Technology Strategy Assessment

Findings from Storage Innovations 2030
Lithium-ion Batteries
July 2023

About Storage Innovations 2030

This report on accelerating the future of lithium-ion batteries is released as part 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

The findings in this report primarily come from two pillars of SI 2030: the SI Framework and the SI Flight Paths. For more information about the methodologies of each pillar, please reference the SI 2030 Methodology Report, released alongside the ten technology reports.

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

Acknowledgments

DOE acknowledges all stakeholders who contributed to the SI 2030 industry input process. Additional information about the stakeholders who participated in the SI Framework and SI Flight Paths activities can be found in Appendix A. The authors would like to acknowledge Patrick Balducci for contributions to the SI Framework. They also would like to acknowledge Ben Shrager for his guidance on both the Flight Paths and Framework activities.

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Background

Lithium-ion batteries (LIBs) are a critical part of daily life. Since their first commercialization in the early 1990s, the use of LIBs has spread from consumer electronics to electric vehicle and stationary energy storage applications. As energy-dense batteries, LIBs have driven much of the shift in electrification over the past two decades. The transition from small-form factor cells and use in electronics to large-scale grid deployment has been enabled by the ability to mass produce cells and make closed-case batteries in several sizes and shapes conducive to arrangement in different high-energy configurations. Grid deployment also has benefited from mass production of large LIB cells for electric vehicles.

Chemistries and Components

Lithium-ion batteries are a class of electrochemical batteries encompassing different chemistry variants that all operate using a similar process. They rely on a “rocking chair” design where Li+ ions are transferred from the cathode to the anode during charging and then back to the cathode during discharging. For most applications, the predominant anode material is graphite or some form of carbon, although lithium titanate (LTO) is used in some higher power or high cycle life scenarios. There are multiple classes of cathode materials, including lithium iron phosphate (LFP), lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), lithium manganese oxide (LMO), and lithium nickel cobalt aluminum oxide (NCA). The electrode active materials listed above are cast on current collectors, which are typically copper (anode) and aluminum (cathode), although LTO anodes also use an aluminum current collector. Each of the classes of cathode materials have different design-specific energies (in Wh/kg) and an expected cycle life for cell-level, standardized conditions as shown in Figure 1.

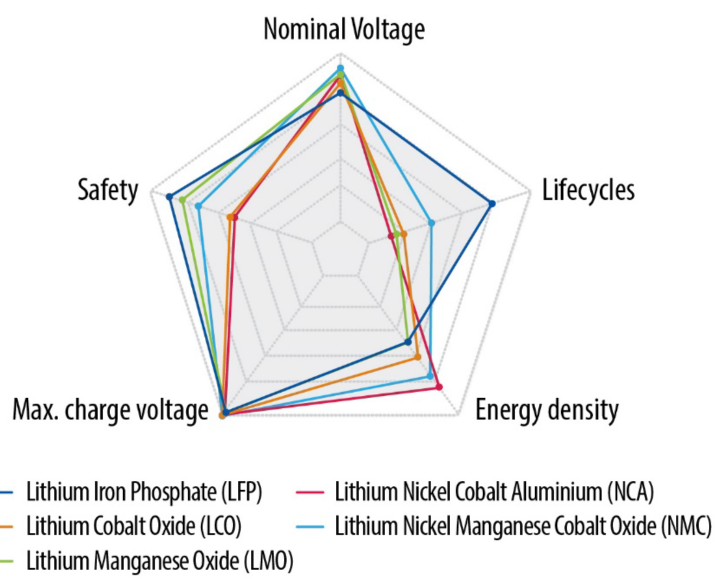

Figure 1. Comparison of different performance metrics for an assortment of LIB cathode chemistries. Adapted from S. Windisch-Kern et al. [1].

In addition to the active materials at the electrodes, LIBs also contain an electrolyte that consists of organic liquid or polymer compounds and a Li-containing salt. The electrolyte enables ion transport during battery operation. Cells also contain a separator that keeps the anode and cathode from touching or shorting. Separators often are microporous and either polymeric, ceramic, or a mixture of both.

Lithium-ion Deployment and Design

LIBs have broad adoption in different areas. For grid and stationary applications, LIBs have been deployed in systems up to hundreds of megawatt-hours to provide support for both small and large applications. Based on their design and configuration, power and energy for LIBs can be thought of as coupled—as capacity or energy increases, so does power capability. This coupling and the ability to design in a range of sizes allow LIBs to be used across multiple types of grid services, including those that rely on higher power, such as frequency regulation, as well as load shifting, which is more demanding on energy needs. While LIBs can be discharged across a range of rates, they are typically used for durations of 10 hours or less. The design of the battery also needs to be specifically targeted toward different applications or use cases. Depending on the nature of the cycling, LIBs often have a life or warrantied life of 10+ years and 1,000+ cycles. Additionally, the application in which the battery is used and how it is controlled can dramatically impact the life of the system.

