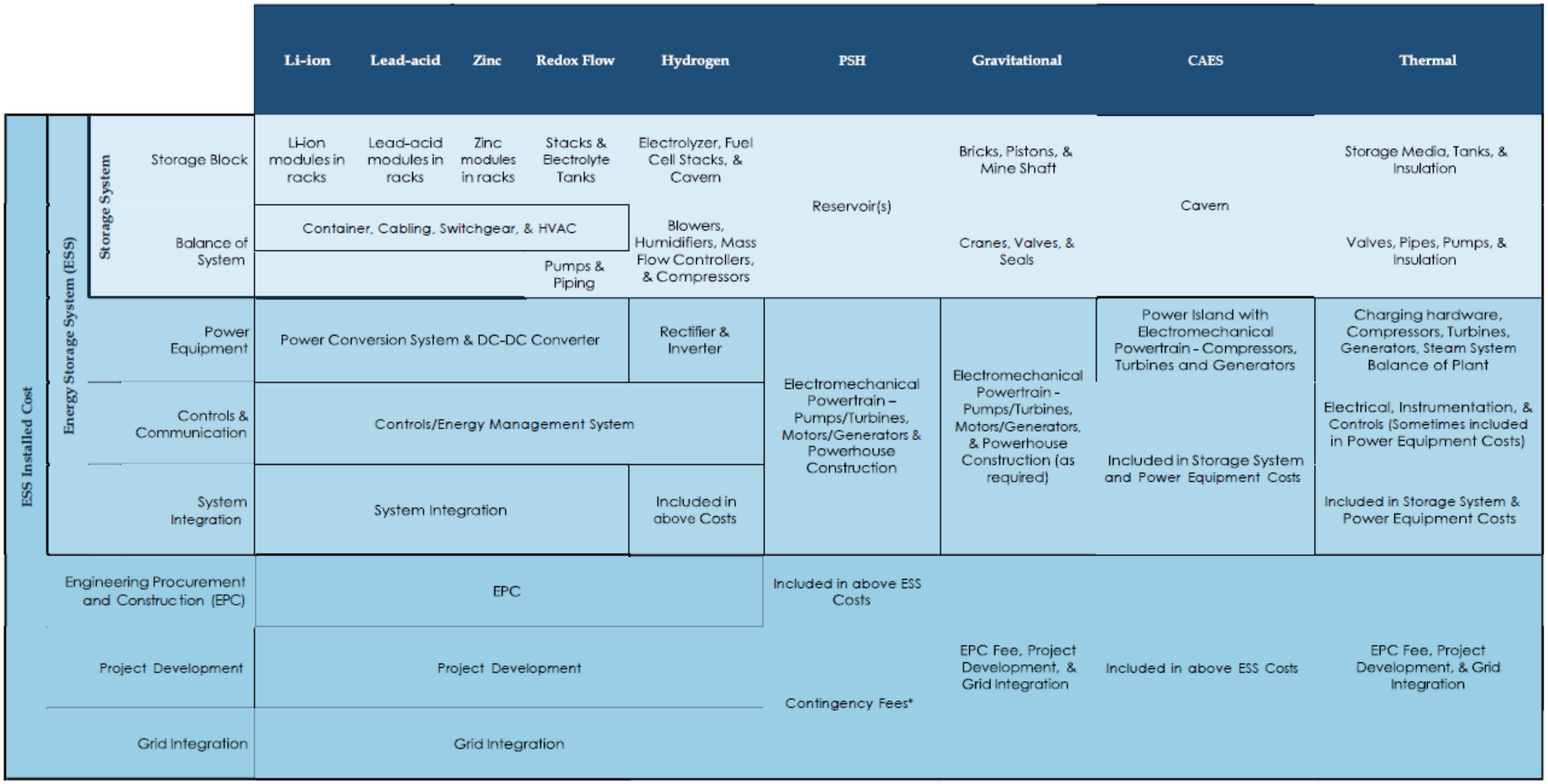
[5] Cost component and energy storage subsystem are used interchangeably



