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Technology Strategy Assessment

Findings from Storage Innovations 2030
Flow Batteries
July 2023

About Storage Innovations 2030

This technology strategy assessment on flow batteries, released as part of the Long-Duration Storage Shot, contains the findings from the Storage Innovations (SI) 2030 strategic initiative. The objective of SI 2030 is to develop specific and quantifiable research, development, and deployment (RD&D) pathways to achieve the targets identified in the Long-Duration Storage Shot, which seeks to achieve 90% cost reductions for technologies that can provide 10 hours or longer of energy storage within the coming decade. Through SI 2030, the U.S. Department of Energy (DOE) is aiming to understand, analyze, and enable the innovations required to unlock the potential for long-duration applications in the following technologies:

- Lithium-ion Batteries
- Lead-acid Batteries
- Flow Batteries
- Zinc Batteries
- Sodium Batteries
- Pumped Storage Hydropower
- Compressed Air Energy Storage
- Thermal Energy Storage
- Supercapacitors
- Hydrogen Storage

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

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

Acknowledgments

DOE acknowledges all stakeholders who contributed to the SI 2030 industry input process. Further information about the stakeholders who participated in the SI Framework activities can be found in Appendix B.

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Background

Introduction

Redox flow batteries (RFBs) or flow batteries (FBs)—the two names are interchangeable in most cases—are an innovative technology that offers a bidirectional energy storage system by using redox active energy carriers dissolved in liquid electrolytes. RFBs work by pumping negative and positive electrolytes through energized electrodes in electrochemical reactors (stacks), allowing energy to be stored and released as needed. With the promise of cheaper, more reliable energy storage, flow batteries are poised to transform the way we power our homes and businesses and usher in a new era of sustainable energy.

History

The principle of the flow battery system was first proposed by L. H. Thaller of the National Aeronautics and Space Administration in 1974, [1] focusing on the Fe/Cr system until 1984. In 1979, the Electrotechnical Laboratory in Japan also made progress in the development of the aqueous Fe/Cr system, which was a project of the New Energy and Industrial Technology Development Organization [2]. In the 1980s, the University of New South Wales in Australia started to develop vanadium flow batteries (VFBs). Soon after, Zn-based RFBs were widely reported to be in use due to the high adaptability of Zn-metal anodes to aqueous systems, with Zn/Br_2 systems being among the first to be reported. In the 1990s, Regenesys Ltd invented RFB systems with NaBr on the positive side and Na_2S_4 on the negative side as electrolytes. Until the 2010s, many types of RFB systems have been proposed, including all-iron, non-aqueous organic, and aqueous organic flow batteries [3]. In recent years, there has been significant progress in improving their performance and reducing their cost. Currently, RFBs, especially VFBs and zinc-bromine RFBs are considered relatively mature technologies and are being actively deployed in a variety of applications.

Commercial Deployments

RFBs have unique characteristics, such as decoupled energy and power, scalability, and potential cost-effectiveness, due to their liquid nature. These features make RFBs well suited for various applications, including utility-scale energy storage, microgrids, renewables integration, backup power, and remote/off-grid power. Below are some notable commercial accomplishments in this area:

- A 100-MW/400-MWh VFB system, the largest of its kind in the world, was put into operation in Dalian in northeast China in 2023 by Rongke Power Company.
- A 7-MW/30-MWh VFB system will be installed by Invinity Energy Systems on the National Grid in the United Kingdom, which should be the largest grid-scale battery ever manufactured in the United Kingdom.
- ESS, Inc., in the United States, ended 2022 with nearly 800 MWh of annual production capacity for its all-iron flow battery.
- China's first megawatt iron-chromium flow battery energy storage demonstration project, which can store 6,000 kWh of electricity for 6 hours, was successfully tested and was approved for commercial use on February 28, 2023, making it the largest of its kind in the world.

- Australia-based Redflow Limited has 2-MWh zinc-bromine RFBs at Anaergia's Rialto Bioenergy Facility in San Bernardino County, CA. The Rialto Bioenergy Facility is converting as much as 700 tons of food waste and 300 tons of biosolids per day into renewable natural gas, renewable electricity, and organic fertilizer.
- Aqueous organic RFB systems with organic active species are potentially cost-effective and viable for widespread adoption because they are not limited by the redox species' natural abundance on Earth. They are being developed by several start-ups, such as Quino Energy, Otoro Energy, Flux XII, and so forth.

RFB Designs

Figure 1 illustrates the three common RFB designs: traditional, hybrid, and redox-targeting RFBs. In a traditional dual-flow battery system with dissolved active species, two electrolyte tanks containing dissolved active species are separated by a membrane. The active species undergo redox reactions during charging and discharging. A hybrid flow battery system employs a solid anolyte active species in addition to a dissolved catholyte active species, providing extra capacity and higher energy density. In contrast, a redox shuttle design stores solid active materials in multiple tanks and a separate tank with a redox shuttle to transport the active species between the solid active tanks. This design enables higher energy density and a reduction in the volume of electrolyte required.

RFBs are commonly noted for their variable duration capabilities, utilizing a materials supply chain separate from lithium batteries, and having the flexibility to separately scale power and energy. This independence of power and energy primarily applies to traditional RFBs and redox-targeting RFBs, but not hybrid RFBs as those contain a solid anode.

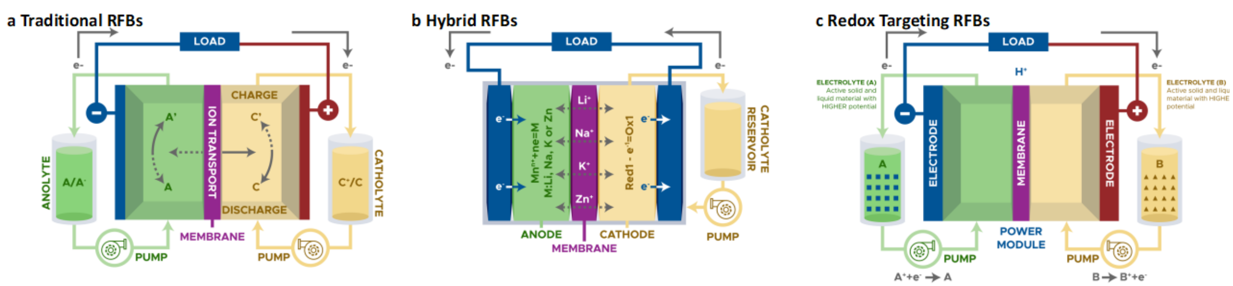

Figure 1. Three basic RFB designs: (a) a standard dual-flow system with only dissolved active species, (b) a hybrid system employing a solid anode active species, and (c) a redox shuttle design with a majority of stationary solid active species in the tanks—accessed by pumped redox shuttles—for increased energy density

Aqueous versus Non-aqueous

Table 1 summarizes the RFB chemistries that are under development. Traditional RFB chemistries can be categorized based on the type of electrolyte—aqueous versus non-aqueous. Potentially high theoretical energy densities are enabled by high-voltage redox couples when non-aqueous electrolytes are used. These RFBs suffer from high resistance and low selectivity of membrane, which impedes acceptable performance. As a result, research activity in this category has been curtailed somewhat until a practical solution can be found. Thus, currently, commercial systems are based on aqueous electrochemical couples, which are characterized by a generally lower energy density; a low membrane resistance that allows high-current operation; and selectivity, which is sufficient to support high coulombic efficiencies.