Due to the flexibility of use across different areas, LIBs have been deployed to support residential needs ranging from single buildings to broad grid-scale installations. While a range of sizes are used, by capacity, most installed LIBs serve grid-scale needs. It is expected that significant growth will continue for installations of LIBs serving use cases of up to 10 hours over the next several years, with the possibility of more than doubling the 2021 investment by the end of 2023 [2], [3]. As of 2022, deployments of batteries for grid-support applications totaled more than 8.5 GW. In 2022 alone, more than 4 GW of batteries were deployed. Of the battery storage technologies, LIBs represent the largest portion of new grid deployments at greater than 90% for 2020 and 2021 [2], [3].

Installations for LIBs rely on large configurations of cells that are arranged in an assortment of parallel and series configurations to make modules and packs or racks. The design of both the modules and packs is dictated by the specific application of interest, specific voltage requirements, and volume and space constraints. Beyond the cells used in the batteries, deployed LIBs for grid applications have multiple other components, which are critical for full functionality. These include a battery management system that controls and monitors the state of the battery, a thermal management system, and often fire suppression systems. Each of these systems is designed to either extend the life of the battery or to reduce the possible impact should the battery fail [4].

Supply Chain Considerations

As with any technology, supply chain concerns exist for different components of LIBs. Of the elements that can be present in the batteries, the most critical are cobalt, nickel, and lithium. Cobalt and nickel are key cathode components that help increase the energy of cells. Currently, the majority of all three elements are obtained from non-domestic sources. Achieving the widespread deployment of grid-scale LIBs and high levels of electric vehicle adoption will require identifying enough of these materials, as well as iron, which can be domestically sourced for the production of LFP cathode active materials, or in the development of additional cathode chemistries using other earth-abundant materials. The demand for cobalt is expected to remain stable because the demand for low-cobalt cathode active materials has increased, both due to concerns with the geopolitical risks for cobalt sourcing and also due to the performance of NMC cathode active materials, which reduce cobalt by increasing the amount of nickel [5]. Additionally, the increased use of LFP provides other opportunities to enhance the stability of cobalt supply chains.

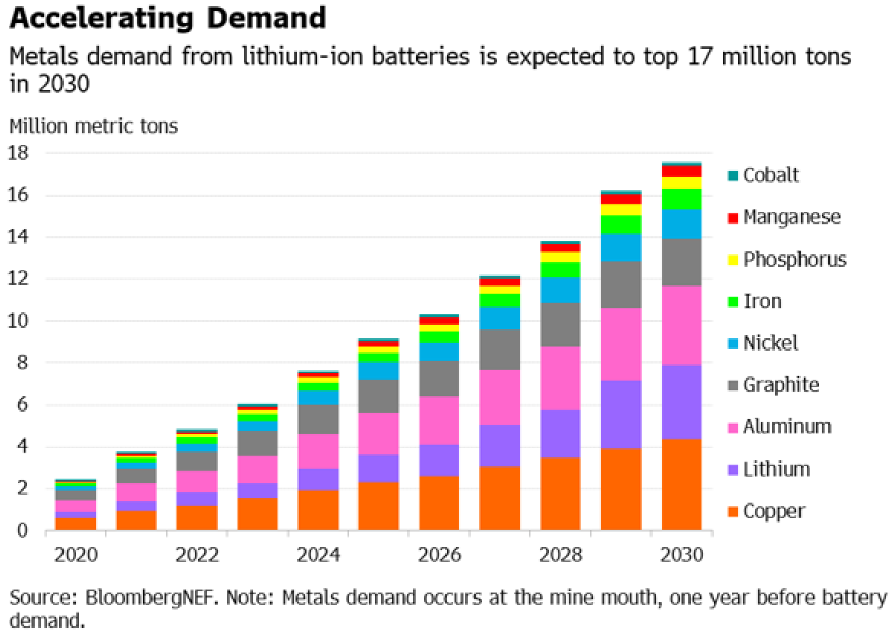

Figure 2. Metals demand based on all chemistries projected up to 2030

Source: Bloomberg Professional Services, Race to Net Zero.

Baseline Cost

The two major chemistries that dominate the LIB industry today are NMC and LFP for their superior energy density and safety characteristics, respectively, which are primary driven by the mobility sector. According to industrial projections, LFP is forecasted to be the major chemistry by 2030 [6]. As a material with no Co or Ni content, LFP is often viewed as having fewer supply chain restrictions than NMC [5], [7] Thus, analyses considered the baseline cost estimates of LFP from the 2030 projection for 100 MW with 10 hours of storage from the Energy Storage Technology Cost and Performance Assessment report from the Pacific Northwest National Laboratory (PNNL), as described in Table 1 [8]. The baseline levelized cost of storage (LCOS) for LFP at 100 MW and 10 hours of duration was estimated as $0.143/kWh per cycle based on the formulation described in the Storage Innovations 2030 Methodology Report. A detailed description of all cost parameters for LIBs is provided in the PNNL cost and performance assessment report [8].