			Li-ion	Lead-acid	Zinc	Redox Flow	Hydrogen	PSH	Gravitational	CAES	Thermal
ESS Installed Cost	Energy Storage System (ESS)	Storage System									
		Storage Block	Li-ion modules in racks	Lead-acid modules in racks	Zinc modules in racks	Stacks & Electrolyte Tanks	Electrolyzer, Fuel Cell Stacks, & Cavern	Reservoir(s)	Bricks, Pistons, & Mine Shaft	Cavern	Storage Media, Tanks, & Insulation
		Balance of System	Container, Cabling, Switchgear, & HVAC			Pumps & Piping	Blowers, Humidifiers, Mass Flow Controllers, & Compressors		Cranes, Valves, & Seals		Valves, Pipes, Pumps, & Insulation
		Power Equipment	Power Conversion System & DC-DC Converter				Rectifier & Inverter	Electromechanical Powertrain – Pumps/Turbines, Motors/Generators & Powerhouse Construction	Electromechanical Powertrain - Pumps/Turbines, Motors/Generators, & Powerhouse Construction (as required)	Power Island with Electromechanical Powertrain - Compressors, Turbines and Generators	Charging hardware, Compressors, Turbines, Generators, Steam System Balance of Plant
		Controls & Communication	Controls/Energy Management System							Included in Storage System and Power Equipment Costs	Electrical, Instrumentation, & Controls (Sometimes included in Power Equipment Costs)
		System Integration	System Integration				Included in above Costs				Included in Storage System & Power Equipment Costs
		Engineering Procurement and Construction (EPC)	EPC					Included in above ESS Costs	EPC Fee, Project Development, & Grid Integration	Included in above ESS Costs	EPC Fee, Project Development, & Grid Integration
		Project Development	Project Development					Contingency Fees*			
		Grid Integration	Grid Integration								

Figure 7. ESSs Included in Total Installed Cost for each Storage Technology

Definitions of Cost Components and Performance Metrics

Defining cost component parameters is necessary to effectively break down system costs in a consistent way. Failing to do so leads to inconsistent results and a misunderstanding of the estimates being produced. The list below aims to provide clarity and defines each of the cost items that appear in Figure 7.

For categories and parameters for non-BESS technologies, information is included in the individual technology sections analysis.

ESS Installed Cost Components

i) **SB ($/kilowatt-hour [kWh])** – includes the unit energy cost for the energy component of the ESS, for example, battery module, rack, and battery management system (BMS) for BESS; electrolyzer, fuel cell stacks, and cavern for HESS; bricks, mass cars, mined shaft, and pressurized water for gravitational storage; and storage medium, tank, and insulation for thermal storage.

ii) **SBOS ($/kWh)** – includes supporting cost components for the SB with container, cabling, switchgear, flow battery pumps, and HVAC for BESS; blowers, humidifiers, mass flow controllers, and compressors for HESS; cranes, valves, and seals for gravitational storage; and valves, pipes, pumps, and insulation for thermal storage.

iii) **Storage System ($/kWh)** – this is the sum of the SB and SBOS costs and is the appropriate level of granularity for some storage technologies such as PSH and CAES.

iv) **Power Equipment ($/kilowatt [kW])** –power conversion system and direct current (DC)-DC converter for batteries, rectifier, and inverter for HESS; electromechanical powertrain and powerhouse for PSH; electromechanical powertrain with or without powerhouse for gravity- based systems; charging hardware, compressors, turbines, generators, and steam system balance of plant for thermal energy storage; and the power island with electromechanical powertrain for CAES.

v) **Controls & Communication (C&C) ($/kW)** – includes the energy management system for the entire ESS and is responsible for ESS operation; also referred to as electrical, instrumentation, and controls (EIC) for thermal powerplants. Typically represented as a fixed-cost scalable with respect to power.

vi) **System Integration ($/kWh)** – cost charged by the system integrator to integrate components of a BESS into a single-functional system. Tasks include procurement and shipment to the site of battery modules, racks with cables in place, containers, and power equipment. At the site, the modules and racks are containerized with HVAC and fire suppression installed and integrated with the power equipment to provide a turnkey system.

vii) **EPC ($/kWh)** – includes nonrecurring engineering costs and construction equipment as well as siting, installation, and commissioning of the ESS.

viii) **Project Development ($/kWh)** – costs associated with permitting, power purchase agreements, interconnection agreements, site control, and financing.

ix) **Grid Integration ($/kW)** – costs associated with connecting the ESS to the grid, including transformer cost, metering, and isolation breakers.