Organic versus Inorganic

Another broad RFB categorization for traditional RFBs is organic versus inorganic redox couples. Aqueous inorganic vanadium RFBs (VFBs) were a technical success, particularly as the system is "symmetric," where the same species can be used as a catholyte (positive charge storer) and an anolyte (negative charge storer). The symmetric design is especially useful because crossover of species is not a major issue anymore and electrolyte rebalancing (needed due to water osmosis over time) effectively allows decades of reliability. However, this chemistry suffers from the volatile cost of vanadium (insufficient global supply), which impedes market growth.

A summary of common flow battery chemistries and architectures currently under development are presented in Table 1.

Table 1. Selected redox flow battery architectures and chemistries

Config	Solvent	Solute	RFB System	Redox Couple in an Anolyte	Redox Couple in a Catholyte
Traditional (fluid-fluid)	Aqueous	Inorganic	All-Vanadium	V(II)/V(III)	V(IV)/V(V)
			Iron-Chromium	Cr(II)/Cr(III)	Fe(II)/Fe(III)
			Vanadium-Bromine	V(II)/V(III)	Br_2/Br^-
		Organic	Anthraquinone-Benzoquinone	AQS/H2AQS	BQDS/H2BQDS
			Phenazine-Ferrocyanide	Phenazine derivatives	Ferrocyanide
			Fluorenone-Ferrocyanide	Fluorenone derivatives	Ferrocyanide
	Non-aqueous	Organic	Ruthenium Complexes	$[Ru(bpy)_3]^{2+}$/ $[Ru(bpy)_3]^{3+}$	$[Ru(bpy)_3]^{+}$/ $[Ru(bpy)_3]^{2+}$
			Chromium-Acetylacetonate	Cr(I)/Cr(II)/ Cr(II)/Cr(III)	Cr(III)/Cr(IV)/ Cr(IV)/Cr(V)
Hybrid	Aqueous	Inorganic	Zinc-Bromine	Zn/Zn^{2+}	Br_2/Br^-
			Zinc-Cerium	Zn/Zn^{2+}	Ce(III)/Ce(IV)
			All-Iron	Fe/Fe(II)	Fe(II)/Fe(III)
			All-Lead	Pb/Pb(II)	Pb(II)/PbO_2
	Non-aqueous	Organic	Lithium-Anthraquinone	Li/Li(I)	Anthraquinone
Redox-targeting	Aqueous		Zinc-Ferrocyanide	Zn/Zn^{2+}	Mediators: $[Fe(CN)_6]^{4-/3-}$ Solid battery materials: $Fe_4[Fe(CN)_6]_3$

Baseline Cost Estimates

The capital costs of each RFB project vary because of site-specific factors, such as location, plant size and technology, required civil works, and other related factors. According to Viswanathan et al. (2022), a 100-MW VFB system with 10 hours of energy storage would have an estimated total installed cost of $384.5/kWh. For a larger 1,000-MW VFB system with the same duration of storage, the estimated total cost is $365.2/kWh.

Table 2 shows cost and performance projections for a 100-MW VFB system with 10 hours of storage in 2030. These projections assume no increase in DOE research and development (R&D) investments and serve as the reference point for future impact assessments.

Table 2. Projected VFB cost and performance parameters in 2030 for a 100-MW, 10-hour VFB storage system

Parameter	Value	Description
Storage Block Calendar Life for Stacks and Pumps	12	Deployment life (years)
Cycle Life (Electrolyte)	10,000	Base total number of cycles
Round-trip Efficiency (RTE)	65%	Base RTE
Storage Block Costs	166.16	Base storage block costs ($/kWh)
Balance of Plant Costs	29.86	Base balance of plant costs ($/kWh)
Controls and Communication Costs	1.12	Controls and communication costs ($/kW)
Power Equipment Costs	101.54	Power equipment costs ($/kW)
System Integration Costs	32.00	System integration costs ($/kWh)
Project Development Costs	42.33	Project development costs ($/kWh)
Engineering, Procurement, and Construction (EPC) Costs	36.81	EPC costs ($/kWh)
Grid Integration Costs	16.97	Grid integration costs ($/kW)
Fixed Operations and Maintenance (O&M) Costs	9.95	Base fixed O&M costs ($/kW-year)
Variable O&M Costs	0.0005125	Base variable O&M costs ($/kWh)

Source: Viswanathan et al., 2022.

Based on these parameter values, levelized cost of storage (LCOS) for 10-hour systems at a rated power of 100 MW and 1,000 MW are projected to be $0.16/kWh and $0.15/kWh, respectively, in 2030 [4].

Pathways to $0.05/kWh

DOE's Energy Storage Grand Challenge Storage Innovations 2030 (SI 2030) engaged flow battery industry experts to examine potential barriers for further development and to help identify the most promising R&D opportunities that can facilitate achieving the $0.05/kWh LCOS goal established by DOE's Long-Duration Storage Energy Earthshot. The SI Flight Paths Team, comprised of staff from several National Laboratories, hosted a 2-hour listening session with industry chief executive officers, chief technology officers, and other leaders on January 12, 2023, to discuss the potential development needs of their current technologies. A total of 22 industry attendees representing 14 commercial flow battery-related companies (i.e., 5 organic-based, 3 vanadium-based, 2 zinc-based, 1 iron-based, 1 sulfur-manganese, and 2 membrane companies) discussed the most impactful impediments limiting widespread deployment of the flow batteries, components, and technologies that could benefit most from further development and cost reductions and opportunities for pre-competitive R&D among industry. The Flight Paths listening session helped identify both key technology areas for development, as well as regulatory and policy implications that may be impacting the development of the technology, which will be discussed in later sections of this report. In terms of technological opportunities, session respondents identified the following areas for technological improvements.

Table 3. Flow battery components that could benefit most from technological improvements

Flow Battery Technology	Percentage of Respondents	Developmental Opportunities
Membranes	27	Higher conductivity, selectivity, and stability/durability
Electrodes	18	Impact of additives on carbon electrodes
Bipolar plate	16	Improved durability and lower cost
Power electronics	16	Improved low-voltage systems
Other (e.g., electrolyte production)	10	Higher efficiency production, domestic supply chains, and reduced transportation costs
Battery management systems/controls	8	Not discussed
Pumps	4	Not discussed

Other discussion topics during the Flight Paths listening session focused on the most promising cost reduction opportunities for flow batteries. As indicated in Table 4, electrolytes, manufacturing, and stack components were considered to be the most promising opportunities for cost reduction.