Table 1. LFP battery cost and performance estimates for 100 MW and 10 hours of storage (2030 estimates)

Parameter	Value	Description
Storage block calendar life	16	Deployment life (years)
Cycle life	2,640	Baseline total number of cycles
Round-trip efficiency (RTE)	85%	Baseline RTE
Storage block costs	106.22	Baseline storage block costs ($/kWh)
Balance of plant costs	27.16	Baseline balance of plant costs ($/kWh)
Controls and communication costs	5.78	Controls and communication costs ($/kW)
Power equipment costs	64.62	Power equipment costs ($/kW)
System integration costs	33.02	System integration costs ($/kWh)
Project development costs	47.62	Project development costs ($/kWh)
Engineering, procurement, and construction (EPC) costs	39.69	EPC costs ($/kWh)
Grid integration costs	21.05	Grid integration costs ($/kWh)

Fixed operations and maintenance (O&M) costs	10.38	Baseline fixed O&M costs ($/kW-year)
Variable O&M costs	0.0005125	Baseline variable O&M costs ($/kWh)
LCOS	0.1432	Baseline estimate of LCOS ($/kWh-cycle)

Pathways to $0.05/kWh

The framework used here to describe the cost and technology pathways for LIBs is a systematic methodology for capturing and synthesizing an industry's sentiments about its technology's future. While many of these results involve quantitative estimates of parameters and LCOS, it is important to remember that they represent subjective perspectives from the industry. Twenty subject matter experts (SMEs) were identified and contacted. These SMEs represent universities, national laboratories, major energy analytical firms, startups, and large industry manufacturers (the names and affiliations of the SMEs are provided in Appendix A). The Framework Team conducted one-on-one interviews, soliciting information regarding pathways to innovation and the associated cost reductions and performance improvements. The innovations defined by the SMEs are presented in Table 2; the innovations in italics were identified by SMEs but were not a part of the framework analysis due to lack of supporting data. Definitions of each innovation are presented in Appendix B. Based on these innovation areas, the SMEs were then asked for additional details, such as budget, timeline, and impact on the storage parameters mentioned in Table 1.

Table 2. List of innovations identified for LIB storage based on input from SMEs

Innovation Category	Innovation
Raw materials sourcing	*Cathode materials mining*[a]
	Domestic sourcing of lithium
Supply chain	Anode materials production
	Mining permitting[a]
	Co-locating manufacturing and mines
Technology components	Sensor and monitoring technologies
Advanced materials development	Solid-state electrolyte improvements
	Anode innovations
	Electrode and electrolyte innovations
	Atomic-level cell dynamics studies[a]
	Fundamental materials research[a]
Manufacturing	Foundational manufacturing RD&D
	Manufacturing process scale-up
	Data-driven manufacturing improvements
	Manufacturing workforce development[a]
Deployment	Controls to improve cycle life
	Deployment policies[a]
	Demonstration
	Deployment efficiency
End of life	Recycling defective cells
	Recycling degraded cells
	Impurities reduction technique
	Rapid battery health assessment

The point estimates of parameters for each innovation (capital required, time to achieve, and improvements to parameters in Table 1) provided by the different SMEs were used to create probability density functions that drove the outcomes of a Monte Carlo simulation. The impact on LCOS was then evaluated based on combining multiple innovations into a portfolio and calculating

[a] *These innovations were identified during the initial interviews with SMEs but did not receive feedback for impact, budget, and timeline from the follow-up. Hence, these innovations were not included in the Monte Carlo simulation and analysis.*

the collective impact within a given portfolio. Each portfolio is formed by using all possible combinations of two to eight innovations as described in the SI 2030 Methodology report. The LCOS impact of each portfolio was applied to the 2030 estimates of the LFP storage baseline parameters shown in Table 1.

The range of LCOS for the top 10% of portfolios (i.e., producing the lowest LCOS) is $0.067 per kWh-cycle to 0.073 per kWh-cycle, which is a 49% to 53% reduction relative to the baseline 2030 projections (Figure 3). These portfolio LCOS values are constructed using the means of the distribution of the Monte Carlo simulation results for the given portfolio. Therefore, if the realized innovation impacts are greater than the mean of the output, the LCOS reductions could be even greater than shown here. More than 80% of the portfolios achieve at least a 37% reduction in LCOS, which corresponds to a final LCOS of $0.09 per kWh-cycle.