Operating Costs

i) **Fixed Operations & Maintenance (O&M) ($/kW-year)[6]** – includes all costs necessary to keep the storage system operational throughout its life that do not fluctuate based on energy throughput, such as planned maintenance, parts, and labor and benefits for staff. This also includes major overhaul-related maintenance which may depend on energy throughput or occurs at fixed time intervals.

ii) **Round-Trip Efficiency (RTE) Losses ($/kWh)** – Round-trip efficiency is simply the ratio of energy discharged to the grid from a starting state of charge to the energy received from the grid to bring the ESS to the same starting state of charge. RTE is < 1 due to losses related to thermal management, auxiliary power consumption, electrochemical losses, power conversion losses, powertrain-related electromechanical losses, energy conversion losses, self-discharge, evaporation, stored heat or gas/air leakage losses. This value for RTE losses is estimated through the cost of the additional electricity and fuel required per kWh of energy discharged due to the losses described.

iii) **Warranty ($/kWh-year)** – annual fees to the equipment provider for contractual performance of quality of materials and equipment and performance assurance of designated lifespan.

iv) **Insurance ($/kWh)** – insurance fees to hold a policy to cover unknown and/or unexpected risks. The terms of this cost may depend on developer reputation, project complexity, location, and financial strength.

Decommissioning Costs

i) **Disconnection, Disassembly, Removal, and Site Remediation ($/kWh)** – costs associated with the disconnection, disassembly, removal, and site remediation. These costs may vary widely based on whether the ESS is in the built environment or outside the built environment, how far materials must be transported, and whether site remediation is necessary.

ii) **Recycling and Disposal ($/kWh)** – net costs associated with recycling and disposing of components less any costs recouped from sale of materials. The value of recouped materials is typically measured in cents/pound.

Performance Metrics

i) **Duration (hours)** – the ratio of rated energy to rated power of the ESS.

RTE (%) – the electrical[7] energy that is discharged to the grid (after accounting for all the losses listed in RTE losses) as a percentage of the total energy[8] used to charge the ESS. Note that RTE for a fixed-system design depends on operating conditions such as charge- discharge power, ambient temperature, state of charge (SOC) range.

ii) **Depth of Discharge (DOD) (%)** – the energy discharged as a percentage of the rated energy capacity of the storage system.

iii) **Cycles (#)** – each charge and discharge correspond to a half cycle, with a charge-discharge pair corresponding to one cycle.

iv) **End of Life** – the condition at which the ESS can no longer provide a minimum required percent of its rated power or energy. As an example, for Li-ion batteries, the end of life is when its available energy is less than 60% of rated energy.

v) **Cycle Life (#)** – is the total number of cycles that an ESS can provide before reaching end of life; is a function of DOD for nonflow BESS.

vi) **Calendar Life (years)** – defined as the maximum duration after which the ESS reaches end of life regardless of operating conditions. For BESS considered in this report, calendar life can depend on the ambient temperature, pressure, humidity, and SOC at which the battery is stored.

It should be noted that some of these items have not been separately considered in this analysis due to current unavailability of data. Warranty, insurance, decommissioning, disassembly, removal, site remediation, and recycling and disposal costs are not well documented in the literature for all technologies and accordingly the values for these metrics have low accuracy.

In this report, warranty costs are included for vanadium RFB and NMC Li-ion BESSs based on industry feedback. Recycling and disposal costs are calculated for LFP, Li-ion NMC, vanadium RFB, and lead-acid batteries as the inverse physical operation of construction and thus a recurrence of the cost of the EPC costs, minus the value of the recoverable materials specific to these battery systems. Some of the costs associated with these items may be partially included in other cost estimates based on the business process used in an ESS (e.g., part of the cost of decommissioning may be embedded in a capital cost quoted by a developer), but the capability to estimate them separately is not available at this time.

