2020 Grid Energy Storage Technology Cost and Performance Assessment

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Disclaimer

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Foreword

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 ESGC is organized around five cross-cutting 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 to identify the research and development opportunities that can impact further cost reductions. This report represents a first attempt at pursuing that objective by developing a systematic method of categorizing energy storage costs, 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.

Not all energy storage technologies could be addressed in this initial report due to the complexity of the topic. For example, thermal energy storage technologies are very broadly defined and cover a wide range of potential markets, technology readiness levels, and primary energy sources. In other areas, data scarcity necessitates a greater understanding of future applications and emerging science. Future efforts will expand the list of energy storage technologies covered while providing regular updates to the data presented in this report and on https://www.pnnl.gov/ESGC-cost-performance.

Finally, numerous complementary analyses are planned, underway, or completed that will provide a deeper understanding of the specific technologies covered in this report. Many of these have been cited herein.

PNNL and the entire ESGC looks forward to working with industry, external researchers, and other stakeholders to improve our understanding of energy storage cost and performance.

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 (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 the U.S. Department of Energy (DOE) HydroWIRES initiative (Mongird et al., 2019). This work aims to: 1) update cost and performance values and provide current cost ranges; 2) 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 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.

Phase 1 of this initiative includes cost and performance metrics for most commercially available energy storage technologies across various energy-to-power ratios:

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

Additional storage technologies will be incorporated in later phases of this research effort to capture more nascent technologies of interest to DOE and other stakeholders.

In addition to current cost estimates and projections, the research team aimed to develop a cohesive organization framework to organize and aggregate cost components for energy storage systems (ESS). This framework helps eliminate current inconsistencies associated with specific cost categories (e.g., energy storage racks vs. energy storage modules). A framework breaking down cost components and definitions was developed to help provide clarity and enable apples-to-apples comparisons, while using data from different industry participants across multiple technologies. The breakdown of these components and definitions was reviewed by various experts across numerous national laboratories and is provided in the next section.

Cost and performance information was compiled for the defined categories and components based on conversations with vendors and stakeholders, literature, commercial datasets, and real-world storage costs for systems deployed across the US. A range of detailed cost and performance estimates are presented for 2020 and projected out to 2030 for each technology. Current cost estimates provided in

this report reflect the derived point estimate based on available data[1] from the reference sources listed above with estimated ranges for each studied technology. In addition to ESS costs, annualized costs and a levelized cost of energy (LCOE) of each technology are also provided to better compare the complete cost of each ESS over the duration of its usable life. Annualized cost measures the cost to be paid each year to cover all capital and operational expenditures across the usable life of the asset while also accounting for additional financial parameters such as taxes and insurance. The unit energy or power annualized cost metric is derived by dividing the total annualized cost paid each year by either the rated energy to yield $/rated kilowatt-hour (kWh)-year or by rated power to yield $/rated kilowatt (kW)-year, where the kWh and kW are rated energy and power of the ESS, respectively. LCOE, on the other hand, measures the price that a unit of energy output from the storage asset would need to be sold at to cover all expenditures and is derived by dividing the annualized cost paid each year by the annual discharge energy throughput[2] of the system.

For battery energy storage systems (BESS), the analysis was done for systems with rated power of 1, 10, and 100 megawatts (MW), with duration of 2, 4, 6, 8, and 10 hours. For PSH, 100 and 1,000 MW systems at 4- and 10-hour durations were considered. For CAES, in addition to these power and duration levels, 10,000 MW was also considered. For HESS, only 100 MW at a 10-hour duration was evaluated. These power and duration choices for each technology represent the commercially available or representative levels. In addition to costs for each technology for the power and energy levels listed, cost ranges were also estimated for 2020 and 2030.

Key findings from this analysis include the following:

- The dominant grid storage technology, PSH, has a projected cost estimate of $262/kWh for a 100 MW, 10-hour installed system. The most significant cost elements are the reservoir ($76/kWh) and powerhouse ($742/kW).
- Battery grid storage solutions, which have seen significant growth in deployments in the past decade, have projected 2020 costs for fully installed 100 MW, 10-hour battery systems of: lithium-ion LFP ($356/kWh), lead-acid ($356/kWh), lithium-ion NMC ($366/kWh), and vanadium RFB ($399/kWh). For lithium-ion and lead-acid technologies at this scale, the direct current (DC) storage block accounts for nearly 40% of the total installed costs.
- CAES is estimated to be the lowest cost storage technology ($119/kWh) but is highly dependent on siting near naturally occurring caverns that greatly reduces overall project costs. Figures Figure ES-1 and Figure ES-2 show the total installed ESS costs by power capacity, energy duration, and technology for 2020 and 2030.
- Looking at total installed ESS cost for a 4-hour duration, CAES may still provide the lowest cost option, showing the potential impact of low cavern costs. Lithium-ion and lead-acid have

[1] Depending on technology and category, the derived point estimate corresponds to the average after removing outliers (lithium-ion 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.

