Storage™

Technology Strategy Assessment Methodology

Storage Innovations 2030 Technical Process

July 2023

About Storage Innovations 2030

This report describes the technical methodology of 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 toward achieving the targets identified in the Long-Duration Storage Energy Earthshot, 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

This report details information about the methodology of the SI Framework and the SI Flight Paths pillars and is released alongside the ten technology reports that utilize this process.

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

Acknowledgments

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Background

Over the past several decades, the U.S. Department of Energy (DOE) has funded or supported dozens of energy storage technologies spanning electrochemical, electromechanical, thermal, flexible generation, and controllable loads, as well as power electronics. While lithium-ion batteries have historically received the most research and development (R&D) funding, reflecting their applicability to the missions of multiple DOE offices, other technologies, including flow batteries and hydrogen storage, have also received significant DOE support.

In 2020, DOE launched the Energy Storage Grand Challenge (ESGC), which is a department-wide coordination framework to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage. These comprehensive objectives require concerted action, guided by an aggressive goal: to develop and domestically manufacture energy storage technologies that can meet all U.S. market demands by 2030. The 2020 ESGC Roadmap outlines a department-wide strategy to accelerate innovation across a range of storage technologies.

In 2021, DOE launched the Long-Duration Storage Shot [2], which established the target to reduce the cost of grid-scale energy storage by 90%, to $0.05/kWh levelized cost of storage (LCOS), for systems that deliver 10+ hours of duration by 2030. The Long-Duration Storage Shot is part of DOE's Energy Earthshots Initiative, which aims to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade. Achieving the Energy Earthshots will help America tackle the toughest remaining barriers to addressing the climate crisis. The Long-Duration Storage Shot will consider all types of technologies—whether electrochemical, mechanical, thermal, chemical carriers, or any combination—that have the potential to meet the necessary duration and cost targets for grid flexibility.

To map out paths to achieve the Storage Shot targets, DOE launched Storage Innovations (SI) 2030 [3], a crosscutting, industry-aware initiative, at the ESGC Summit in September 2022. SI 2030, as a major activity under the ESGC Framework, identifies technological routes toward the Long-Duration Storage Shot, and carries out congressional direction by analyzing which long-duration capable energy storage technologies have the greatest potential to achieve future goals and benefit from widespread deployment on the nation's electricity grid.

Through SI 2030, DOE seeks to understand the full landscape of long duration-capable technologies and the specific innovations required to unlock the potential for long-duration applications in a variety of these technologies. To engage the storage community in this effort, SI 2030 has launched three components: the SI 2030 Framework, the SI 2030 Prize, and the SI 2030 Flight Paths.

1. **SI Framework:** This pillar is creating an industry-aware R&D "framework," aiming to project and estimate the impact of R&D activities on future storage cost targets. This approach is aimed at guiding the highest impact R&D investments by facilitating one-on-one conversations around the future of the 10 energy storage technologies [3]. The primary goals of the Framework are to stochastically model the future outcomes of potential investment portfolios on storage technology LCOS and craft strategies around the highest impact investments and technology suitability across different use cases.
2. **SI Prize** [4]**:** While the Framework targets established or mid-stage technologies, the Prize invited the storage community to propose early-stage, emerging, and innovative energy

storage ideas that may be disruptive to industry in the future. The competition closed in December 2022 and the winners were announced on February 27, 2023 [5].

3. **SI Flight Paths:** SI Flight Paths complements the Framework by providing a collaborative forum to discuss technology R&D opportunities and the potential for pre-commercial R&D pathways. The Flight Paths effort was composed of nine industry listening sessions held January through March 2023, bringing together industry representatives to take part in technology-focused discussions about specific technology areas.

Flight Paths to Technology Goals

The Flight Paths effort has involved working with U.S. long-duration energy storage (LDES) technology industries to achieve two primary objectives:

1. Define pre-commercial research and related efforts (e.g., standards development, market analyses) that can ensure the commercial viability of LDES technologies by 2030.
2. Encourage the formation of technology-based industry consortia that can help navigate these pathways.

Working with stakeholders, the Flight Paths effort identifies and defines research pathways that utilize pre-commercial efforts to address R&D needs common across many innovators in a specific storage technology area. In this manner, the Flight Paths effort is organized in a way that may leverage DOE and National Laboratory research capabilities to an entire storage technology area, thereby multiplying the chances of commercial viability of key LDES technologies by 2030.

The first step in the Flight Paths were the "Pitch Sessions," which brought together technology developers throughout the LDES spectrum—from established companies to startups and academic researchers—and a team of technology experts from across the National Laboratory system, to conduct and evaluate a series of brief pitches about the numerous technologies under development. The ESGC Laboratory Coordination Team[a] led a series of live pitch sessions in person during the September 2022 ESGC Summit, followed by virtual sessions in November. In total, there were 29 pitches held virtually during the November 2 and November 3 sessions and 8 in-person pitches at the ESGC Summit, with National Laboratory experts providing input and evaluations regarding the viability of technologies to achieve commercial viability. Based on the ESGC Laboratory Coordination Team's input and the evaluations of the pitch sessions and specific congressional direction, DOE selected the 10 LDES technologies described in these reports for further analysis.

