Energy Earthshots
U.S. Department of Energy

Storage™

Technology Strategy Assessment

Findings from Storage Innovations 2030

Zinc Batteries

July 2023

About Storage Innovations 2030

This technology strategy assessment on zinc 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 and SI Flight Paths activities can be found in Appendix A.

The authors gratefully acknowledge SI activity coordination by Benjamin Shrager (Office of Electricity, DOE). The Zinc Battery Flight Paths listening session was facilitated by Erik Spoerke (Sandia National Laboratories) and Esther Takeuchi (Brookhaven National Laboratory; Stony Brook University) and the Framework Study was conducted by Justin Connell and Sanja Tepavcevic (Argonne National Laboratory). The authors would also like to thank Kate Faris, Whitney Bell, and others from ICF Next for their excellent organization of the Zinc Batteries Flight Paths listening session and the additional support they provided for SI activities. The authors would also like to acknowledge the leadership of and contributions to the Framework Study by Patrick Balducci (Argonne National Laboratory).

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Background

High-Level History

Zinc (Zn) was used as the negative electrode (anode) of batteries dating to the early 1800s, when Alessandro Volta formed early voltaic piles from stacks of alternating copper and Zn. The low-cost, high-energy density, safety, and global availability of Zn have made Zn-based batteries attractive targets for development for more than 220 years. The Zn-carbon battery, originally developed in the later 1800s, was manufactured as a popular primary battery until the 1980s [1]. Although still in limited use today in the United States, Zn-carbon cells were eventually replaced by alkaline Zn-MnO_2 batteries introduced as primary dry cells in 1952 and patented by Paul A. Marsal, Karl Kordesch, and Lewis Urry in 1960 [2-4]. These batteries have become some of the most commercially successful batteries to date, commonly recognized as AA, AAA, C, D, and 9V batteries in everyday use. Initially developed in the 1920s, ZnNi batteries were explored in the 1970s and 1980s as rechargeable batteries capable of hundreds (today ~1,000) of deep discharge cycles, potentially suitable for application in electric vehicles [5-7]. Primary Zn-air batteries, commonly recognized as “button cells” today, were originally patented in 1933 by G. W. Heise [8] and are still in widespread use (e.g., in hearing aids and some film cameras) [5]. Collectively, these historical batteries serve as the inspiration for several of the most commercially advanced batteries for grid-scale storage to date.

Chemistries

Zn-MnO_2 batteries, traditionally primary (not rechargeable) batteries, have been adapted to create low-cost secondary (rechargeable) batteries. These batteries often use an alkaline aqueous electrolyte and are considered more environmentally friendly than other types of batteries as indicated by the U.S. Environmental Protection Agency’s certification of these primary batteries for landfill disposal in the United States. Commercial primary Zn-MnO_2 batteries have an energy density of up to 150 Wh/kg or 400 Wh/L because of the high capacity of the Zn-anode (820 mAh/g) and the MnO_2 cathode (616 mAh/g for “2 electron” or 308 mAh/g for “1 electron” reactions) [4]. As a secondary battery, these systems have been deployed with energy densities on the order of 100 Wh/L and there are anticipated pathways to production at less than $50/kWh [5, 9]. These batteries use a Zn anode and specific forms of manganese dioxide (MnO_2) as the positive electrode (cathode). During electrochemical cycling of the secondary battery, the charge is balanced across the cell by hydroxide ions that move across a porous separator. The expected half-reactions at each electrode and the overall reaction of the cell during discharge are [5]:

Cathode: $MnO_2 + H_2O + e^- \rightarrow MnOOH + OH^-$ [$E^0 = +0.30V$]

Anode: $Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^-$ [$E^0 = +1.28V$]

Overall: $Zn + 2MnO_2 + H_2O \rightarrow ZnO + 2MnOOH$ [$E^0_{cell} = +1.58V$]

Zn-Ni batteries have a practical energy density of up to 140 Wh/kg or 300 Wh/L and are capable of approximately 500 charge-discharge cycles [5, 10]. Zn–Ni cells also use an aqueous solution of KOH as the electrolyte and Zn as the anode material, with the same fundamental anode reaction during discharge. In this case, the cathode is nickel oxyhydroxide (NiOOH), which converts to nickel hydroxide [$Ni(OH)_2$] during discharge [5]:

Cathode: $NiOOH + H_2O + e^- \rightarrow Ni(OH)_2 + OH^-$ [$E^0 = +0.49V$]

$$\textbf{Anode: } Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^- \; [E^0 = +1.28V]$$

$$\textbf{Overall: } Zn + 2NiOOH + H_2O \rightarrow ZnO + 2Ni(OH)_2 \; [E^0_{cell} = +1.77V]$$