Table 4. The most promising cost reduction opportunities (Flight Paths listening session, January 12, 2023)

Cost Reduction Opportunities	Percentage of Respondents
Electrolytes	30
Manufacturing	30
Stack components	28
Power electronics	10
Other	3

The Energy Storage Grand Challenge SI 2030 Framework Team further explored flow battery cost reduction opportunities to understand the magnitude and impact of potential R&D investments. The Framework Team interviewed 26 flow battery subject matter experts (SMEs) who represented 20 organizations, ranging from industry groups (e.g., ESS, Inc., Lockheed Martin Corporation) to vendors (e.g., Primus Power, Largo Inc.) and National Laboratories (e.g., SLAC National Accelerator Laboratory). All 20 organizations participated in interviews where the Framework Team solicited information regarding pathways to innovation and the associated cost reductions and expected performance improvements. The innovations defined by the SMEs are presented in Table 5 and are consistent with the Flight Paths findings described above. Definitions of each innovation are presented in Appendix A.

Table 5. Taxonomy of innovations for RFB

Innovation Category	Innovation
Raw materials sourcing	Mining and metallurgy innovations
	Secondary sourcing
Supply chain	Supply chain analytics
Technology components	Low-cost membranes with high selectivity and durability
	Power performance
	System design and packaging
Manufacturing	Manufacturing for scalable flow batteries
Advanced materials development	Novel active electrolytes
	Bipolar plates
	Separators/Membranes
	Accelerating the discovery loop for battery metrics and materials
Deployment	Scaling and managing the energy storage system
	Demonstration projects
End of life	Enhancing domestic recycling

Once the innovations were defined, SMEs were further contacted in order to obtain their input regarding the requirements and timelines for investment and potential impacts on performance (e.g., round-trip efficiency, cycle life) and cost (e.g., storage block, balance of plant, operations and maintenance [O&M]) for each innovation. A Monte Carlo simulation model was used to explore the range of potential impacts of research, development, and deployment investment by evaluating tens of thousands of combinations of innovations and impacts, the goal of which was to determine what portfolios of innovations had the highest probability of achieving the Energy Storage Grand Challenge LCOS target of $0.05/kWh. Required investment levels were also observed. The Monte Carlo simulation tool then randomly combined each innovation with two to seven other innovations and, based on the combinations of innovations selected by the model and the range of impacts estimated by industry, the tool produced the distribution of achievable outcomes by 2030 with respect to LCOS (Figure 2). The LCOS range with the highest concentration of simulated outcomes is in the $0.057 to $0.064/kWh range. However, some portfolios substantially reduce LCOS, with the highest impact portfolios (top 10% as calculated by the model) resulting in an LCOS of between $0.052 and $0.057/kWh—approximately 2.8 times lower than current 2030 projections. Note that the marked region indicates the range of LCOS calculated by the model for the top 10% of the portfolios.

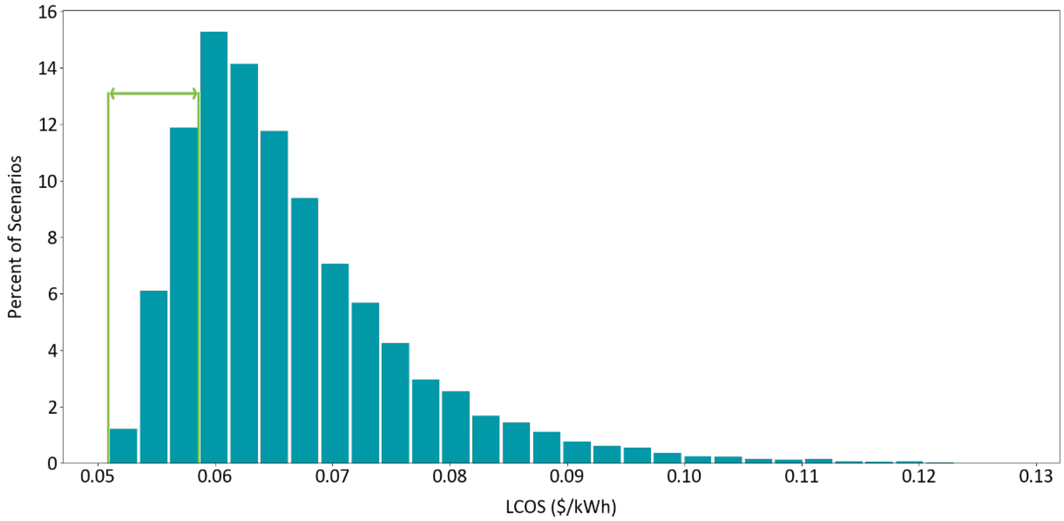

Figure 2. RFB portfolio frequency distribution across LCOS

The results of the Monte Carlo simulation for the thousands of portfolios that fall within the top 10% in terms of LCOS impact are presented in Figure 3. The vertical line demonstrates that the mean portfolio cost is $325 million, which represents the marginal investment over currently planned levels required to achieve the corresponding LCOS improvements. Total expenditure levels with the highest portfolio densities in the top 10% are in the $350 million to $425 million range, and the timeline required for achieving these LCOS levels is estimated at 8 to 12 years.