However, recycling and disposal is a cost component that will grow in importance due to financial, risk, and environmental considerations. Analysis of the warranty, insurance, decommissioning, disassembly, removal, and site remediation components will be pursued in later phases of this continued research effort as more information becomes available. Additionally, future efforts will attempt to expand the list of performance characteristics tracked to provide a more complete assessment of each technology's capabilities.

[6] In this report, the O&M variable cost of \$0.0005/kWh related to consumables used in the 2020 report has been removed due to lack of clarity of source materials.

[7] This work considers only electrical energy output during discharge

[8] Except for hybrid thermal energy storage, this work considers only electricity input during charge.

Learning Rates vs. Fixed Percent Decline for 2030

Typically, learning rates have been used to project cost reductions as manufacturing output increases. Using the learning rate approach requires knowledge of two parameters: 1) future demand and 2) the correct learning rate. Historical analysis of mature energy technologies can be used to better inform the expected rate of cost reduction as manufacturing capacity increases. For example, learning rate for established technologies such as combustion turbines are reported at 20% for up to cumulative deployments of 1,000 MW, followed by a lowering to 10% for deployments up to 100,000 MW (Gritsevskyi & Nakićenovi, 2000). Photovoltaics and wind turbines also have the 20% learning rate curve for deployments up to 800 MW and 2,000 MW, respectively. However, during the initial stages of deployment, all three technologies show a lower learning rate based on the lower slope of cost drop vs. deployment, which was not quantified but appear to be 10% for gas turbines and lower for photovoltaics. This gap was addressed by Wei, Smith, and Sohn (2017), who determined the learning rate for cost is relatively flat initially, followed by a steep curve corresponding to the 20% learning rate upon attaining a minimum deployment threshold to benefit from scale, then by a lower learning rate as deployments increase further.

This work uses the same learning rates for Li-ion, lead-acid, and flow batteries as used in the 2020 ESGC report. Learning rates can be used for technologies such as Li-ion batteries that have a 10-year period of deployment history in the transportation and grid storage sectors. For RFBs and lead-acid batteries, due to uncertainties in deployment, learning rates are not directly applicable. In the 2020 report, learning rates were assumed for these technologies, while using the estimated Li-ion deployment. The same approach was followed in this report. For example, the nominal DC SB learning rate for RFBs is set at 4.5%, 1.5% for lead-acid batteries, compared to 10% for Li-ion batteries, corresponding to cost drops of 17%, 6%, and 35%, respectively. For the rest of the categories for battery-based systems, the learning rates were kept the same for all batteries as described in the ESGC 2020 report.

Due to the uncertainties in both anticipated deployments and the correct learning rate to use during the initial phase, this work assumes a fixed-cost drop for zinc batteries, gravity, and thermal storage systems. For example, a 20% cost drop in DC SB and 10% drop in DCBOS was assumed for zinc batteries, while keeping the cost drops for power equipment in line with Li-ion BESS, while system integration, EPC, and project development costs are maintained at 90% of Li-ion BESS 2030 values.

Technologies Considered

Lithium-ion Batteries

Li-ion batteries are one of the most widely used technologies for consumer electronics and electric vehicle applications due to their high energy density[9] and cycling performance. These systems store electrical energy in electrodes that can accommodate lithium within their host lattice or matrix, called intercalation or insertion compounds. Presently, most commercial Li-ion batteries consist of a graphite anode, a lithium-containing transition metal oxide or phosphate cathode, and a nonaqueous Li-ion- conducting liquid electrolyte. When using a graphite anode, cells are often characterized by the different cathode materials used (e.g., $LiCoO_2$, $LiNi_xMn_yCo_zO_2$ [NMC], $LiNi_xCo_yAl_zO_2$ [NCA], or $LiFePO_4$ [LFP]). The basic cell components are packaged in a cylindrical, prismatic or pouch format to form the basic repeating unit.

For large-scale stationary storage systems, costs for Li-ion can be analyzed at various levels including the DC SB (groups of cells and associated wiring and racking), and the DC BOS. Costs for DC SB and equipment comprising ESSs are tracked and available from multiple sources with this report focused on quantifying the additional costs of system integration, EPC, project development, grid integration, and operations required for a functional energy storage deployment. Current cost data were obtained from several sources and with developer interviews. 2030 cost projections were accomplished by using defined learning rates for the various cost components. For a detailed description of the methodology used, see the 2020 Cost and Performance Report.