With the identification of representative LDES technology areas completed, the next step in the Flight Paths effort was for the ESGC Laboratory Coordination Team to develop listening sessions, conducted in January through March 2023, for proponents of each technology. National Laboratory experts led each listening session, which were approximately 2-hour virtual forums for input. In these sessions, the laboratory leads presented a series of discussion prompts to interested industry participants, who responded to the questions individually. These prompts were customized by the laboratory leaders for each session. Example questions included the following:

[a] The ESGC Laboratory Coordination Team includes Argonne National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories.

- What is the Technology Readiness Level and the Manufacturing Readiness Level of your particular technology?
- What are the most impactful impediments limiting the widespread deployment of your technology?
- What specific technical and/or market barriers are there for longer discharge durations (10-24 hours)?
- What would make public resources (e.g., state, regional, or federal testing sites, technoeconomic tools, technical expertise) more valuable for you?
- Can you identify specific "precompetitive" innovations or developments that would advance your technology?
- Is lack of a trained workforce currently a critical limitation for your success? What type of training or curricular development would you recommend for growing the workforce in this area?

Clearly, a very important factor in these listening sessions was obtaining engagement from members of the industry in each of these technology areas. Through a public launch at the 2022 ESGC Summit, distribution through ESGC and other communications media, and outreach to various industry associations, each listening session generated a significant amount of input and valuable discussion around each specific technology area.

Framework Study Methodology

The ESGC is critical to achieving diverse societal objectives, from decarbonization to reliability and resilience. The R&D Framework is designed to better organize future governmental investments to ensure the ESGC's success in the context of a rapidly evolving industry and use case landscape. The 8-step Framework, which is presented in Figure 2, was designed to enable the development of a tool that could be used to inform potential portfolios of future R&D investments. The overarching objectives of the Framework Study are to (1) characterize the suitability of different technologies for the different use cases defined in the ESGC, and (2) identify potential high-impact R&D areas for future investment. The remainder of this section outlines each of the eight steps of the Framework.

Identify individual innovation opportunities

Step 1: Assess R&D trajectory status quo
Step 2: Assess gaps with respect to improving technology cost/performance
Step 3: Define innovations that could be relevant to energy storage gaps
Step 4: Assess potential impacts of these innovations

Assess portfolios of interventions

Step 5: Implement Monte Carlo model
Step 6: Evaluate portfolios of interventions

Analyze modeled outcomes

Step 7: Conduct suitability evaluations
Step 8: Report on metrics

Figure 1. The 8-Step Framework Approach

Step 1: Assess R&D Trajectory Status Quo

The first step in the Framework Study was to establish the R&D trajectory status quo for a given technology, or to project performance and cost parameters out to 2030 given no change in R&D investment trends. These values, which included cost metrics such as storage block costs, balance of plant costs, and fixed and variable operations and maintenance (O&M) costs, along with performance metrics such as round-trip efficiency (RTE) and cycle life, were used to define the baseline against which all future impacts were measured. The V. Viswanathan et al. (2022) report, which was published under the ESGC, was used to establish the baseline for all technologies, with the exception of supercapacitors and sodium-ion batteries. For these technologies, several industry publications were used to define the needed cost and performance metrics [6].

It is important to note that while these publications represent the best available sources of data, any estimates prepared during the COVID-19 pandemic could be subject to significant volatility due to the presence of supply chain disruptions that have led to high rates of cost inflation, reaching 7% in the U.S. in 2021. These challenges were recognized in V. Viswanathan et al. (2022), and attempts were made by the authors to address them. For instance, the inflation rate used in the levelized cost calculations in V. Viswanathan et al. (2022) was doubled from 1.4% in the previous study to 2.8%. Since that rate is applied to each energy storage system over its economic life, which extends out 20-60 years, and inflation has cooled significantly thus far in 2023, this higher rate would appear reasonable. With that noted, the authors of this study recognize the higher levels of uncertainty associated with any recent energy storage cost estimates due to the COVID-19 pandemic and resulting global economic instability.

Step 2: Assess Gaps with Respect to Improving Technology Cost/Performance

Step 2 of the Framework Study is designed to establish a taxonomy of innovations, along with definitions of each innovation, through a series of interviews with relevant subject matter experts (SMEs). The taxonomy for lead-acid batteries is presented in Table 1. The innovation categories are common to all technologies; however, the innovations are specific to individual technologies. Therefore, Table 1 is just an example of an innovations taxonomy table, while the table for each technology will be unique.

Members of the research team reached out to hundreds of SMEs across the 10 chosen technology ecosystems and conducted interviews designed to elicit individual views on innovations with the potential for improving the cost and performance of the given technology.