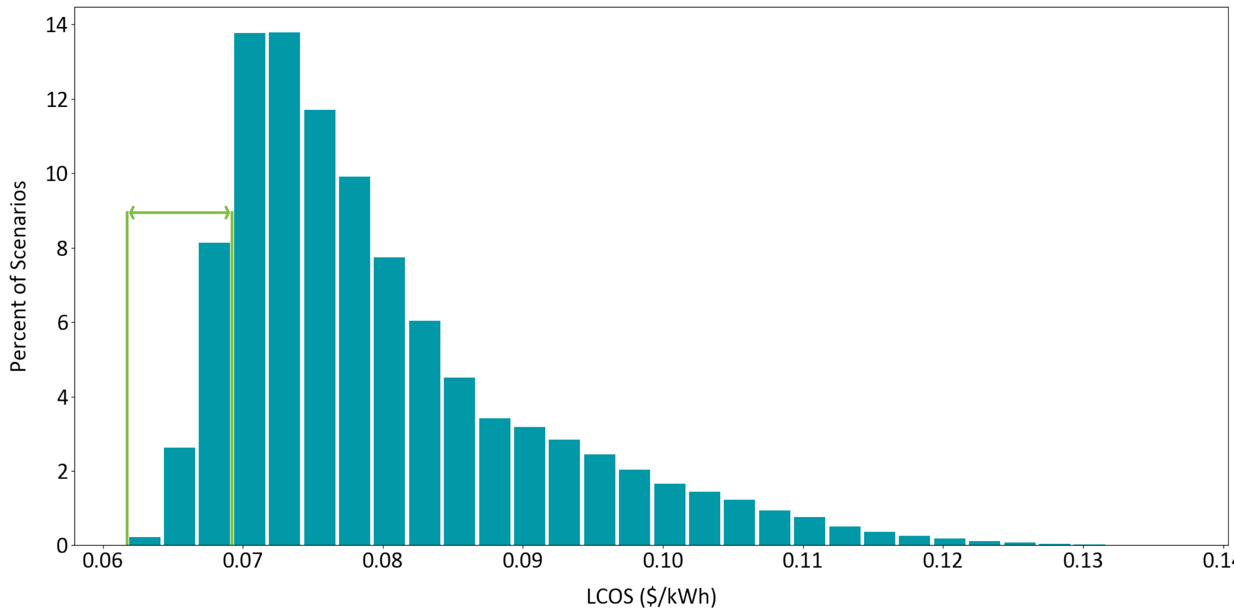

Figure 3. Distribution of mean LCOS for each portfolio based on the impact of the portfolio's innovations. The marked region shows the top 10% of portfolios that achieve the greatest LCOS reductions.

The rest of the analysis focuses on the top 10% of portfolios to better understand how investment impact can be maximized. These results are presented in Figure 4. The dollar values across the x-axis represent the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements. The vertical line demonstrates that the mean portfolio's cost is $1,063 million. Total expenditure levels with the highest portfolio densities in the top 10% roughly follow a normal distribution, which means that there are some high-impact portfolios that cost significantly less than the mean. While some innovations are more impactful than others, the wide shape of the normal distribution in the results indicates that there are no individual innovations that dominate the LCOS impact or expenditure of the portfolio. The timeline required to achieve these LCOS levels is estimated at 8 to 13 years. This extended timeline is largely driven by advanced materials research, which requires a significant amount of testing and validation.