[2] Annual discharge energy throughput is the total energy discharged each year and is simply the product of rated energy, number of cycles per year, and the depth of discharge (DOD), accounting for assumed downtime.

similar costs, with the slightly higher storage block cost for the lithium-ion chemistries compensated by the need for a DC-DC converter for the lead-acid system. RFBs and PSH have the highest capital costs, primarily due to greater impact of stacks and powerhouse, respectively.

- There is a demonstrated effect of power-related scaling for fixed duration, shown in Figure ES-1 and Figure ES-2. This also shows how various technologies switch places in installed cost ranking based on duration, with PSH showing the lower capital cost at 10-hour duration, and higher cost at 4-hour duration. Technologies with independent power and energy costs and low energy costs, like CAES, are only marginally impacted in terms of unit power costs by changes in discharge duration.
- On an annualized cost basis (Figure ES-3), for 10-hour duration systems, CAES and PSH are projected to have the most cost-effective position for 2020 ($29/kWh and $36/kWh, respectively, for a 100 MW system). HESS, in spite of lower capital cost, is nearly tied with redox flow when considered on an annualized basis ($56/kWh and $65/kWh, respectively) due to the higher round-trip efficiency (RTE) of the RFB. While capital cost for lithium-ion LFP was only marginally lower than lithium-ion NMC, its annualized cost is significantly lower ($93/kWh vs. $140/kWh) due to its higher cycle life. For the same reasoning, lithium-ion LFP is higher than redox flow on an annualized cost basis for the 100 MW, 10-hour system, even though its capital cost is lower. Lead-acid batteries, with a capital cost on par with lithium-ion, have an annualized cost nearly three times higher due to their lower cycle life, DOD, and round-trip efficiency.
- Looking at the annualized costs for 100 MW, 4-hour duration systems, CAES, PSH, and RFB systems benefit from much higher cycle life compared to the remaining systems. Lead-acid batteries are significantly impacted by the lower allowable DOD and lower round-trip efficiency at the 4-hour rate in the current modular configuration. Single-cell string configurations may offer significant performance improvements for lead acid. Overall, the annualized cost results show the importance of the performance metrics such as round-trip efficiency, DOD, and cycle life.
- The 2020 installed cost ranges were determined for most technologies using factors of 0.9 and 1.1, the only exception being salt cavern costs, which exhibit a wide range of costs depending on cavern type.
- The 2030 scenario installed cost estimates were obtained by using higher learning rates[3] for lithium-ion and redox flow storage blocks, with the same learning rates used for the rest of the cost categories. For 2030 projections, CAES remains the most cost-effective ESS on a total installed cost basis as well as an annualized cost basis for a 100 MW, 10-hour system. A steep drop in HESS price, as provided by Hunter et al. (In Press), could enable these systems to be competitive with CAES in future scenarios. At the higher learning rates, lithium-ion BESS, may be more cost competitive with PSH by 2030 for 10-hour duration.
- Regarding 2030 installed ESS cost for 100 MW, 4-hour systems, higher learning rate scenarios (e.g., 12-16%) could allow lithium-ion LFP ($299/kWh) and lithium-ion NMC ($300/kWh) to be

[3] Learning rate is percent cost decrease for doubling of cumulative capacity

more competitive with CAES ($291/kWh). Similar learning rates applied to redox flow ($414/kWh) may enable them to have a lower capital cost than PSH ($512/kWh) but still greater than lead-acid technology ($330/kWh).

Major findings from this analysis are shown in Figures Figure ES-1 and Figure ES-2. Values presented show the derived point estimates for total installed ESS cost by technology, power capacity (MW), and energy duration (hr). Figure ES-1 provides estimates for 2020, while Figure ES-2 shows estimates for2030. A figure showing ranges in addition to point estimates for 100 MW, 10-hour systems and 100 MW, 4-hour systems is provided in the Comparative Results section later in this report. Additional cost ranges, while shown in the technology-specific sections of this report, will be provided in comparative figures in the online database for each technology, year, power capacity, and energy duration combination analyzed in this report. Annualized cost and LCOE ranges for 100 MW, 10-hour and 100 MW, 4-hour systems are shown in Figure ES-3 and provided in the Annualized Cost of Storage and Levelized Cost of Energy section.