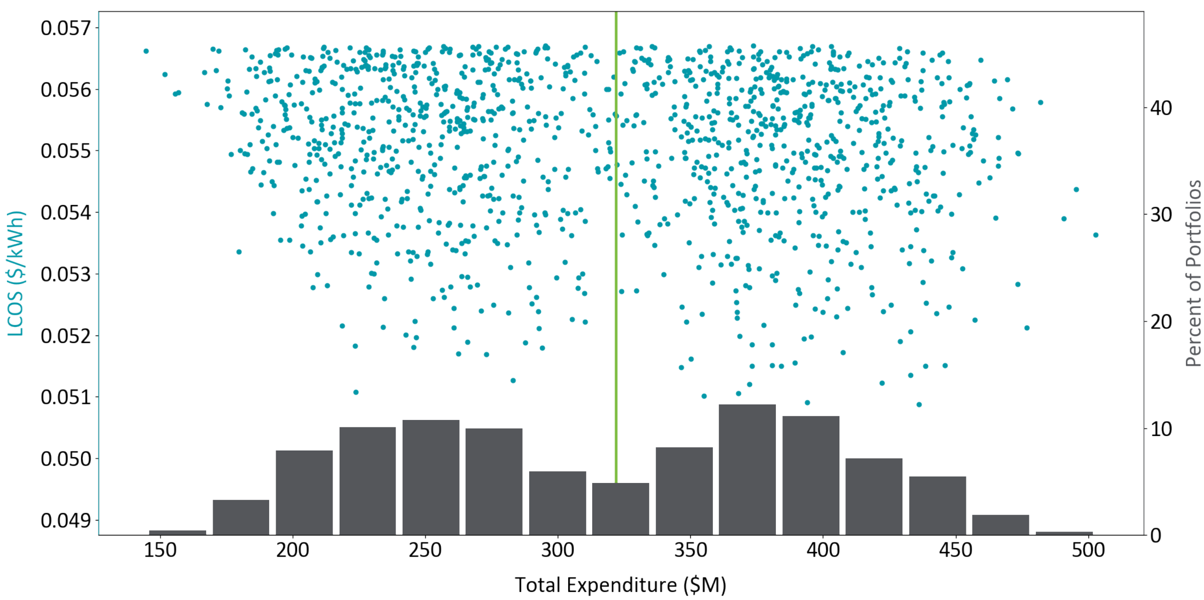

Figure 3. LCOS and industry expenditures for the top 10% of RFB portfolios

Note that the impact of each layered innovation is not additive. To account for this, the Monte Carlo model uses innovation coefficient matrices that assign a value between 0 and 1 for each pair of innovations. These innovation coefficients indicate what fraction of savings potential for each innovation is independent of the other one. In this manner, a value of 1.0 represents two entirely independent innovations, where cost savings will stack linearly, and a value of 0.0 represents two entirely overlapping innovations, where only the more impactful innovation will have an effect on LCOS. Working with SMEs, the research teams established innovation coefficients that are used to measure the combined impact.[a] Innovation coefficients for each innovation pairing are presented in Appendix C.

SMEs also were asked for their preferences regarding the investment mechanism, selecting among National Laboratory investments, R&D grants, loans, and technical assistance. Table 6 presents the preferences for each mechanism. National Laboratory investments, typically with collaboration from universities and industry, were favored for most basic research efforts, including novel active electrolytes, low-cost membranes, and bipolar plate. R&D grants were supported for larger industry-focused efforts (e.g., enhanced domestic recycling, demonstration projects), while loans were selected for innovations involving industrial processes and demonstration projects that would require significant industry investment. Note that cells with asterisk (*) indicate that it is the preferred mechanism.

Table 6. SME preferences for investment mechanisms in RFB innovations. Cells with asterisks (*) represent the preferred mechanism. (Technical Assistance includes advice or guidance on issues or goals, tools and maps, and training provided by government agencies or National Laboratories to support industry.)

Innovation	National Laboratory Research	R&D Grants	Loans	Technical Assistance
Mining and metallurgy innovations	14.3%	21.4%	28.6%	35.7%*
Secondary sourcing	20.0%	26.7%*	26.7%	26.7%
Supply chain analytics	38.9%*	22.2%	11.1%	27.8%
Low-cost membranes with high selectivity and durability	31.3%	50.0%*	12.5%	6.3%
Power performance	27.8%	44.4%*	11.1%	16.7%
System design and packaging	14.3%	57.1%*	21.4%	7.1%
Manufacturing for scalable flow batteries	11.8%	47.1%*	41.2%	0.0%
Novel active electrolytes	41.2%*	35.3%	11.8%	11.8%
Bipolar plates	41.7%*	33.3%	8.3%	16.7%
Separators/Membranes	40.9%*	31.8%	13.6%	13.6%
Accelerating the discovery loop for battery metrics and materials	50.0%*	31.3%	0.0%	18.8%
Scaling and managing the energy storage system	17.4%	34.8%*	30.4%	17.4%
Demonstration projects	13.6%	36.4%*	36.4%	13.6%
Enhancing domestic recycling	30.4%*	26.1%	17.4%	26.1%

[a] To demonstrate how innovation coefficients work, the innovation coefficient for the combined investment in mining/metallurgy innovations and enhanced domestic recycling is 0.13, which means that the Monte Carlo simulation tool would only include 10% of the defined impact of the second innovation (e.g., enhanced domestic recycling) when added to the first innovation (e.g., mining/metallurgy innovations). The reason for the low coefficient for these innovations are that both affect the raw materials that are used in the manufacturing process (i.e., virgin versus recycled materials). An innovation coefficient of 1.0 indicates that 100% of the impact of the second investment will be added to the impact of the first innovation, while a coefficient of 0 means that the second investment would add no additional value.

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 4. Innovations such as novel active electrolytes and manufacturing for scalable RFBs appear to have great potential to improve the cost of RFB projects.

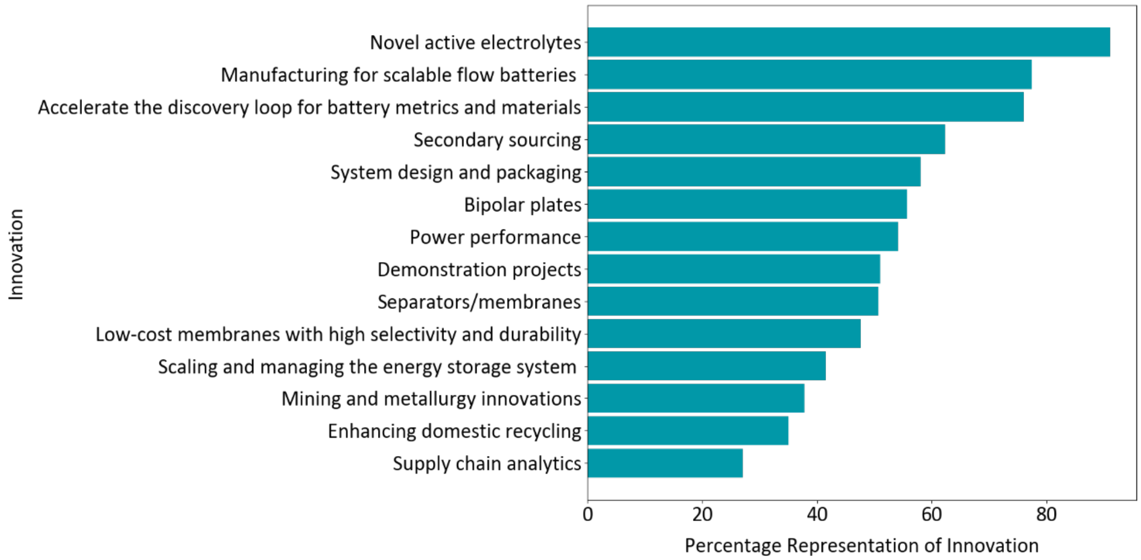

Figure 4. Representation of innovations in the top 10% performing RFB portfolios

R&D Opportunities

Based on the SMEs' estimates provided to the Framework Team (see Table 7), novel active materials, manufacturing for scalable flow batteries, secondary sourcing (materials extraction), demonstration projects, and accelerating the discovery loop for battery metrics and materials consistently yield metrics in the top tier, designated by cells with asterisks (*). Cells with daggers (†) indicate mid-tier metrics, and cells with double daggers (‡) indicate the lowest tier. When reviewing the values in Table 7, the values for mining and metallurgy innovations indicate that investing $35.9 million over 4.5 years could reduce storage block costs by 25.4% while improving cycle life by 20% and round-trip efficiency by 5%. Cycling improvements are the most significant contributor to reduced LCOS for flow batteries, and several innovations demonstrate strength in this metric. The Framework Team recognizes that some estimates are aggressive and optimistic yet remain worthy of our attention as they demonstrate a strong directional cue from the industry that these innovations show great promise and have broad-based industry support. Enhanced domestic recycling, supply chain analytics, and mining/metallurgy were not viewed as promising by the industry. More detailed data, including minimum and maximum values and standard deviations for each metric, are presented in Appendix D.