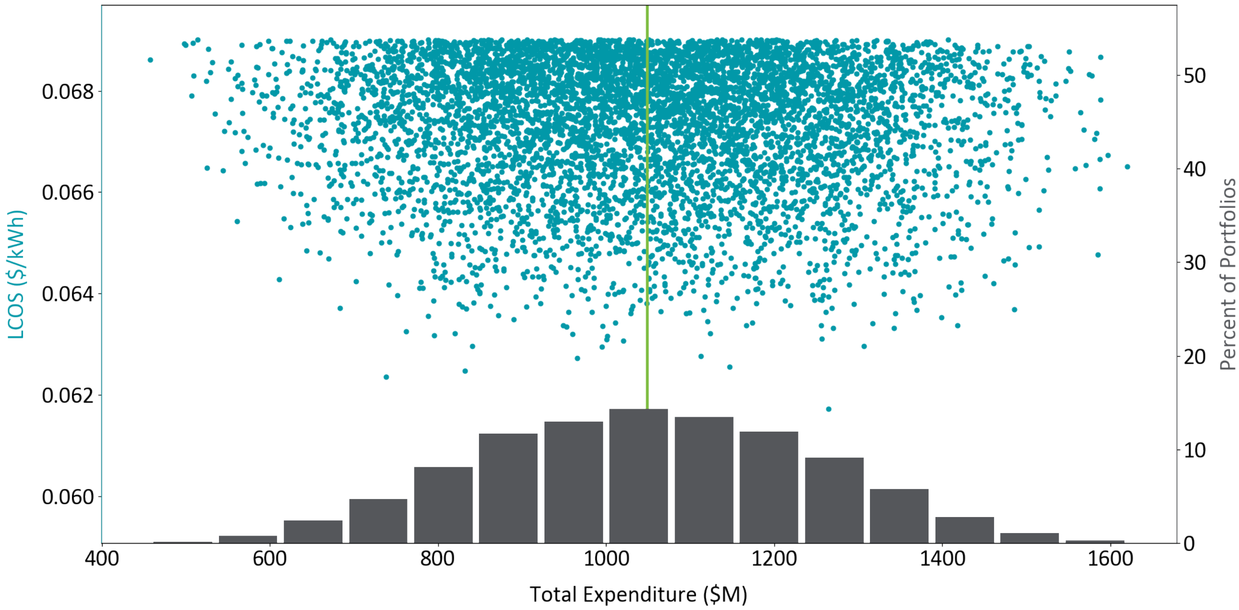

Figure 4. LCOS and expenditures for the top 10% of portfolios for LIBs. The axis on the left labels the scatterplot of expected LCOS for each portfolio versus total expenditure, while the axis on the right labels the histogram of expenditures. This means that the histogram shows the distribution of the dots on the scatterplot. The vertical line marks the median expenditure.

Rapid health assessment was recognized as the most common innovation among all top-performing portfolios (Figure 5). It is important to note the significance and impact of end-of-life studies for LIBs because two of the most common innovations among the top-performing portfolios come from End of Life (italicized). The innovations under Manufacturing (bolded) have high representation among all top-performing portfolios and Manufacturing is the most common innovation category among the top-performing portfolios. Anode innovations is one area that would have a high degree of impact as a stand-alone change; however, it falls lower in the rating when considering lower combination coefficients when paired with other advances. A detailed description of the combination coefficients is presented in Appendix C of this report.

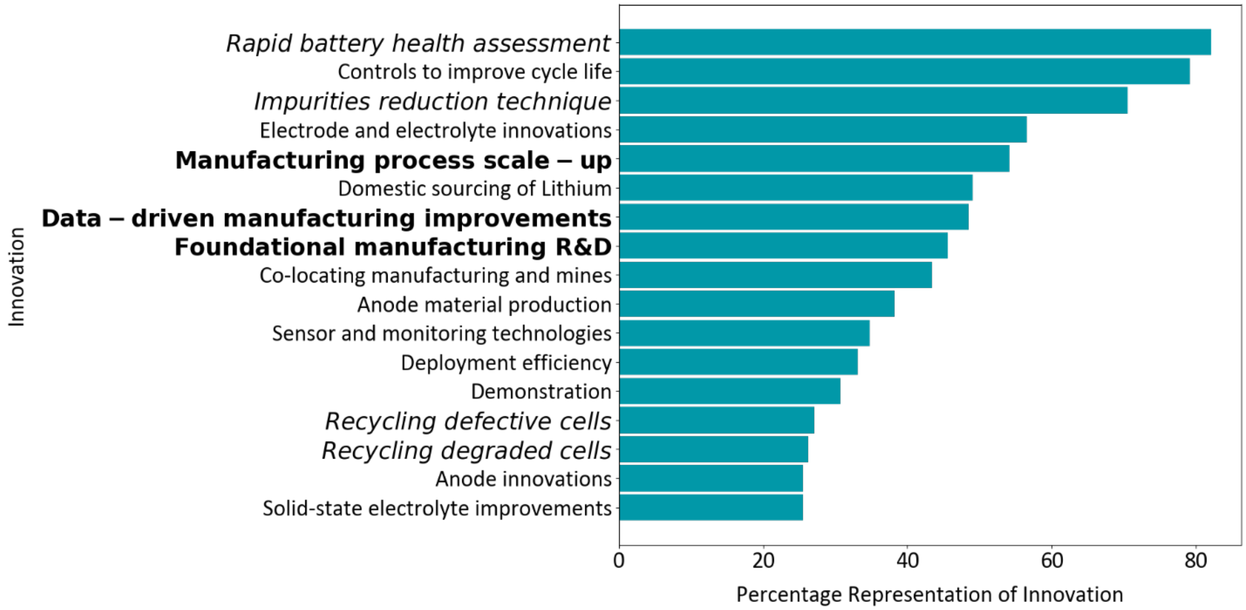

Figure 5. The percentage of portfolios in the top 10% (resulting in the least LCOS) that include each innovation. End-of-life innovations are italicized and manufacturing innovations are bolded.

The SMEs also provided their insights on how these innovations should be funded (Table 3). The responses designated by asterisks (*) are the most preferred for the innovation. The SMEs believe that most of the innovations are best achieved through National Laboratory Research and RD&D grants. Innovations under End of life show p from all channels, which makes sense given that these are some of the most important and pressing innovations (Figure 5). SMEs had different ps for investment mechanisms with manufacturing-focused innovations; however, one underlying trend is that financial assistance for domestic companies was perceived as a way to incentivize onshoring.

Table 3. SMEs' ps for investment mechanisms. (Technical Assistance includes advice or guidance on issues or goals, tools and maps, and training provided by government agencies or national labs to support industry.)