Table 1. Taxonomy of innovations

Innovation Category	Innovation
Raw materials sourcing	Mining and metallurgy innovations
	Alloying in lead sources
Supply chain	Supply chain analytics
Technology components	Re-design of standard current collectors
	AGM-type separator
	Minimizing water loss from the battery
Manufacturing	Advanced manufacturing for lead-acid batteries
Advanced material development	Novel active material
	Improving paste additives - carbon
	Improving paste additives - expanders or other
	Novel electrolytes
Deployment	Scaling and managing the energy storage system
	Demonstration projects
End of life	Enhancing domestic recycling

Based on the input received through these interviews, the Framework Team prepared an innovation taxonomy with definitions for each technology and surveys designed to obtain SME input on the suitability, budget requirements, preferred R&D interventions, investment timelines, and cost and performance impacts of investment in each innovation.

Step 3: Define R&D Interventions That Could Be Relevant to Energy Storage Gaps

SMEs were asked their preferred method of R&D intervention most suitable for each innovation in a given technology. The options included National Laboratory research, R&D grants, subsidized capital (loans), or technical assistance. The SMEs' preferences with respect to investment mechanisms for each innovation are presented in each individual technology report.

Step 4: Assess Potential Impacts of R&D Interventions

In Step 4, the SMEs were asked to define investment requirements and the impact of each innovation defined in Step 2. SMEs were asked to quantify, for each innovation, the investment requirements, both funding levels and duration, and the expected size of the impact for several performance (e.g., RTE, energy density, cycle life) and cost (e.g., storage block costs, O&M costs) metrics. SME-derived impacts for individual innovations, which serve as the input data for the Monte Carlo simulation tool, are presented in the appendices for the individual technology reports. These impacts are U.S. centric, as were the cost projections defined in Step 1. Although the estimates are tied exclusively to the U.S. experience, global deployments and innovations that influence future costs would be necessarily embedded in those estimates. Within the context of the SME contacts carried out for this study, both the marginal investment levels and impacts presented in the technology reports were assumed to be U.S.-focused.

Step 5: Implement Monte Carlo Simulation Model

The Monte Carlo simulation model begins by creating the full list of possible portfolios and examining each portfolio separately. Portfolios are comprised of a unique set of innovations, each of which has a timeline, budget, and a list of effects on cost and performance metrics. An innovation's effects on these parameters are specified by probability distribution functions, derived from survey responses. For each portfolio, the effect of each innovation on the parameters is randomly determined using the corresponding probability distributions. Finally, innovation coefficients, which are described in the next section, are applied to the innovation with less impact on LCOS in each pair within the portfolio and the impacts are combined. Applying the impacts to the base attributes of the technology determines their resulting values for 2030, given the innovation portfolio. This is repeated many times to determine the mean and standard deviation of each portfolio's resulting LCOS.

Applying the Effects of Innovations

Not all innovations will have impacts that stack directly. For example, advances in mining and recycling processes are mutually exclusive in many respects, since recycled materials can displace newly mined materials. This means that a component can only be made as cheaply as the cheaper of the two materials available and cost savings from each innovation do not stack. To account for this, the Monte Carlo simulation tool uses innovation coefficient matrices, which assign a value between 0 and 1 for each pair of innovations. These innovation coefficients indicate the fraction of the savings potential for each innovation, independent of the other one. This way, a 1 represents two entirely independent innovations, where cost savings will stack linearly, and a 0 represents two entirely overlapping innovations, where only the more impactful innovation will have an effect on LCOS. An example innovation coefficient matrix, which was developed for zinc batteries, is presented in Table 2.

The goals of this process guide its implementation in the Monte Carlo simulation as follows:

- Mutually exclusive innovations should not stack their cost-savings effects.
- Independent innovations should stack geometrically so that two 10% cost reductions reduce the total cost to 90% and then 81%.
- Partially independent innovations should partially stack the cost-savings effects.
- The interactions between each and every pair in the full portfolio of funded innovations should be considered.
- The cost-savings effects of a pair should be at least as good as the most impactful innovation in the pair.