New information and methodology changes included for 2021 estimates are provided below. The Li-ion battery technology is mature and has been commercially deployed for grid-scale storage.

Lead-Acid Batteries

The lead-acid battery technology is mature and has been commercially deployed for grid-scale storage.

Vanadium Redox Flow Batteries

An RFB is a unique type of rechargeable battery architecture in which the energy is stored in one or more soluble redox couples contained in external electrolyte tanks (Yang et al., 2011). Liquid electrolytes are pumped from the storage tanks through electrodes where the chemical energy in the electrolyte is converted to electrical energy (discharge) or vice versa (charge). The electrolytes flowing through the cathode and anode are often different and referred to as catholyte and anolyte, respectively. Between the anode and cathode compartments is a membrane (or separator) that selectively allows cross-transport of a charge-carrying species (e.g., H^+, Cl^-) to complete the electrochemical reaction. Mixed-acid electrolytes have a wider SOC operating range of 10-90% (Cipriano, 2021) compared to conventional sulfuric-acid-based electrolytes with an SOC range of 10-80% (Mittal, 2021), leading to higher vanadium utilization. This, coupled with their higher concentration, results in an energy density twice that of conventional sulfuric-acid-based batteries, resulting in lower cost (Cipriano, 2021. At lower SOC, battery performance suffers during discharge, while at higher SOC, bipolar plate corrosion (Mittal, 2021) and gassing (Cipriano, 2021) reduce stack and electrolyte life, respectively.

Depending on stack design, the RFB can provide as much as twice its rated power for up to one hour (Torikai & SHIBATA, 2021). While some systems do not provide rated power across the entire SOC range, most developers include additional electrolyte in the tank to ensure the rated power is sustained across the 0–100% SOC range. Note that the actual SOC range as seen by the BMS would be in a tighter range such as 10-90%, with SOC excursions beyond this range prevented to ensure performance and reliability, with minimal need for electrolyte balancing (Cipriano, 2021; Mittal, 2021; Watson, 2021).

In traditional battery designs like Li-ion, the stored energy is directly related to the amount of electrode material and increasing the power capacity of these systems also increases the energy capacity and vice versa as more cells are added. In RFB systems, the power and energy capacity can be varied separately. The power (kW) of the system is determined by the size of the electrodes, number of cells in a stack, and number of stacks in the battery system, whereas the energy storage capacity (kWh) is determined by the concentration and total volume of the electrolyte. Both energy and power can be easily adjusted for storage from a few hours to days, depending on the application. This flexibility makes RFB an attractive technology for a variety of grid-scale applications with a wide range of power and energy needs. Using the same stack power capacity, increasing durations (energy levels) are accommodated by increasing the electrolyte quantity, while an application requiring greater power for the same energy content can be met by simply adding more stacks, and an application requiring greater power and energy is met by increasing the stack count and electrolyte volume. The vanadium redox flow battery technology is mature and has been commercially deployed for grid-scale storage.

Zinc-Based Batteries

There are several technologies and configurations that employ metallic zinc as the battery anode. For this study, four zinc-based technologies were analyzed: nickel-zinc (Ni-Zn), zinc-bromine (in flow and static designs), and zinc-air. The component costs and performance were analyzed for each technology based on developer specifications with additional projections made to match the power and duration targets for this study. High-level details on developer-provided information for the zinc technologies are given below:

- Ni-Zn – one developer-provided information for 2 hours, another for 2 and 4 hours, while a third developer-provided information for 2-100 hours.
- Zinc-bromine (flow) – information was available only from one developer at the 4-hour rate.
- Zinc-bromine (nonflow) – information was available only from one developer at the 4-hour rate. The same unit energy cost was applicable for 3–12-hour durations as well.
- Zinc-air – information was available only from one developer for 8–100-hour duration.

Since most zinc-based manufacturers have not deployed systems rated at > 10 MW, the study for zinc- based technology is limited to 10 MW.