Table 7. Impacts of the proposed R&D investment levels, mean investment requirements, and timelines. (For the Impacts of Proposed R&D Investment Levels tables, asterisks (*) represent the top tier, daggers (†) represent mid-tier, and double daggers (‡) represent the lowest tier.)

Innovation	Storage Block Cost Impact (%)	Cycle Life Improvement (%)	Round-trip Efficiency Impact (%)	Mean Investment Requirement (million $)	Mean Timeline (years)
Mining and metallurgy innovations	-25.4% *	20.0% ‡	5.0% ‡	35.9 ‡	4.5 †
Secondary sourcing	-30.4% *	50.0% *	5.0% ‡	29.0 †	3.6 †
Supply chain analytics	-22.6% †	35.0% *	16.0% *	5.4 *	2.5 *
Low-cost membranes with high selectivity and durability	-18.6% ‡	6.5% ‡	4.5% ‡	22.4 †	3.5 *
Power performance	-17.6% ‡	35.0% †	12.0% †	12.9 *	4.8 ‡
System design and packaging	-19.9% †	27.5% †	7.5% †	9.8 *	3.6 †
Manufacturing for scalable flow batteries	-36.6% *	35.0% *	15.0% *	35.6 †	5.1 ‡
Novel active electrolytes	-36.0% *	41.3% *	20.4% *	37.1 ‡	4.4 †
Bipolar plates	-12.2% ‡	29.0% ‡	10.3% †	22.2 ‡	3.3 *
Separators/Membranes	-20.2% †	23.8% ‡	14.8% *	23.1 †	4.6 ‡
Accelerating the discovery loop for battery metrics and materials	-23.0% †	33.8% †	13.3% *	10.4 *	3.4 *
Scaling and managing the energy storage system	-13.6% ‡	35.0% †	7.0% †	40.3 ‡	3.9 ‡
Demonstration projects	-18.8% †	7.5% ‡	5.0% ‡	99.4 ‡	4.7 ‡
Enhancing domestic recycling	-24.2% †	52.5% *	5.0% ‡	16.1 ‡	3.6 †

The recommended investment levels and timeline by innovation also are identified in Table 7. Most investments are in the $5 million to $40 million range (except for demonstration projects) and require investments over 3 to 5 years. Mining/Metallurgy, scaling and managing the energy storage system, demonstration projects, and novel active electrolytes require significant investment in industrial processes and project development and, therefore, require more investment and time. An emerging pattern is the number of innovations that yield fairly solid impacts at relatively low investment levels, including accelerating the discovery loop for battery metrics and materials, enhancing domestic recycling, supply chain analytics, power performance, and system design and packaging. Investment in these innovations, along with those in separators/membranes, would yield solid reductions in LCOS at modest investment levels. However, to achieve levels at or near the $0.05/kWh target, deep investment in advanced manufacturing for scalable flow batteries and novel active electrolytes that involve development and validation of advanced controls and management systems are required.

From both the Flight Paths and Framework efforts, several key research areas were identified for flow battery technologies where additional research and investment would benefit their development.

- **Separators/Membranes:** Flow battery membranes physically separate the positive and negative electrolytes while allowing the transfer of charge-carrying ions during charging and discharging of the battery. Improving the conductivity of current membranes can help increase the efficiency of flow batteries but must be done in conjunction with maintaining or increasing the selectivity of the membrane in order to minimize crossover of the active species. The strength and durability of the membranes can also be improved. Increasing the strength of membrane materials allows for thinner, less resistive membranes to be used in stack construction, thereby reducing costs. Improving the ability of these membranes to resist chemical attack during operation can increase the overall flow battery lifetime and reduce the overall project costs associated with flow batteries. Given the different designs (pure flow and hybrid) and different electrolyte properties (acidic, basic, and near neutral), several types of membranes are needed to meet all of the application needs. In all cases, a clear idea of the trade-off between improved performance and lower cost needs to be developed and disseminated to industry. Additional research for understanding how much of the membrane is functional and active during the electrochemical process also was identified as a need, with the goal of providing a design tool for developers that can help them understand how to best utilize selected membranes under different conditions. Finally, two other areas identified by industry as near-term needs were improving the scale-up and manufacturing of membrane materials, which can significantly reduce their costs when produced at scale, and research into non-perfluorosulfonic acid membranes.

- **Electrolytes:** The use of flowing electrolytes in flow batteries enables the separation of power and energy, making flow batteries an ideal candidate for longer duration applications. However, the cost of these electrolytes will need to be reduced to make long-duration energy storage (LDES) applications cost-effective. Electrolyte production currently requires significant capital to create raw materials for the electrolyte and new processes are needed that are more efficient and environmentally friendly. Both current and new electrolyte technologies need to be designed around what can be manufactured domestically at a low cost. Increasing the energy density of electrolytes also was identified as a development need for flow battery technologies. Increasing the energy density can help reduce the total property costs of a project and can lower the capital cost of the system. Focus was placed on the transportation costs of these electrolytes for LDES deployments with an increased need to develop methods where the electrolyte is constituted on-site, thus reducing the cost for factory build-out and excessive transportation costs. Other industry comments focused on better defining the electrolyte recycling opportunities at end of life. While some flow battery technologies are establishing "leasing" models where the electrolyte is taken back by the developer at the end of storage deployment, a holistic review of the recycling opportunities for all chemistries is needed.
- **Manufacturing/Supply Chains:** Flight Paths industry participants indicated an average technology readiness level for flow batteries of 6 (ranging from 3 to 10), with an average manufacturing readiness level of 5.4 (ranging from 1 to 8). In both the Flight Paths and Framework, the need for improved supply chains and the manufacturing of flow batteries and components were identified as a critical developmental need for the industry. Developing a larger, coordinated supply chain effort across several different industries is needed for flow batteries to compete with the "giga-scale" lithium-ion systems currently being deployed. Several flow battery components have the opportunity to leverage adjacent markets (e.g., fuel cells, desalination) that could be mutually beneficial and non-competitive if explored. When asked about what a competing technology would identify as a limitation of the technology, Flight Paths respondents identified supply chains as one of the top items. Based on feedback received from the Framework, the manufacturing of scalable flow batteries and supply chain analysis are commonly cited topics. Some SMEs have suggested that implementing a small business model akin to the automotive industry's approach to manufacturing and supply chain could yield advantages.
- **Power Electronics:** Flow batteries and other low-voltage, high-current technologies may require DC-to-DC step-up prior to DC-to-AC conversion, leading to increased systems cost. Crosscutting opportunities exist for developing more low-voltage capable DC-to-AC conversion power electronics.