Table 2. Innovation coefficient matrix for zinc batteries

Innovation	Mining and metallurgy innovations for battery-grade Zn metal	Supply chain analytics for sustainable sourcing	Inactive material cost reduction	Separator innovation	Pack/system-level design	Implementation of manufacturing best practices	Developing a manufacturing ecosystem	Improved Zn metal performance	Cathode materials optimization and new materials discovery	Advanced electrolyte/additive development	Standardization of testing and safety requirements	Demonstration projects	Enhancing domestic recycling
Mining and metallurgy innovations for battery-grade Zn metal	–	0.25	0.50	0.50	0.50	0.35	0.35	0.25	0.50	0.50	0.50	0.50	0.15
Supply chain analytics for sustainable sourcing	0.25	–	0.20	0.25	0.50	0.40	0.50	0.25	0.20	0.30	0.50	0.50	0.20
Inactive material cost reduction	0.50	0.20	–	0.10	0.25	0.45	0.85	0.65	0.65	0.20	0.50	0.75	0.40
Separator innovation	0.50	0.25	0.10	–	0.55	0.40	0.50	0.60	0.65	0.60	0.40	0.60	0.40
Pack/system-level design	0.50	0.50	0.25	0.55	–	0.25	0.65	0.55	0.60	0.60	0.50	0.55	0.30
Implementation of manufacturing best practices	0.35	0.40	0.45	0.40	0.25	–	0.20	0.40	0.40	0.40	0.45	0.65	0.50
Developing a manufacturing ecosystem	0.35	0.50	0.85	0.50	0.65	0.20	–	0.50	0.50	0.50	0.50	0.65	0.25
Improved Zn metal performance	0.25	0.25	0.65	0.60	0.55	0.40	0.50	–	0.50	0.75	0.50	0.65	0.50
Cathode materials optimization and new materials discovery	0.50	0.20	0.65	0.65	0.60	0.40	0.50	0.50	–	0.55	0.55	0.65	0.45
Advanced electrolyte/additive development	0.50	0.30	0.20	0.60	0.60	0.40	0.50	0.75	0.55	–	0.55	0.60	0.55
Standardization of testing and safety requirements	0.50	0.50	0.50	0.40	0.50	0.45	0.50	0.50	0.55	0.55	–	0.85	0.50
Demonstration projects	0.50	0.50	0.75	0.60	0.55	0.65	0.65	0.65	0.65	0.60	0.85	–	0.50
Enhancing domestic recycling	0.15	0.20	0.40	0.40	0.30	0.50	0.25	0.50	0.45	0.55	0.50	0.50	–

These objectives are achieved by applying the innovation coefficient to the innovation with the smaller impact on LCOS in each combination of two innovations within a portfolio. For example, imagine that a portfolio is made up of four innovations, "I1", "I2", "I3", and "I4," which have the effect on storage block cost described in Table 3. These values represent the percentage impacts on storage block costs if the innovation was funded at the prescribed levels. Thus, a value of -0.1 would equate to a 10% reduction in storage block cost. The effect on storage block cost is described as determined by the survey responses. An innovation could, in theory, increase or reduce storage block costs. An innovation could be pursued to expand the cycle life of the technology, for example, even if it increased the storage block cost.

Table 3. Simplified example of a portfolio

	Storage Block Cost			
Innovation	Low	High	Mean	Std
I1	-0.1	-0.6	-0.2	0.1
I2	0.1	0.2	0.1	0.0
I3	-0.1	-0.2	-0.15	0.01
I4	0	0	0	0.0

The Monte Carlo simulation tool would use the data to create a Gaussian distribution and randomly select an impact for the innovation. For one scenario in the simulation, the portfolio results in I1 with a 30% cost reduction, I2 with a 10% cost increase, I3 with a 15% cost reduction, and I4 with a 0% effect on storage block cost. These effects are propagated through the LCOS formula to determine which one causes the greatest effect on LCOS and the innovations are sorted from lowest to highest. For this simple example, this would yield I2, I4, I3, I1. Next, innovation coefficients are assigned to their corresponding innovations by examining the combinations of pairs within the portfolio.

I2 gets innovation coefficients a, b, c	From combinations I2I4, I2I3, I2I1
I4 gets innovations coefficients d, e	From combinations I4I3, I4I1
I3 gets innovation coefficient f	From combination I3I1
I1 gets innovation coefficient 1	Because it is the most impactful innovation

Innovations are then applied to the base parameters of the technology to determine the parameters once the portfolio is complete (Equation 1):

$$\mathrm{new}_{\mathrm{sbc}} = \mathrm{base}_{\mathrm{sbc}} * (1 + I2_{sbc} * a * b * c) * (1 + I4_{sbc} * d * e) * (1 + I3_{sbc} * f) * (1 + I1_{sbc}) \tag{1}$$

where

new_{sbc} = Estimated achievable storage block costs in 2030 with defined RD&D investments under consideration of innovation coefficients;

$base_{sbc}$ = Base 2030 storage block costs based on current forecasts; and

I = Innovation coefficient.

By simulating many randomly generated scenarios for the same portfolio, an understanding of the expected impact of the portfolio can be generated. This expected impact is reported as a mean and standard deviation for the LCOS of the portfolio.

Calculating Levelized Cost of Storage

LCOS forms the metric against which all portfolios are measured. Each portfolio is judged on its ability to reduce LCOS and achieve the $0.05/kWh goal established in the ESGC Roadmap. The methodology used to calculate LCOS is presented here.

Table 4 presents the user inputs to the Monte Carlo simulation model that contribute to calculating LCOS. The remainder of this section defines the methods used to account for each component of the LCOS equation.