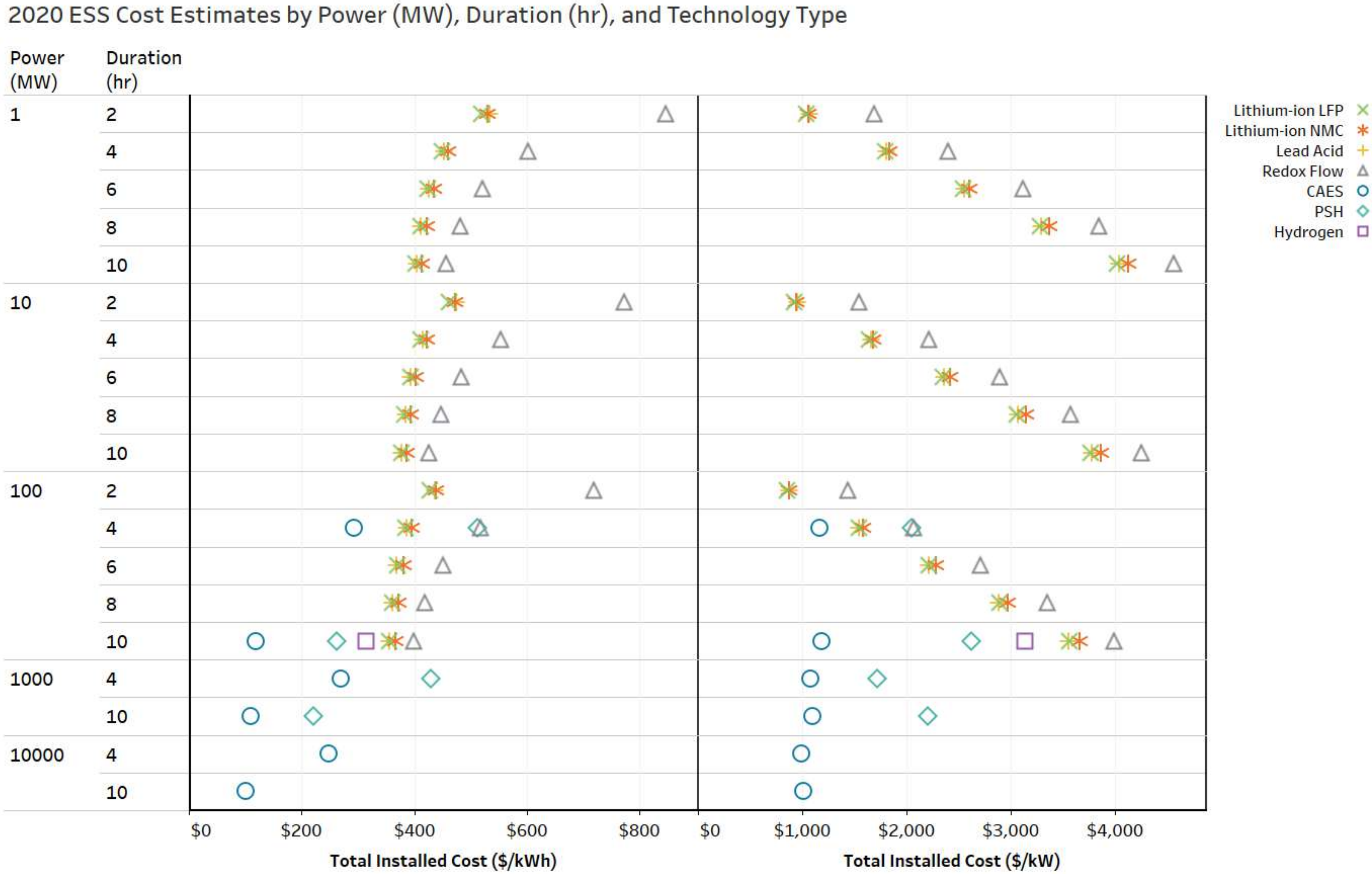

Figure ES-1. Comparison of Total Installed ESS Cost Point Estimates by Technology, 2020 Values