Innovation	National Laboratory Research	RD&D Grants	Loans	Technical Assistance
Domestic sourcing of lithium	15%	23%	31% *	31% *
Anode materials production	25% *	25% *	25% *	25% *
Co-locating manufacturing and mines	50% *	25%	0%	25%
Sensor and monitoring technologies	42%	50% *	0%	8%
Solid-state electrolyte improvements	40% *	30%	10%	20%
Anode innovations	25% *	25% *	25% *	25% *
Electrode and electrolyte innovations	44% *	33%	0%	22%
Foundational manufacturing RD&D	21%	29% *	21%	29% *
Manufacturing process scale-up	0%	20%	40% *	40% *
Data-driven manufacturing improvements	40% *	30%	20%	10%
Controls to improve cycle life	36%	46% *	0%	18%
Demonstration	40% *	40% *	10%	10%
Deployment efficiency	29% *	29% *	14%	29% *
Recycling defective cells	25%	33% *	17%	25%
Recycling degraded cells	25% *	25% *	25% *	25% *
Impurities reduction technique	27% *	27% *	18%	27% *
Rapid battery health assessment	35% *	35% *	6%	24%

Pre-Competitive RD&D Opportunities

The development of LIBs for long-duration energy storage (LDES) benefits significantly from parallel efforts in the commercialization of LIBs for transportation and shorter duration grid storage. The alignment is especially beneficial in areas related to manufacturing; however, the transportation and short-duration markets have yet to drive domestic manufacturing. That said, there still exists unique areas specific to the RD&D for LDES that will benefit LIBs moving forward. As shown above, many of the opportunities for RD&D advancement suggest the ability to attain an LCOS below \$0.10/kWh; however, achieving the target of \$0.05/kWh appears difficult based on current analysis. Key RD&D topics can be roughly grouped into activities associated with advanced controls, advanced materials development and production, and advanced processes for manufacturing. Many of these areas were directly called out in both the Flight Paths and Framework discussions for LIBs. With respect to impact, the most direct and immediate advances, as identified during the different sessions and discussions, align with advanced control and analysis methods for life extension. These also are the most direct to apply without significantly impacting or changing how current manufacturing is performed.

Advanced Controls and the Use of Data to Extend Life

Controls and the use of data constituted some of the highest or most impactful innovations identified for LDES LIBs. As noted in Table 3, investment in these areas through a grant process or through funding at the National Laboratories is preferred by SMEs. The pre-competitive aspect of control development needs to be targeted toward advances for early prediction and alignment with aging physics. However, the advances generated are likely to be readily integrated in a proprietary, product-specific manner into advanced demonstrations with more ease than some other routes. In part, this is because these advances, while requiring physical hardware, are likely to align more with software development, implementation, and deployment, making them some of the more direct methods to integrate with existing and near-term deployments of LIBs. These tools for rapid battery health assessment and controls to improve cycle life account for two of the top three innovations in Figure 5, which were identified during the Framework interview sessions and also were brought up during the Flight Paths listening session.

How LIBs are used and maintained can directly impact the life of the system. Optimizing controls for life extension and resiliency will require continued and new RD&D associated with rapid and direct failure mode classification and quantification and the ability to directly align failure with system design. Such advances offer the possibility of directly tailoring the use of a system to co-optimize life and economic benefits while ensuring that systems can still provide resiliency. Failure mode analysis also provides an opportunity to better predict the real-time state of health and state of safety of LIB systems.

While the developments associated with advanced controls tend to be software based, there is significant underlying RD&D that needs to occur across multiple-length scales—from a core understanding of material degradation to how system design and management impact spatial distributions of aging in systems. These are some of the key activities that are aligned with the U.S. Department of Energy (DOE) grant and National Laboratory funding mechanisms. With the physically generated or collected data, this area of research will be able to leverage many recent advances in digital architecture, including digital twins, artificial intelligence, and machine learning, and expand the impact for LIB LDES.

Advanced Materials Development and Production

LDES will require a combination of both long cycle life and extended calendar life. Depending on the use case, there will be a need for systems to be maintained at a sufficiently high state of charge (SOC) to provide needed energy on-demand for resiliency purposes. For current LIB systems, maintaining a high SOC for extended periods of time is one of the most significant drivers for capacity fade in calendar life applications. To mitigate this fade, advances for both the positive and negative electrodes of the cell can improve high SOC issues. On the negative electrode side, advances will be needed to decrease reactivity and control solid electrolyte interphase growth during cycling. Possible candidates include different oxide materials, such as lithium titanate (LTO); however, in its current form, LTO and similar systems would still need advances in production to meet the cost targets.

Positive electrode materials with lower reactivity, including those with low Ni and Co, also are needed. This is mainly due to supply chain considerations, as noted in the National Blueprint for Lithium Batteries released by the Federal Consortium for Advanced Batteries [9]. Supply chain impacts and competition with the use of LIBs for the transportation sector are likely to push added emphasis to other materials, including LFP for LIB LDES. The shift to LFP, other olivine materials, or materials such as lithium manganese oxide also may help mitigate some of the calendar aging concerns. The identification of new materials with low production costs and high stability is still needed.