Table 4. Table of user inputs to the Monte Carlo simulation model that contribute to calculating LCOS

Parameter	Variable Name	Description
Project life (years)	$life_{proj}$	The lifetime of the project before it becomes more economical to decommission the plant than to replace worn out components: For batteries, this is 25 years; for pumped storage hydropower and compressed-air energy storage, it is 60 years; and for hydrogen, it is 30 years.
Calendar life (years)	$life_{cal}$	The calendar life of major components that may need replacement or augmentation before the end of the project life. This ignores the effects of charging and discharging the device.
Storage system power (kW)	P_{disch}	The rated power output of the project.
Storage system duration (h)	$duration$	The maximum duration for which the system can provide rated power.
Depth of discharge (fraction of total)	dod	The typical depth of discharge that will be used throughout the life of the project to avoid excessive degradation. The Framework Study assumes an 80% depth of discharge.
Down time (fraction of total)	dt	The fractional amount of time that the system will be offline for maintenance. The Framework Study uses a 5% down time assumption.
Cycle life (cycles)	$life_{cycles}$	The number of cycles for which major components (e.g., storage block) can be operated before being replaced or incurring major refurbishment costs.
Round-trip efficiency (fraction of total)	η_{RTE}	The fraction of electricity taken in from the grid that goes back to the grid as electricity.
Discharge efficiency (fraction of total)	η_{disch}	The fraction of stored energy that is seen at the meter as electricity returned to the grid.
Storage block cost ($/kWh)	SBC	The upfront capital cost of the part of the system that stores energy.
Balance of plant cost ($/kWh)	bop	This includes upfront cost for everything that supports the storage block, such as the container, cabling, switchgear, HVAC, and other similar components.
Fixed operations and maintenance (O&M) cost ($/kW per year)	OM_{fix}	The cost of operating and maintaining the system for 1 year on standby.
Variable O&M cost ($/kWh)	OM_{var}	The cost of operating and maintaining the system that is driven by energy throughput.
Renovation cost ($/kWh)	$reno$	The cost of replacing, augmenting, or renovating major components that wear out before the end of the project life.
Controls and communications cost ($/kW)	$ctrcomm$	The upfront capital cost to set up the controls and communications necessary to operate the system.
Power equipment cost ($/kW)	pwr	The upfront capital cost of the power inverter and/or other necessary power equipment.
System integration cost ($/kWh)	$sysint$	The upfront capital cost required to connect all of the components of the plant with one another.
Project development cost ($/kWh)	$prjdev$	The upfront capital cost of siting, permitting, and other project development activities related to planning.
Engineering, procurement, and construction (EPC) cost ($/kWh)	EPC	The upfront cost of EPC.
Grid integration cost ($/kW)	$grid$	The upfront capital cost for grid interconnection.

Parameter	Variable Name	Description
Average cost of electricity ($/kWh)	E_{price}	The average cost of the electricity used to charge the device in 2030, which was assumed to be $0.025/kWh.
General inflation (year-over-year growth factor)	r_{infl}	The expected rate of inflation in the U.S. economy over the life of the project. The Federal Reserve target inflation rate of 2.0% was used.
Nominal discount rate (year-over-year discount factor)	r_{nom}	The nominal discount rate is used to account for the time value of money. This includes general inflation and is equivalent to the real discount rate + the inflation rate. A nominal discount rate of 7.6% was used in the Framework Study.
Replaceable parts cost rate (year-over-year growth/discount rate)	r_{reno}	The average inflation/discount rate expected for the replaceable parts over the next decade, which includes the effect of general inflation.

Renovation and Replacement Cost, Accounting for Residual Value

This calculation assumes that the land used is leased and that all components, except for those covered in the renovations, have negligible residual value at the end of the project's life. In reality, some other components, such as purchased land and interconnection agreements, may have residual value; however, this will be project- and region-specific. Ignoring the residual value of the components would put some technologies at an artificial disadvantage when compared with others. For example, if renovations were not accounted for, lithium-ion batteries would have all of the costs of the project amortized over 6 years, even though the power electronics, balance of plant, and other systems could be used for another 15 to 20 years. In reality, owners would augment or replace the storage block to extend the project life until maintaining and upgrading the plant cost more than building a new one. The life of the replaceable components is calculated using the minimum of the cycle and calendar lives, assuming that the device is cycled to its depth of discharge once per day (Equation 2):

$$life_{reno} = \min\left(life_{cal}, \frac{life_{cycles}}{dod*365}\right) \qquad (2)$$

where

$life_{reno}$ = the life of the replaceable parts in years;

$life_{cal}$ = the calendar life of the replaceable parts in years;

$life_{cycles}$ = the cycle life of the replaceable parts; and

dod = the depth of discharge.