- **Electrodes, Bipolar Plates:** RFBs need to utilize adjacent markets (e.g., fuel cells) to help lower the cost of electrodes and bipolar plates. RFBs also need a better understanding of electrode constituents (e.g., binders in carbon electrodes) and their impact on performance and lifetime.

Additional Opportunities and Discussion

Flight Paths responses were not limited to technology advancements only but offered insights into market and other regulatory barriers that are limiting technology maturation. An example word cloud shown in Figure 5 highlights the range of issues facing RFB developers.

Figure 5. Flight Paths responses to "What are the most impactful impediments limiting the widespread deployment of your technology?"

In addition to demonstrating the bankability of RFB technologies, the length of interconnection queues, lack of market opportunities, and domestic supply and manufacturing chains were identified as impediments to wider scale deployment of RFB technologies.

- **Interconnection Queues:** For new transmission-connected projects, getting into the interconnection queue can be a multi-year process, resulting in significant project delays. These delays increase project costs and limit flow batteries and other early-stage technologies from being deployed, thus limiting the validation of their performance in the field. Improving the process for smaller projects/developers to obtain approval via the interconnection queue was a need identified by industry participants.
- **Bankability:** Newer technologies must develop an established record of past performance to access additional capital for scale-up. If companies do not have the demonstration opportunities or investments to establish the bankability requirements, they can limit or stall their growth. When asked "What keeps your chief executive officer/chief technology officer up at night?," Flight Paths respondents mentioned financing/bankability as the primary concern with issues around bridging the gaps in economies of scale and winning

early business. Increased demonstration opportunities and opportunities to independently validate their technologies along the development process could help lower this barrier.

- **Valuation of Long-Duration Storage:** Flow batteries are ideally suited for longer duration (8+ hours) applications; however, existing wholesale electricity market rules assign minimal incremental value to longer durations. Flow battery developers must balance meeting current market needs while trying to develop longer duration systems because most of their income will come from the shorter discharge durations. Currently, adding additional energy capacity just adds to the cost of the system. Developers noted that they are seeing incremental capacity increases supporting 4- to 10-hour systems but indicated that establishing a market or value proposition for LDES technologies was critical for advancing the technology.

- **Other Topics:** Industry respondents identified the need to establish standards for flow batteries, improve engagement/education with authorities having jurisdiction (AHJs), and offer tax credits for electrolyte production. Defined standards for measuring both the performance of flow battery systems and facilitating the interoperability of key flow battery components were identified as a key need by industry. Increasing engagement with AHJs with regard to flow batteries can help overcome fear of the unknown and reduce any additional approval time required for flow battery deployments. Industry also expressed that the tax credits for electrolyte production are important but currently require domestic content in order to claim them, which is difficult without having the supply chain already established in the United States.

Table 8. Comparison of identified key innovations from the Flight Paths and the Framework

Pathways	Technical Innovations	Non-Technical Innovations*
Flight Paths	• Membranes • Electrolytes • Manufacturing/Supply chains • Power electronics • Electrodes, bipolar plates	• Interconnection queues • Bankability • Standardization • Tax credits
Framework	• Manufacturing for scalable flow batteries • Novel active electrolytes • Separators/Membranes • Secondary sourcing • Supply chain analytics • Accelerating the discovery loop for battery metrics and materials	• Regulatory hurdles • Electrolyte leasing option • Standardization of the RFB system • Start-up versus big company

* Non-technical topics were not analyzed in the Framework and are summarized based on the SME interviews.

Pre-Competitive R&D Opportunities

Industry identified several areas of pre-competitive R&D where investments and the National Laboratories can help industry advance the technology:

- Improved electrolyte production from lower carbon resources and alternative domestic resources that are not specific to any one chemistry

- In situ refurbishment/maintenance of electrolyte to lower O&M costs

- Development of artificial intelligence/machine learning platforms for materials/cells
- The addition of reliability data to the DOE Global Energy Storage Database and the development of a database on suppliers and cost scaling
- Systems integration, lower cost power electronics, support for DC coupling advances, and standards for interchangeable/replaceable parts

When asked what would make DOE resources more valuable to industry, most of the discussion focused on the need to ensure that intellectual property and trade secrets were protected when working with DOE facilities and capabilities, as well as being able to access these capabilities in a timely manner. The development and dissemination of techno-economic and other tools that are open-sourced and available for industry for further development with their proprietary information also were discussed. These tools need to be more than just available for downloading with support for teaching industry the approach and understanding the methodology behind them. Increased collaboration with industry also was identified, with the goal of moving beyond letters of support for laboratory efforts to more active engagement with industry consortia. Industry and laboratory consortia can help create common definitions, develop common approaches to higher fidelity modeling (e.g., degradation modeling), and surmount common commercialization problems. More open access to DOE testing facilities, at all scales, is also valuable for providing independent validation of the technologies.

Appendix A: Innovation Matrix and Definitions

Table A.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	Mining and metallurgy innovations
	Secondary sourcing
Supply chain	Supply chain analytics
Technology components	Low-cost membranes with high selectivity and durability
	Power performance
	System design and packaging
Manufacturing	Manufacturing for scalable flow batteries
Advanced materials development	Novel active electrolytes
	Bipolar plates
	Separators/Membranes
	Accelerating the discovery loop for battery metrics and materials
Deployment	Scaling and managing the energy storage system
	Demonstration projects
End of life	Enhancing domestic recycling

Mining and metallurgy innovations include hydrometallurgical processes, extracting metals as a byproduct of other mining processes, or multi-metal mining. This category also includes innovations that would improve the purity and efficiency of metal extraction, such as vanadium.

Secondary sourcing includes the extraction of materials from secondary sources, such as biosynthesis and waste streams (e.g., spent catalysts in an oil refinery or industrial waste), so that the cost can be lowered via these sources.

Supply chain analytics include innovations and analysis that reduce risk in the supply of critical flow battery materials (e.g., vanadium, bromine, zinc). Examples include lowering the rising costs and lead time of critical materials, identifying alternative materials for system components, and improving subsystem assembly efficiency and cost.

Low-cost membranes with high selectivity and durability include innovations that replace the current high-cost sulfonated tetrafluoroethylene-based membranes but still maintain high ionic conductivity, low crossover, and excellent stability.

Power performance includes innovations that improve power performance, such as uniform flow and electric field design; plumbing design for reducing shunt current; bipolar plates with mechanical stability, high conductivity, and ease of recycling (such as carbon-coated metal bipolar plates); electrode coating to reduce interfacial resistance and increase electrolytic activity; energy-efficient balance of plant (pumps and piping); and enhanced electric demand response.