Due to the significant differences among the zinc technologies considered, the available information from developers on cost, O&M, and performance have a wide range. While for the BESS technologies addressed in Phase 1, this work has used a nominal scaling factor for higher power and energy content, for zinc-based technologies, due to data provided by most developers restricted to only one or two durations, this scaling factor is not applied, with data provided by each vendor for various durations retained as is.

A new trend in the Ni-Zn industry is to leverage lead-acid manufacturing efficiencies and use equipment and plants designed for lead-acid manufacture. This involves investment by lead-acid equipment manufacturers in Ni-Zn manufacturing (International, 2021) and Ni-Zn manufacturers actively seeking out lead-acid plants for Ni-Zn manufacturing (Burz, Macher, & Baker, 2021). There is potential to use some of this equipment for other nonflow zinc-based chemistries as well.

Compressed-Air Energy Storage

CAES involves using electricity to compress air and store it in underground caverns. When electricity is needed, the compressed air is released and expands, passing through a turbine to generate electricity. There are various types of this technology including adiabatic systems and diabatic systems. The difference between these two configurations is that adiabatic systems capture and store the heat generated through the compression process to reuse later in the air expansion process in order to generate a larger amount of power output. For diabatic systems, the heat generated during compression is simply released. Newer applications of this technology include development of isothermal CAES. This technology removes heat across multiple stages of compression to reach a temperature closer to ambient, making it easier and more economic to store.

CAES is designed to fill markets where longer duration (12-24 hours) is needed. While CAES has been demonstrated to deliver longer duration storage, its cost effectiveness is limited by the availability and design of the caverns.

Pumped Storage Hydropower

As noted in the 2020 report, PSH is a mature technology that includes pumping water from a lower reservoir to a higher one where it is stored until needed. When released, water from the upper reservoir flows back down through a turbine and generates electricity. There are various configurations of this technology, including open loop (one or more of the reservoirs are connected to a natural body of water) and closed loop (reservoirs are separate from natural waterways). Existing turbine technologies also offer different features and capabilities, including fixed speed, advanced speed, and ternary.

Gravity Energy Storage

Gravity-based ESSs can take many forms, from pressurized water that lifts a piston within a mined shaft to heavy bricks that are lifted by a crane to store energy. In each case, the stored energy is converted into kinetic energy that generates electricity using generators. The systems offer the potential for scalable energy outputs, for example doubling shaft depth increases stored energy content by a factor of four; whereas, for storage based on lifting heavy blocks, scaling with respect to energy is enabled by increasing the mass of each block. The different types of gravity ESSs covered in this section are:

- Heavy bricks lifted by cranes
- Rail-based gravity storage
- Pressurized water that lifts a heavy piston within a mined shaft with power equipment below ground
- Pressurized water that lifts a heavy piston within a mined shaft with power equipment above ground.

Gravity-based systems use stored gravitational potential energy for conversion to electricity via a generator. Energy is stored by lifting 35-ton concrete blocks using a six-arm crane powered by a motor during periods of excess electricity and electricity is generated by dropping the blocks with the motor running in reverse (John, 2019; Pedretti, 2021; Spector, 2018; Vault, 2021). The control software directs smooth movement of the blocks considering wind conditions and inertia. A demonstration system has been running in Switzerland for a year, using a one-armed crane and 500 kg concrete blocks. The blocks are built on site using recycled building material with minimal fresh cement, keeping costs low while being environmentally viable. Per the specifications, this system has an RTE of 85–90%, a life of 30-40 years, responds within a few milliseconds, and ramps to maximum power in 2.5 seconds. The performance specifications are in line with Li-ion battery technology, while the life is two to three times higher.

Currently, 500-ton weights are used in existing mine shafts or custom-built shafts 150 to 1,500 m deep (Gravitricity, 2021), with power of 1–20 MW per shaft, and total energy content ranging from 8–192 MWh depending on the number of weights used per shaft. These weights are suspended by several cables that lift them during charge and drop them in a controlled manner during discharge. Efforts are ongoing to develop projects in Europe and South Africa using existing or custom-built shafts. The higher unit block weight lends itself to a smaller footprint, while movement of the blocks within a mineshaft offers protection from severe wind. A 250-kW demonstration unit has been commissioned using an aboveground 15 m high rig and has demonstrated a response time of 1 second from 0–100% of rated power (Gravitricity, 2021). The demonstration was completed, and the system was being decommissioned in July 2021 (Blair & Apps, 2021). An RTE of 85% and calendar life of 50 years is estimated (Gravitricity).