The LCOS calculation accounts for a renovation and replacement plan that extends the project life. Note that Equation 2 only makes sense at the edge case, where replaceable parts life is equal to the project life in the context of Equation 3, where the unnecessary cost of replacing the parts is fully offset by the residual value:

$$reno_{PV} = \sum_{n=0}^{\lfloor life_{proj}/life_{reno} \rfloor} \frac{reno(1+r_{reno})^{n*life_{reno}}}{(1+r)^{n*life_{reno}}} - reno \qquad (3)$$

where

$reno_{PV}$ = the present value of the renovation and replacement costs for initial deployment and any necessary replacements;

$\lfloor\ \rfloor$ = the floor function, which rounds its contents down to the next integer;

$life_{proj}$ = the life of the project, which is 25 years;

$life_{reno}$ = the lifetime of the replaceable parts when cycling to the given depth of discharge once per day in years;

reno = the renovation, replacement, and augmentation cost;

r_{reno} = the replaceable parts cost rate; and

r = the real discount rate, which is the nominal discount rate minus inflation $(r_{nom} - r_{infl})$.

If the replaceable parts have residual value at the end of the project's life, this value is recouped by the project. The residual value is calculated using straight-line depreciation from the cost of the last replacement (Equation 4). This is discounted to the present value and combined with the present value of all renovation costs to determine the overall project net present cost of the renovation investments (Equation 5).

$$reno_{Residual} = reno\left[1 - \frac{(life_{proj}\ mod\ life_{reno})}{life_{reno}}\right](1 + r_{reno})^{\left\lfloor\frac{life_{proj}}{life_{reno}}\right\rfloor * life_{reno}} \tag{4}$$

where

$reno_{Residual}$ = the residual value of the replaceable parts at the end of the project life;

reno = the renovation, replacement, and augmentation cost;

$life_{proj}$ = the life of the project, which is 25 years for batteries;

$life_{reno}$ = the lifetime of the replaceable parts when cycling to the given depth of discharge once per day in years; and

r_{reno} = the replaceable parts cost rate.

$$reno_{NPV} = reno_{PV} - \frac{reno_{Residual}}{(1+r)^{life_{proj}}} \tag{5}$$

where

$reno_{NPV}$ = the net present value of the renovation costs, considering initial deployment, necessary replacements, and residual value at 25 years;

$reno_{PV}$ = the present value of the cost for renovations over the life of the project;

$reno_{Residual}$ = the residual value of the replacement parts at the end of the project life;

r = the real discount rate, which is the nominal discount rate minus inflation; and

$life_{proj}$ = the life of the project, which is 25 years.

Determining the Total Overnight Capital Cost per kWh

Using the input values, the program starts by combining all of the capital expenditure values into an overnight capital cost for the project, broken down by energy and power systems. The energy system considers storage block, balance of plant, system integration, project development, and engineering, procurement, and construction (EPC) costs. The power system considers controls and communications, power equipment, and grid integration costs.

Power system capital cost is converted from \$/kW rated power to \$/kWh delivered to the grid using the rated duration of the battery ($duration$) using the relationship $E_{cycle} = P_{disc} * duration$. In this relationship, the energy delivered to the grid with one full cycle is E_{cycle} and the rated power discharged to the grid is P_{disc}. Similarly, energy system capital cost is converted from $/kWh energy stored in the device to $/kWh put on the grid using the relationship $E_{cycle} = \frac{E_{stored}}{\eta_{disc}}$. In this relationship, E_{stored} is the rated energy capacity of the energy storage device and η_{disc} is the discharge efficiency. The two capital costs are summed to get the overnight capital cost per kWh provided to the grid. All of these steps are contained in Equation 6:

$$CC_{NPV} = \frac{SBC+reno_{NPV}+bop+sysint+prjdev+EPC}{\eta_{disch}} + \frac{ctrcom+pwr+grid}{duration} \qquad (6)$$

where

CC$_{NPV}$ = the formula for the net present value of capital investments in the system;

SBC = the storage block cost;

reno$_{NPV}$ = the net present value of renovations, replacements, and augmentation cost;

bop = the balance of plant cost;

sysint = the system integration cost;

prjdev = the project development cost;

EPC = the EPC cost;

η_{disch} = the discharge efficiency;

ctrcom = the controls and communications cost;

pwr = the power equipment cost;

grid = the grid integration cost; and

duration = the duration at the rated discharge power.