System design and packaging includes innovations that reduce the cost and improve the efficiency of stacks and the overall system, such as reducing the cost of secondary containers, physical separation of electrolyte (laminar flow overlapping), sealing materials in a leakproof manner, and an integrated battery management system with optimized cell distribution.

Manufacturing for scalable flow batteries includes innovations that would generate a manufacturing process for flow batteries completely different from current methods. This would include the manufacturing of electrolyte, membrane, carbon felt/cloth, bipolar plates, subsystem assembly, stacks, or other processes designed to make manufacturing greener. These innovations would reduce product variability, such as in electrolyte mixing, battery formation, performance validation, and manufacturing time and energy requirements, while increasing the automation of processes.

Novel active electrolytes include innovations for using novel electrolytes featuring non-corrosive, low-hydrogen evolution; stable pH; low crossover; and high chemical stability. This also includes the innovation of catholytes that couple with sodium metal at a reasonable temperature (100°C versus currently 300°C), and electrolytes with reasonable performance at high concentrations.

Bipolar plates include innovations that use novel bipolar plates with either alternative materials, such as carbon or plastic composites that deliver both performance and low cost, or the coating of metals that can make bipolar plates thinner and free of defects.

Separators/Membranes include innovations for using novel membranes from commodity materials that are low cost and provide satisfactory properties, such as high ionic conductivity, high durability, and excellent permeability. This also includes innovations that use novel approaches for membrane manufacturing, such as additive manufacturing.

Accelerating the discovery loop for battery metrics and materials includes innovations that apply artificial intelligence/machine learning to accelerate material discovery and predict flow battery life and performance. This would include in-line monitoring methods for the battery status, whether spectroscopic or electrochemical.

Scaling and managing the energy storage system includes innovations for integrating and managing many stacks in a stationary energy storage system. This also includes innovations to mitigate challenges, such as electrolyte stability in open air, temperature control versus degradation, and high-capacity/cell number stacks. These combined innovations would lead to a turnkey energy storage system for multiple use cases, similar to products offered in the lithium-ion battery industry.

Demonstration projects include innovations that are combined in a demonstration project for a specific deployment. This would likely be conducted through a consortium of companies or utilities, with DOE and private entities both contributing to the project. Analytics support could be supplied by National Laboratories. This also includes innovations for system transportation, performance simulation and validation, leakproof design, and so forth.

Enhancing domestic recycling includes innovations that enhance recycling automation and domestic capacity and reduce its environmental impact. This could include hydrometallurgy for secondary element production, recycling electrolytes, and recovering byproducts to improve the value proposition for recycling. This also could include innovations that plan for the recycling of the battery during the design and manufacturing stages rather than designing purely for battery performance and then devoting resources to determine the best method for recycling the battery. This includes strategies to recycle/refurbish the battery at its deployment location to extend its economic lifetime.

Appendix B: Industry Contributors

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

Participant	Institution
Dr. Z. Gary Yang	ZGY Power LLC
Patrick T. Sullivan	Flux XII LLC
Dr. Julia Song	Energy Storage Systems Inc.
Dr. Eugene Beh	Quino Energy
Mike L. Perry	Largo Inc.
Dr. Brennan Gantner	Skip Technology
Greg Cipriano	WattJoule
John F. DeBoever	WattJoule
Kevin Meagher	The Sun Company
Dr. Markus Schatz	Riverside Specialty Chemicals Inc.
Dr. Michael Marshak	Otoro Energy Inc.
Dr. Tyler Evans	Sharp End Energy, LLC
Dr. Jagjit Nanda	SLAC National Accelerator Laboratory
Dr. Thomas J. Rabbow	AvCarb Material Solutions
Craig Husa	Lockheed Martin Corporation
Dr. Steven Reece	Lockheed Martin Corporation
Matt Harper	Invinity Energy Systems
Matthew Walz	Invinity Energy Systems
Russ Weed	CleanTech Strategies LLC
Mark Higgins	Redflow Limited
Dr. Dagmar Becker	Redflow Limited
Tom Stepien	Primus Power
Tom Turcotte	Vault 44.01 (Formerly of Enlighten Innovations Inc.)
Joe Turcotte	Enlighten Innovations Inc.
Dr. Sai Bhavaraju	Enlighten Innovations Inc.
Dr. Conghua Wang	TreadStone Technologies, Inc.

Appendix C: Innovation Coefficients

Table C.1. Innovation coefficients

Innovation	Mining and metallurgy innovations	Secondary sourcing	Supply chain analytics	Low-cost membranes with high selectivity and durability	Power performance	System design and packaging	Manufacturing for scalable flow batteries	Novel active electrolytes	Bipolar plates	Separators/Membranes	Accelerating the discovery loop for battery metrics and materials	Scaling and managing the energy storage system	Demonstration projects	Enhancing domestic recycling
Mining and metallurgy innovations	–	0.20	0.05	1.00	1.00	1.00	0.95	0.50	1.00	1.00	0.75	1.00	1.00	0.10
Secondary sourcing	0.20	–	0.40	1.00	1.00	1.00	0.97	0.75	1.00	1.00	0.80	1.00	1.00	0.40
Supply chain analytics	0.05	0.40	–	0.95	1.00	0.80	0.70	0.60	0.60	0.80	0.90	0.70	0.70	0.85
Low-cost membranes with high selectivity and durability	1.00	1.00	0.95	–	0.30	0.80	0.80	0.95	0.98	0.60	0.90	0.95	0.95	0.98
Power performance	1.00	1.00	1.00	0.30	–	0.75	0.90	0.85	0.95	0.50	0.90	0.90	0.90	1.00
System design and packaging	1.00	1.00	0.80	0.80	0.75	–	0.60	0.95	0.90	0.95	0.85	0.60	0.80	0.90
Manufacturing for scalable flow batteries	0.95	0.97	0.70	0.80	0.90	0.60	–	0.80	0.70	0.75	0.90	0.60	0.80	0.60
Novel active electrolytes	0.50	0.75	0.60	0.95	0.85	0.95	0.80	–	0.95	0.85	0.80	0.95	0.95	0.60
Bipolar plates	1.00	1.00	0.60	0.98	0.95	0.90	0.70	0.95	–	0.98	0.95	0.90	0.95	0.95
Separators/Membranes	1.00	1.00	0.80	0.60	0.50	0.95	0.75	0.85	0.98	–	0.85	0.90	0.95	0.95
Accelerating the discovery loop for battery metrics and materials	0.75	0.80	0.90	0.90	0.90	0.85	0.90	0.80	0.95	0.85	–	0.80	0.90	0.90
Scaling and managing the energy storage system	1.00	1.00	0.70	0.95	0.90	0.60	0.60	0.95	0.90	0.90	0.80	–	0.50	0.60
Demonstration projects	1.00	1.00	0.70	0.95	0.90	0.80	0.80	0.95	0.95	0.95	0.90	0.50	–	0.80
Enhancing domestic recycling	0.10	0.40	0.85	0.98	1.00	0.90	0.60	0.60	0.95	0.95	0.90	0.60	0.80	–