Parallel with the development of active materials, which have increased stability, there is a need to continue to advance electrolytes for LDES. Electrolyte development responses were split into two areas by the SMEs—the first being solid-state electrolytes, which were viewed as high impact, while other broader electrolyte advances were identified as moderate impact advancement. In both cases, the advanced electrolytes are needed to achieve very high cycle life in excess of 10,000 cycles and a calendar life of 20+ years. To achieve such a long life, it is necessary for electrolytes to have both low chemical and electrochemical degradation rates. Electrolyte systems that significantly reduce costs, including possible advances in aqueous electrolytes or systems with easy-to-produce salts and solvents, will benefit cost reduction for LDES.

Advanced Manufacturing

Unlike the previous two sets of innovations, most manufacturing advances for LIBs would benefit from funding through the Notice of Opportunity for Technical Assistance (NOTA) or possibly through future debt/financing programs. For both NOTA and the loan programs, an appropriate explanation of purpose and intent is still needed. Most LIB manufacturing processes are well established globally. There are key gaps in the domestic production of battery materials, components, and cells. Some of these gaps are starting to be addressed through recent battery manufacturing awards from DOE. The foundational RD&D needed to advance the manufacturing of LIBs includes recycling processes, efforts to reduce impurities in sources for active materials development, and methods to advance electrode manufacturing and design. Methods to scale innovations more directly also are identified as opportunities to impact the cost of production.

Additional Opportunities and Discussion

While not directly linked to the ability to achieve cost targets based on dollars per kilowatt-hour, a concern for LIB LDES is overall system safety. Improving safety is seen as a key need to impact non-performance system and deployment cost and risk. RD&D associated with improving safety was highlighted in multiple venues as a key innovation worthy of focus. Each of the different RD&D innovations in the previous section has parallel tracks that can be linked to improving safety. For materials, the advancement of lower flammability electrolytes and stable cathode materials are key opportunities. Similar controls that can readily identify the state of safety and also capture data from multiple streams to make real-time assessment and mitigation should unexpected conditions be detected will help advance LIB deployment for LDES. In the manufacturing realm, the design and development of system architectures that minimize or fully prevent propagation of failure between cells are needed. These new architectures also need to ensure that the impact on cost or energy density does not become prohibitive.

As with other LDES technologies, LIBs for LDES would benefit from efforts to address the soft costs of deployment, including permitting, siting, and construction costs. It was noted that costs can vary based on where the deployment resides; however, unlike the current trajectory of LIBs, the other costs are not seeing significant decreases. It was suggested that policy and efforts to aid in streamlining permitting and siting discussions be implemented.

Similarly, supply chains for materials are critical for broad adoption of LIBs for LDES applications. Even if steps are taken to mitigate or minimize the use of Ni and Co for the positive electrodes in LDES applications, there will remain a key need for Li. This is a key point that was raised in both the Flight Paths and Framework discussions. Finding and maintaining domestic sources of Li and other critical battery materials will be needed for any of the RD&D advances to be successful.

Appendix A: Industry Contributors

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

Participant	Institution
August N. Steinbeck	EnerSmart Storage Holdings LLC
Bong Chill Kim (Paul)	EoCell, Inc.
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Oliver Gross	Stellantis
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Prof. Michael Pecht	University of Maryland
Scott Trimboli	University of Colorado, Colorado Springs
Stephan Fernandes	Customized Energy Solutions
Tanvir R. Tanim	Idaho National Laboratory
Venkat Srinivasan	Argonne National Laboratory

Appendix B: Innovation Matrix and Definitions

Table B.1. List of innovations by innovation category. Some innovations apply to cavern storage and tank storage; however, some only apply to tank storage.

Innovation Category	Innovation
Raw materials sourcing	Cathode material mining
	Domestic sourcing of lithium
Supply chain	Anode materials production
	Mining permitting
	Co-locating manufacturing and mines
Technology components	Sensor and monitoring technologies
Advanced materials development	Solid-state electrolyte improvements
	Anode innovations
	Electrode and electrolyte innovations
	Atomic-level cell dynamics studies
	Fundamental materials research
Manufacturing	Foundational manufacturing RD&D
	Manufacturing process scale-up
	Data-driven manufacturing improvements
	Manufacturing workforce development
Deployment	Controls to improve cycle life
	Deployment policies
	Demonstration
	Deployment efficiency
End of life	Recycling defective cells
	Recycling degraded cells
	Impurities reduction technique
	Rapid battery health assessment

Cathode materials mining: Diversify cathode materials (e.g., Co, Ni, Ti, Fe) mining operations to increase price stability.

Domestic sourcing of lithium: Increase the domestic mining and processing of lithium.

Anode materials production: Reliable production of anode materials, such as graphite and silicon.

Mining permitting: Identify and conduct studies on potential mine sites to reduce the time needed and the cost to develop them.