Determining the Present Value of O&M Costs in $/kWh

The cost of fixed O&M each year is converted to $/kWh using the rated duration of the plant. The cost of variable O&M per kWh of nominal storage each year is determined by first multiplying the variable O&M cost by the annual energy throughput to get the annual variable O&M cost. Then, the annual variable O&M cost is divided by nominal energy storage to get $/kWh of nominal storage. The fixed and variable O&M costs are then summed and discounted to the present value. The present value from each year of the project life is then summed to get the total present value of O&M cost. All of these steps are contained in Equation 7:

$$OM_{PV} = \sum_{n=0}^{life_{proj}-1} \frac{{}^{OM_{fix}}/_{duration} + cycles_n * OM_{var}}{(1+r)^n} \qquad (7)$$

where

OM$_{PV}$ = the formula for the present value of O&M cost per kWh of rated capacity;

life$_{proj}$ = the life of the project, which is 25 years;

OM$_{fix}$ = the fixed O&M cost for year *n*;

duration = the duration at the rated discharge power;

cycles$_n$ = the number of cycles in year *n*, which is calculated as $dod * 365(1 - dt)$, where dt is the down time;

OM$_{var}$ = the variable O&M cost per kWh discharged; and

r = the real discount rate, which is the nominal discount rate minus inflation.

Determining the Levelized Cost of Electricity Lost to Round-Trip Efficiency

The cost of charging the energy storage device should not be considered when calculating LCOS. Rather, this cost should be attributed to the levelized cost of energy for the generator that provides it. LCOS should only account for the cost of storing the energy and is a useful tool for comparing the cost of different storage technologies with one another. It is not a tool for comparing the cost of an energy storage system with a generator system. Lost electricity due to imperfect RTE is a cost of storage, however, and should be considered (Equation 8). The price of energy used in this calculation is \$0.025/kWh.

$$E_{loss} = \frac{E_{price}}{\eta_{rte}} - E_{price} \quad (8)$$

where

E_{loss} = the levelized cost of energy loss due to round-trip efficiency;

E_{price} = the average cost of electricity; and

η_{rte} = round-trip efficiency.

Putting It All Together

The final calculation of LCOS comes from ARPA-e's DAYS formula[b] and is mathematically equivalent to annualizing the costs in the case where the battery is operated in the same manner day after day, year after year. This formulation has the advantage of leaving flexibility for different modes of operation across the battery's lifetime. Equation 9 presents the formula for calculating the LCOS for each storage technology:

$$LCOS = (CC_{NPV} + OM_{PV})\left(\sum_{n=0}^{life_{proj}-1} \frac{cycles_n}{(1+r)^n}\right)^{-1} + E_{loss} \quad (9)$$

where

CC_{NPV} = the net present value of the capital expenditures, including deployment, renovation and replacement, and residual cost;

OM_{PV} = the present value of O&M costs for the project;

$life_{proj}$ = the life of the project, which is 25 years;

$cycles_n$ = the number of cycles in year n, which is calculated as $dod * 365(1 - dt)$, where dt is the down time;

r = the real discount rate, which is the nominal discount rate minus inflation; and

E_{loss} = the levelized cost of energy loss due to round-trip efficiency.

Step 6: Evaluate Portfolios of Interventions

The objective of this step is to determine which interventions, or sets thereof, are most critical for achieving high-impact scenarios. The Monte Carlo simulation tool plots the frequency distribution of LCOS outcomes (Figure 2(a)) and the innovations that appear most frequently in the top 10% in terms of low LCOS outcomes (Figure 2(b)). The results of the analysis for lead batteries are

[b] https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS_ProgramOverview_FINAL.pdf

presented in Figures 2(a) and 2(b). In Figure 2(a), the marked region identifies the top 10% of portfolios. In Figure 2(b), the percentage representation identifies the percentage of portfolios in the top 10% of all portfolios which include that innovation. Thus, Figure 2(b) demonstrates that the Re-Design of Standard Current Collectors was included in more than 90% of the portfolios falling in the top 10% in terms of LCOS reduction.