A 50 MW project is being developed on 20 acres in a gravel mine in Pahrump, Nevada (Storage, 2020). The project is expected to comprise of 10 multi-rail tracks, with 210 cars packed with material weighing 75,000 tons (Weed, 2021). The project targets frequency regulation and other ancillary services. Drive motors draw electricity from the grid to move the cars uphill and operate as generators when the cars descend. By increasing the number of cars, the energy content is increased. The system is scalable and ranges from 5 MW to 1 GW, with a duration of 15 minutes to 10 hours. The life is estimated at 40 years (Advanced Rail Energy Storage, Undated) with an RTE of 90% and response time of 10 and 17 seconds to full discharge and full charge, respectively (Weed, 2021).

Gravity Power (Santa Barbara, California) uses water pressure to hold a heavy piston weighing more than 8 million metric tons (Moore, 2021). When electricity is needed, the piston drops with pressurized water turning turbines and generating electricity. The piston height is set at half the shaft depth, while the distance moved along the shaft is equal to piston height. Thus, doubling shaft height increases stored energy content by a factor of four, lowering unit energy costs. A variation of this approach corresponds to piston height and diameter set equal to each other, with the distance moved along the shaft limited to half the piston height (Heindl Energy, 2021; Werner, 2021). Doubling the piston diameter results in stored energy increase by a factor of 16 (2^4). The power equipment in these technologies is similar to that used in PSH, the only difference being their location is either on the surface or underground. The RTE of these systems increases with system power capacity, as the pumps/turbines and motors/generators are more efficient at larger sizes and is in the 78.5–84% range with an estimated plant life of 60 years. These systems have not been commercially deployed or validated by a demonstration project. While the equipment used in these systems are commercially available, sealing of water within the shaft as the piston moves needs to be validated.

For this study, analysis was conducted for 100 MW and 1,000 MW systems of durations 2, 4, 6, 8, 10, 24 and 100 hours since the lowest power level for which data was provided was 50 MW.

Thermal Energy Storage

Thermal energy storage comprises multiple pathways where the input and output energy are either heat or electricity. Conventional thermal storage uses concentrating solar-thermal power (CSP) to heat the storage media, which typically is a molten nitrate salt with composition 60 wt.% $NaNO_3$-40 wt.% KNO_3, also known as solar salt. Efforts are underway to use electrical resistive heating to replace CSP, with additional storage media considered such as crushed rock, sand, concrete, brick, or cast iron. Liquid air energy storage (LAES) involves liquefaction of air using a standard refrigeration cycle, followed by extracting stored energy by heating the liquid air, resulting in orders of magnitude higher volume, to generate electricity by driving a gas turbine.

The different types of thermal energy systems, based on how they are charge, are:

- Pumped heat energy storage (PHES) (AC in, AC out)
- Sensible heat-based thermal energy storage[9] such as heat storage media such as molten salt, sand, concrete, thermal oil (AC in, AC out)

- LAES (AC in, AC out)
- Latent heat energy storage, which is in the applied research stage; no response was received from the developers contacted and it is not covered in this report[10]
- Thermochemical energy storage, which is in the applied research stage and is not covered in this report.

All systems considered had electricity input and output. Charging is done by electricity input (heater for sensible heat, power for compressor for pumped heat storage, and power for refrigeration cycle for LAES) with an exception for some hybrid systems where fuel is also used. These additional hybrid systems, beyond CAES, are included to assess the cost and performance of molten salt and liquid air storage media integrated with gas turbines. A brief review of thermal energy storage technologies is presented and is by no means an exhaustive list of technology designs that have been proposed in the literature.

The total installed energy capacity of thermal storage was 234 GWh as of 2019, with space heating dominant, while molten-salt-based electricity storage had a 21 GWh share (IRENA, 2020) with the total numbers expected to grow to 850 GWh by 2030 at the high end, with molten-salt-based electricity storage assumed to dominate at roughly 630 GWh, of which 73 GWh are additional planned capacity, while additional deployments beyond planned capacity range from 55 to 540 GWh. While molten-salt- based storage is at the commercial stage, solid-state sensible heat (sand, concrete, rocks) , high- temperature latent heat-based storage and LAES at the prototype/demonstration stage, and thermochemical storage are in the applied research stage.