Co-locating manufacturing and mines: Policies and permissions to strategically locate manufacturing near mines or ports of import.

Sensor and monitoring technologies: Sensors to gather more data beyond voltage, current, and temperature to improve the understanding of battery health and aid in certification for second-life applications.

Solid-state electrolyte improvements: Improve solid-state electrolyte chemistries for higher power densities that can achieve economies of scale and are safe.

Anode innovations: Si and Li anodes, aimed at increased energy density and reduced cost.

Electrode and electrolyte innovations: Batteries with extremely long cycle and calendar life (> 25 years of life) used especially in the grid and industrial applications.

Atomic-level cell dynamics studies: Improve the understanding of the dynamic process of ions moving through the electrolyte and how this transfer degrades electrodes.

Fundamental materials research: Create battery chemistries that use only abundant materials (e.g., sodium-based batteries) or dramatically improve safety.

Foundational manufacturing RD&D: Invest in innovative manufacturing processes and machines to manufacture new chemistries and increase automation.

Manufacturing process scale-up: Facilitate the scale-up of promising manufacturing technologies and techniques that have been proven on the laboratory scale.

Data-driven manufacturing improvements: Develop data-driven approaches to help companies reduce the learning curve (i.e., increase productivity and yield more quickly).

Manufacturing workforce development: Create formal training that prepares workers for jobs across the battery manufacturing industry.

Controls to improve cycle life: Improve the understanding of battery degradation and use this to develop controls that improve cycle life.

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

Demonstration: Accelerate the commercialization of new battery technologies through demonstration.

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

Recycling defective cells: Improve the identification and recycling of cells that do not meet quality control standards during manufacturing.

Recycling degraded cells: Develop processes that will enable cost-effective recovery of precious and non-precious materials from batteries.

Impurities reduction technique: Research and development for advancement in the separation of metals and refinement of impurities.

Rapid battery health assessment: Improve the understanding of the degradation and development of rapid assessment techniques to determine the remaining battery life and performance (e.g., determine the suitability for second use).

Appendix C: Innovation Coefficients

Table C.1. Innovation coefficients

Innovation	Domestic sourcing of lithium	Anode materials production	Co-locating manufacturing and mines	Sensor and monitoring technologies	Solid-state electrolyte improvements	Anode innovations	Electrode and electrolyte innovations	Foundational manufacturing RD&D	Manufacturing process scale-up	Data-driven manufacturing improvements	Controls to improve cycle life	Demonstration	Deployment efficiency	Recycling defective cells	Recycling degraded cells	Impurities reduction technique	Rapid battery health assessment
Domestic sourcing of lithium	–	1	0.75	1	1	1	1	1	1	1	1	1	1	0.75	0.5	0.5	1
Anode materials production	1	–	1	1	0.75	0.25	0.75	0.75	0.75	0.75	1	1	1	0.75	1	1	1
Co-locating manufacturing and mines	0.75	1	–	1	1	1	1	0.75	0.75	1	1	1	1	1	1	1	1
Sensor and monitoring technologies	1	1	1	–	1	1	0.5	1	1	1	0.5	1	1	1	1	1	0.25
Solid-state electrolyte improvements	1	0.75	1	1	–	0.7	1	1	1	1	0.25	0.75	0.75	1	1	1	0.75
Anode innovations	1	0.25	1	1	0.7	–	0.9	1	1	1	0.5	1	1	1	1	1	0.25
Electrode and electrolyte innovations	1	0.75	1	0.5	1	0.9	–	1	1	1	0.5	1	1	0.75	0.5	1	0.5
Foundational manufacturing RD&D	1	0.75	0.75	1	1	1	1	–	0.25	0.75	1	1	1	0.5	0.75	1	1
Manufacturing process scale-up	1	0.75	0.75	1	1	1	1	0.25	–	1	1	1	1	1	1	1	1
Data-driven manufacturing improvements	1	0.75	1	1	1	1	1	0.75	1	–	1	1	1	1	1	1	1
Controls to improve cycle life	1	1	1	0.5	0.25	0.5	0.5	1	1	1	–	1	1	1	1	1	0.25
Demonstration	1	1	1	1	0.75	1	1	1	1	1	1	–	0.5	1	1	1	1
Deployment efficiency	1	1	1	1	0.75	1	1	1	1	1	1	0.5	–	1	1	1	1
Recycling defective cells	0.75	0.75	1	1	1	1	0.75	0.5	1	1	1	1	1	–	0.5	0.75	1
Recycling degraded cells	0.5	1	1	1	1	1	0.5	0.75	1	1	1	1	1	0.5	–	0.75	1
Impurities reduction technique	0.5	1	1	1	1	1	1	1	1	1	1	1	1	0.75	0.75	–	1
Rapid battery health assessment	1	1	1	0.25	0.75	0.25	0.5	1	1	1	0.25	1	1	1	1	1	–

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