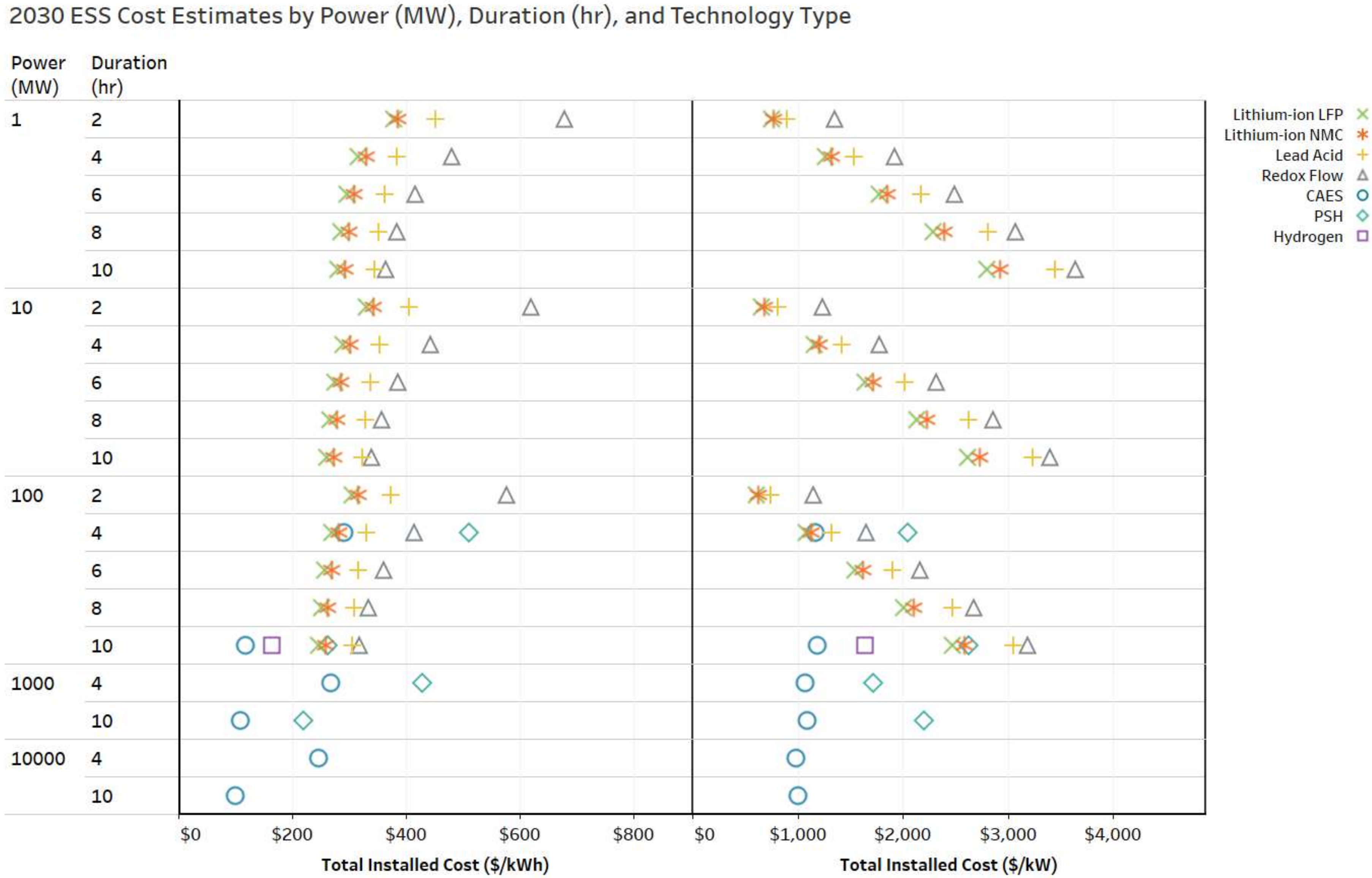

Figure ES-2. Comparison of Total Installed ESS Cost Point Estimates by Technology, 2030 Values