Appendix D: Descriptive Statistics for Individual Innovations

Table D.1. Descriptive statistics for individual innovations

Innovation_cat	Innovation	Budget_low	Budget_high	Budget_mean	Budget_std	Timeline_low	Timeline_high	Timeline_mean	Timeline_std	sbc_low	sbc_high	sbc_mean	sbc_std	cyc_low	cyc_high	cyc_mean	cyc_std
Raw materials sourcing	Mining and metallurgy innovations	2.00	100.00	35.90	36.90	1.00	10.00	4.45	3.08	-0.08	-0.60	-0.25	0.19	0.20	0.20	0.20	0.00
	Secondary sourcing	1.00	100.00	29.00	37.67	1.00	10.00	3.55	2.58	-0.10	-0.60	-0.30	0.17	0.50	0.50	0.50	0.00
Supply chain	Supply chain analytics	0.00	40.00	5.41	10.32	0.50	5.00	2.54	1.56	-0.03	-0.50	-0.23	0.16	0.10	0.60	0.35	0.35
Technology components	Low-cost membranes with high selectivity and durability	0.25	100.00	22.35	28.51	1.00	10.00	3.45	2.83	-0.05	-0.35	-0.20	0.11	0.03	0.10	0.07	0.05
	Power performance	0.25	50.00	12.85	14.05	1.00	15.00	4.75	4.11	0.00	-0.30	-0.19	0.09	0.20	0.50	0.35	0.21
	System design and packaging	0.50	25.00	9.75	9.07	1.00	15.00	3.64	3.59	-0.02	-0.50	-0.21	0.12	0.05	0.50	0.28	0.32
Manufacturing	Manufacturing for scalable flow batteries	1.00	100.00	35.64	38.56	1.00	20.00	5.07	5.23	-0.03	-0.66	-0.35	0.18	0.10	0.60	0.35	0.35
Advanced materials development	Novel active electrolytes	0.25	100.00	37.10	32.93	1.00	20.00	4.42	5.20	-0.09	-0.60	-0.34	0.21	0.20	0.60	0.41	0.18
	Bipolar plates	0.25	50.00	22.19	17.37	1.00	10.00	3.25	2.60	-0.01	-0.30	-0.14	0.11	0.05	0.60	0.29	0.28
	Separators/Membranes	0.25	100.00	23.09	27.03	1.00	20.00	4.57	5.09	-0.01	-0.35	-0.21	0.14	0.05	0.60	0.24	0.25
	Accelerating the discovery loop for battery metrics and materials	0.25	41.00	10.35	12.40	1.00	10.00	3.42	2.68	-0.02	-0.50	-0.23	0.19	0.10	0.60	0.34	0.25
Deployment	Scaling and managing the energy storage system	1.00	250.00	40.29	66.20	1.00	15.00	3.86	3.48	-0.03	-0.25	-0.16	0.09	0.20	0.50	0.35	0.21
	Demonstration projects	3.00	501.00	99.44	160.10	1.00	15.00	4.69	3.68	-0.05	-0.35	-0.20	0.12	0.05	0.10	0.08	0.04
End of life	Enhancing domestic recycling	0.25	100.00	16.11	25.01	1.00	10.00	3.63	2.87	-0.01	-0.50	-0.24	0.24	0.05	1.00	0.53	0.67

sbc = storage block cost, cyc = lifetime cycles

Innovation_cat	Innovation	rte_low	rte_high	rte_mean	rte_std	bpc_low	bpc_high	bpc_mean	bpc_std	fom_low	fom_high	fom_mean	fom_std	vom_low	vom_high	vom_mean	vom_std
Raw materials sourcing	Mining and metallurgy innovations	0.05	0.15	0.08	0.06	-0.05	-0.93	-0.49	0.62	-0.05	-0.05	-0.05	0.00	-0.05	-0.05	-0.05	0.00
	Secondary sourcing	0.05	0.15	0.08	0.06	-0.05	-0.93	-0.49	0.62	-0.05	-0.05	-0.05	0.00	-0.05	-0.05	-0.05	0.00
Supply chain	Supply chain analytics	0.05	0.60	0.21	0.26	-0.05	-0.93	-0.49	0.34	-0.05	-0.30	-0.16	0.11	-0.05	-0.30	-0.15	0.12
Technology components	Low-cost membranes with high selectivity and durability	0.04	0.15	0.08	0.06	-0.02	-0.93	-0.49	0.44	-0.01	-0.50	-0.20	0.26	-0.01	-0.50	-0.20	0.26
	Power performance	0.05	0.20	0.13	0.06	-0.06	-0.93	-0.52	0.38	-0.01	-0.50	-0.18	0.22	-0.01	-0.50	-0.20	0.26
	System design and packaging	0.05	0.15	0.10	0.05	-0.01	-0.93	-0.49	0.35	-0.05	-0.50	-0.19	0.21	-0.05	-0.50	-0.22	0.25
Manufacturing	Manufacturing for scalable flow batteries	0.10	0.30	0.18	0.10	-0.10	-0.93	-0.57	0.33	-0.20	-0.35	-0.25	0.07	-0.20	-0.30	-0.25	0.07
Advanced materials development	Novel active electrolytes	0.04	0.60	0.26	0.20	-0.20	-0.93	-0.57	0.30	-0.04	-0.50	-0.26	0.19	-0.04	-0.30	-0.18	0.13
	Bipolar plates	0.02	0.30	0.12	0.09	-0.05	-0.93	-0.49	0.42	-0.02	-0.50	-0.26	0.17	-0.02	-0.30	-0.16	0.12
	Separators/Membranes	0.01	0.60	0.19	0.21	-0.05	-0.93	-0.49	0.42	-0.01	-0.50	-0.24	0.18	-0.01	-0.50	-0.25	0.20
	Accelerating the discovery loop for battery metrics and materials	0.10	0.60	0.23	0.21	-0.05	-0.93	-0.49	0.41	-0.10	-0.50	-0.30	0.20	-0.10	-0.50	-0.28	0.17
Deployment	Scaling and managing the energy storage system	0.01	0.15	0.09	0.07	-0.10	-0.93	-0.38	0.35	-0.06	-0.50	-0.22	0.20	-0.06	-0.10	-0.08	0.03
	Demonstration projects	0.05	0.15	0.08	0.06	-0.05	-0.93	-0.30	0.42	-0.05	-0.10	-0.09	0.03	-0.05	-0.10	-0.09	0.03
End of life	Enhancing domestic recycling	0.05	0.15	0.10	0.07	-0.10	-0.93	-0.52	0.59	-0.05	-0.50	-0.22	0.25	-0.01	-0.05	-0.03	0.03

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

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