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[9] As explained later, the CSP is replaced with electrical heating.

[10] Azelio, a Swedish developer, is actively commercially marketing a latent heat energy storage system and claims a few commercial sales.

Thermal storage for CSP is active where the storage medium flows between two tanks, or passive in a thermocline-type system, with a heat transfer fluid flowing through the stationary solid-state thermal energy storage medium such as concrete to exchange heat (Fernández et al., 2019). Note that all commercially deployed thermal energy storage systems for CSP are active. Active storage is direct when the storage medium also serves as the heat transfer fluid as is the case for solar tower power plants, whereas it is indirect when a synthetic oil heat transfer fluid exchanges heat with the storage medium in a heat exchanger.

Solar salt, consisting of a eutectic mixture of sodium and potassium nitrate, operates in the 290–565°C range, storing sensible heat at a capital cost of $20–25/kWh thermal for solar salt storage media cost, (Abrams, Farzan, Lahiri, & Masiello, 2014; C. W. Forsberg, McDaniel, & Zohuri, 2021; Nunes, Queiros, Lourenco, Santos, & Castro, 2016). Temperature limits are set by the salt melting point and decomposition temperatures. The upper decomposition temperature limit may be extended by varying the salt composition and controlling gas composition over the storage tank. The hot salt is either sent directly to a steam generator or a heat transfer fluid is used to transfer heat from the salt to the steam generator. As part of a study summarizing three different pathways for DOE’s Gen3 CSP roadmap, Mehos et al. (2017) describes ongoing work to develop a salt system consisting of chlorides of sodium, potassium, and magnesium with a melting point of 400°C and a decomposition temperature exceeding 1,000°C, with the operating temperature range of 500°C to 720°C (Augustine, Kesseli, & Turchi, 2020). Detailed cost breakdowns are also given for the salt and salt tanks. Note that chemically reducing conditions need to be maintained to avoid corrosion (C. Forsberg, Sabharwall, & Sowder, 2020). This chloride system was not selected to go forward for a MW-scale demonstration. However, the DOE is supporting a scaled down prototype of the chloride storage medium at the National Renewable Energy Laboratory.

Each tank has a foundation, pumps, and insulation and is instrumented to measure temperature, pressure, molten salt level, and flow rate (Bauer, Odenthal, & Bonk, 2021). The current maximum height and diameter are typically 13 m and 40 m, respectively, with storage capacity of up to 30,000 tonnes in a single tank. Research is focused on molten salts, tank design, pumps, valves, and instrumentation.

As of 2017, there were three solar tower power plants totaling 140 MW and one parabolic trough plant rated at 5 MW using solar salt as both heat transfer fluid and storage medium, also known as direct thermal storage, and 21 parabolic trough plants using a eutectic mixture of diphenyl and diphenyl oxide heating oil as heat transfer fluid and solar salt as storage medium (indirect thermal storage) with power rating in the 50-280 MW range (Fernández et al., 2019). This has grown to 12 tower projects and 34 parabolic trough projects (Kelly, 2021b). The National Renewable Energy Laboratory NREL maintains a database of operating plants (National Renewable Energy Laboratory, 2022).

Hydrogen

There are multiple HESS configurations that may be useful in different use cases. The configuration analyzed in this report, however, is bidirectional storage using fuel cells. This configuration further involves using a PEM electrolyzer to generate hydrogen from water with an electrical current (releasing oxygen as a byproduct) before compressing and storing the hydrogen in underground salt caverns until needed. The hydrogen is later re-electrified using the fuel cells to produce electricity.
HESS consists of three major components:

- Charging system includes electrolyzer modules, BOP, water-handling units, mass flow controllers, electrolyzer management system, compressor, and rectifier.
- Discharging system consists of stationary fuel cell modules, BOP, gas-handling units, blowers, mass flow controllers, fuel cell management system, and inverter.
- The storage system typically includes pipes or a cavern.

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