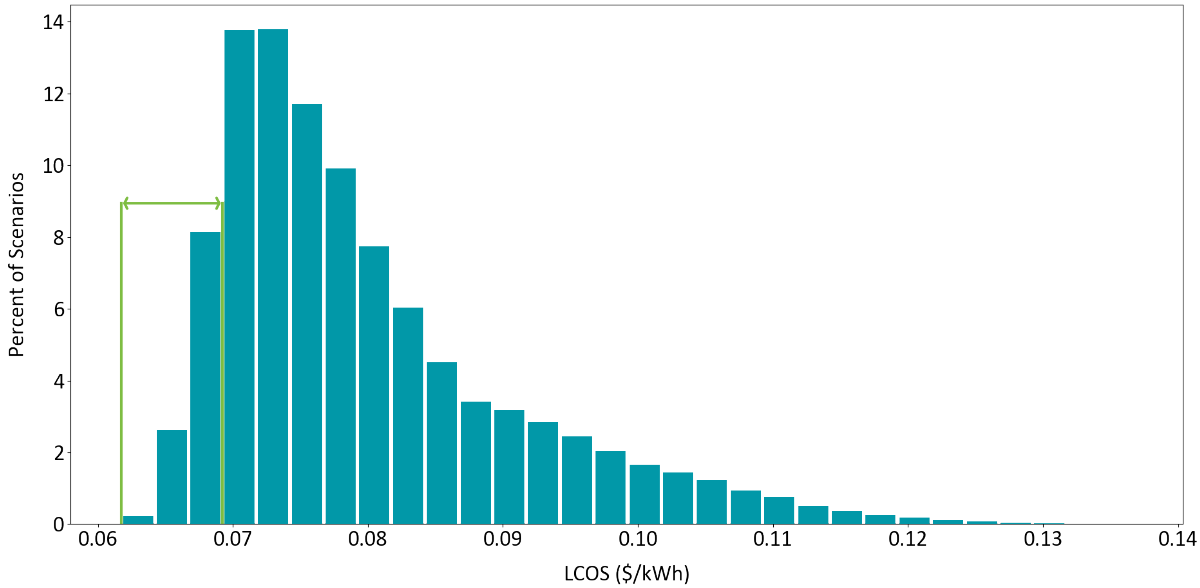

Figure 2(a). Portfolio frequency distribution measured by LCOS

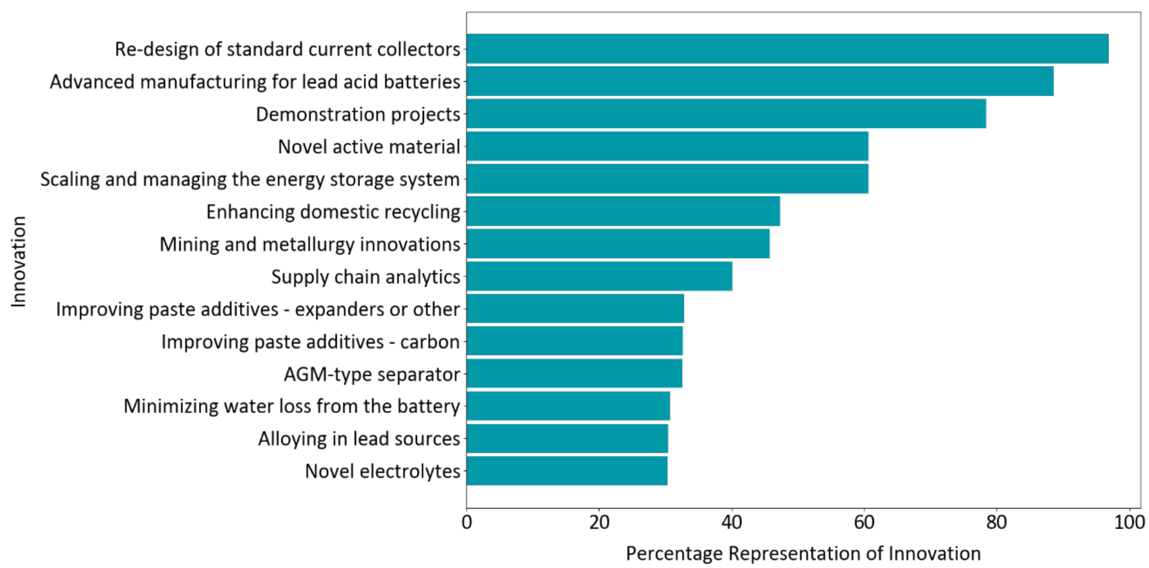

Figure 2(b). Frequency of innovations appearing in top 10% of portfolios achieving low LCOS

Step 7: Conduct Suitability Evaluations

Step 7 is designed to assess the suitability with respect to each of the technologies for the use cases defined in the ESGC Roadmap. The Framework Team used multiple-criteria decision analysis (MCDA) to calculate a performance index for each technology. MCDA provides a flexible method for analyzing complex multiple objectives and priorities that are hard to quantify in monetary terms with a structured decision-making process.

This MCDA analysis included four steps: (1) define the objectives and attributes, (2) determine the impacts, (3) quantify the preferences, and (4) model/evaluate each technology. SMEs completed a form that allowed them to weight the relative importance of several goals assigned in the ESGC Roadmap to each use case. The SMEs then rated the suitability of the specific technology under examination with respect to achieving each of the relevant goals today and as predicted for 2030 under current R&D investment trends. An MCDA tool was developed by the Framework Team that used the data received from the SMEs to establish an MCDA suitability performance index for each technology as applied to each of the ESGC Roadmap use cases.

Step 8: Report on Metrics

The final step in the Framework is to report on the metrics for each innovation, including minimum, maximum, mean, standard deviation, and the suitability performance index. Portfolios also were defined by the Monte Carlo simulation model and evaluated based on their ability to drive down the LCOS metric.

Calibration

The final step in the Flight Paths and the Framework was a calibration effort to ensure some measure of consistency in the findings and develop explanations for any marked inconsistencies. This occurred through meetings of the National Laboratory team on the findings after the listening sessions, utilizing outputs from each effort and discussions around these findings. These calibrations provided the integration of the qualitative outputs from the Flight Paths with the more quantitative results from the Framework to identify promising precompetitive research pathways and develop the SI strategy.

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