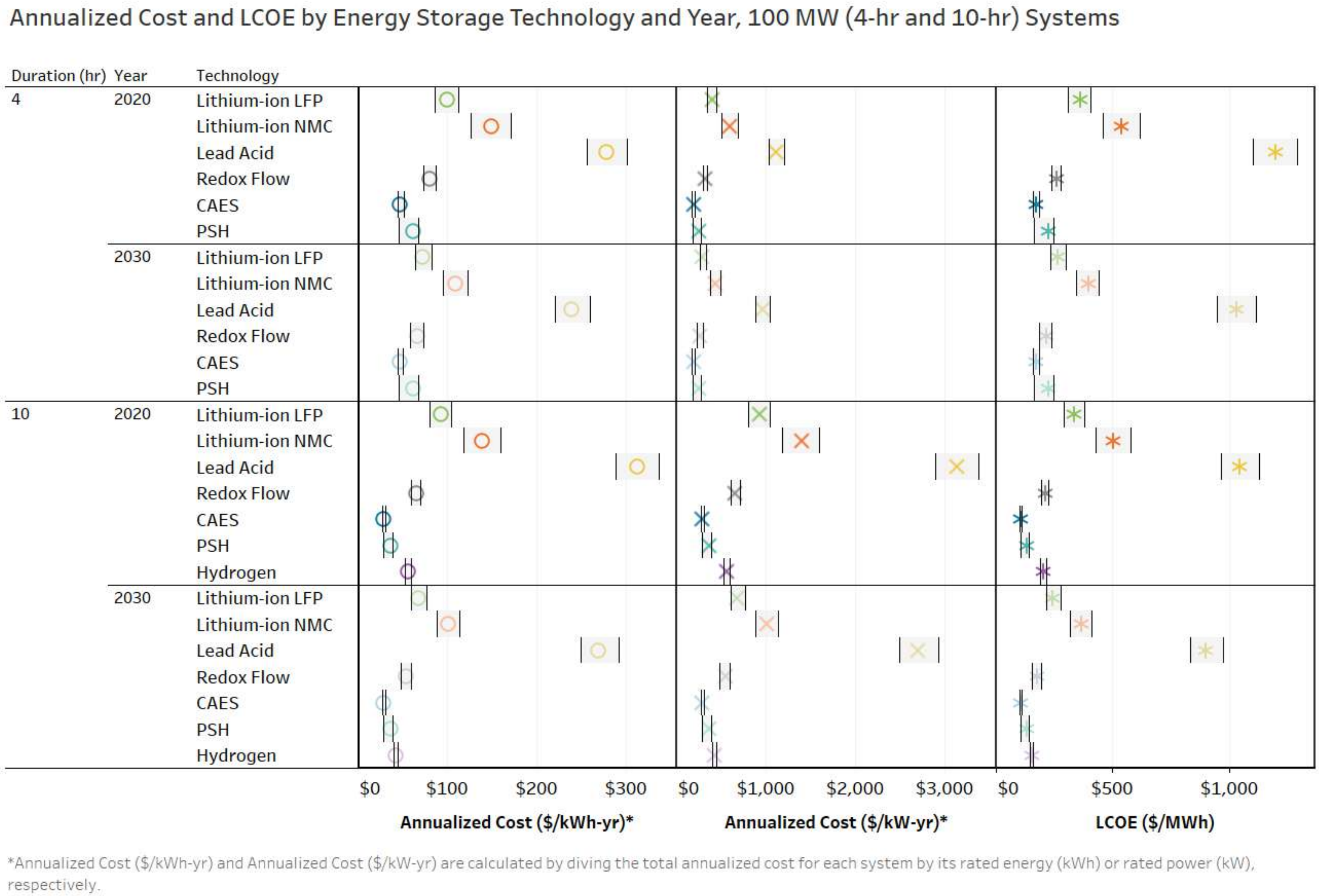

Figure ES-3. Comparison of Annualized Costs and LCOE by Technology, Duration, and Year

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Acronyms

AC	alternating current
Ah	ampere-hour
BESS	battery energy storage system
BLS	U.S. Bureau of Labor Statistics
BMS	battery management system
BOP	balance of plant
BOS	balance of system
C&C	controls & communication
C&I	civil and infrastructure
CAES	compressed-air energy storage
DC	direct current
DOD	depth of discharge
DOE	U.S. Department of Energy
E/P	energy to power
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
ESGC	Energy Storage Grand Challenge
ESS	energy storage system
EV	electric vehicle
GW	gigawatts
HESS	hydrogen energy storage system
hr	hour
HVAC	heating, ventilation, and air conditioning
kW	kilowatt
kWe	kilowatt-electric
kWh	kilowatt-hour
LCOE	levelized cost of energy
LFP	lithium-ion iron phosphate
MW	megawatt
MWh	megawatt-hour
NHA	National Hydropower Association
NMC	nickel manganese cobalt
NRE	non-recurring engineering
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PCS	power conversion system
PEM	polymer electrolyte membrane
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydro
PV	photovoltaic
R&D	research & development
RFB	redox flow battery
RTE	round-trip efficiency

SB	storage block
SBOS	storage balance of system
SCADA	sensors, supervisory control, and data acquisition
SM	storage module
SOC	state of charge
USD	U.S. dollars
V	volt
Wh	watt-hour

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