Primary **Zn-Air batteries** offer potentially high energy density of up to 440 Wh/kg or 1,670 Wh/L and provide a constant, flat voltage discharge profile [5, 11]. Like Zn–MnO_2 and Zn–Ni batteries, commercial Zn–air batteries have a Zn anode and KOH electrolyte with the same basic anode reaction. In this case, the reacting species at the cathode are atmospheric oxygen and water from the electrolyte to form hydroxyl ions that migrate to the anode [5]:

$$\textbf{Cathode: } O_2 + 2H_2O + 4e^- \rightarrow MnOOH + OH^- \; [E^0 = +0.40V]$$

$$\textbf{Anode: } Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^- \; [E^0 = +1.28V]$$

$$\textbf{Overall: } 2Zn + O_2 \rightarrow 2ZnO \; [E^0_{cell} = +1.68V]$$

These air-based systems are complicated by the need to “breathe” oxygen (air), and the oxygen reduction and oxidation reactions at the cathode require catalysts that are either prohibitively expensive (e.g., Pt, Ag, Ir) or are not yet sufficiently efficient or durable (e.g., transition metal catalysts), and few catalysts are capable of performing both oxidation and reduction reactions needed for a rechargeable system. This is an active area of research.

Zn-Br batteries commercially comprise both static and flow battery configurations. Both batteries typically use an aqueous Zn-halide electrolyte and rely on the reversible plating (reduction) and stripping (oxidation) of a Zn metal anode. The overall (discharge) electrochemistry for both systems is represented by the following reactions [12]:

$$\textbf{Cathode: } Br_2 + 2e^- \rightarrow 2Br^- \; [E^0 = +1.09V]$$

$$\textbf{Anode: } Zn \rightarrow Zn^{2+} + 2e^- \; [E^0 = +0.76V]$$

$$\textbf{Overall: } 2Zn + Br_2 \rightarrow 2Zn^{2+} + 2Br^- \; [E^0_{cell} = +1.85V]$$

Because of the potentially hazardous nature of the bromine (Br_2) used in these batteries, they are typically assembled in the discharged state. Upon charging, Zn metal deposits on the anode while Br_2 forms at the cathode, complexing with Br^- to form soluble Br_3^- species. This highly reversible reaction leads to high cycle life (full depth of discharge) with daily cycles for 10 years (flow battery) and 20 years (static, sealed cells).

There are other promising variations of Zn-based batteries, presently still in development, which use slightly acidic or neutral pH electrolytes and rely on protons or Zn ions to balance charge during electrochemical cycling (in some cases, these batteries may be considered Zn-ion batteries).

Current Commercial Usage

Primary alkaline Zn-MnO_2 batteries and Zn-air batteries remain widely used today to power smaller portable consumer electronics. Emerging demonstrations and deployments of grid-scale Zn-MnO_2 batteries include backup power (assurance), grid stabilization, and renewable solar integration (particularly for microgrids) for both residential and commercial applications. Larger deployments are exemplified by Urban Electric Power’s 1 MWh alkaline battery backup system for the San Diego Supercomputer Center. Static Zn-Br systems are also finding traction for microgrids, behind-the-meter applications (e.g., peak shifting), and renewables integration. An EOS Zn-Br system is planned to provide 35 MWh of storage, capable of 10 hours of discharge, as part of a 60 MWh solar-plus-storage microgrid developed by Indian Energy (Southern California). Technology providers also envision grid applications, including transmission upgrade deferrals, congestion management, and resiliency. Information about Zn-Br flow batteries (such as those manufactured and deployed by Australian company RedFlow) can be found in the companion Technology Strategy Assessment: Flow Batteries, released as part of SI 2030. Companies such as Zinc8 Energy Solutions and e-Zinc are developing Zn-air batteries for microgrids and both commercial and residential behind-the-meter applications, including energy cost reduction, renewables integration, and power quality. Although not yet deployed, these systems, which target up to 24 hours of discharge duration, are beginning to see demonstrations, such as e-Zinc's planned 40 kW system supporting a 1 MW solar array in Camarillo, CA. Zn-ion batteries, which are touted as a potentially more sustainable alternative to Li-ion batteries, are in development by companies such as Salient Energy (Canada) and Enerpoly (Sweden). Finally, Zn-Ni systems have identified stationary storage markets that support data centers and telecom industries, although there may be emerging applications in defense-related mobility and commercial aerospace as well. ZincFive (Tualatin, OR) markets a series of commercial Zn-Ni batteries for applications such as non-interruptible power supply, backup power, and starting batteries. U.S. developer ZAF Energy (also developing Zn-air) is developing Zn-Ni batteries as potential replacements for lead-acid and even some lithium-ion batteries in industrial, distributed energy, and mobility applications. AEsir Technologies, a spinoff of ZAF Energy, is building a 600,000-square-foot gigafactory in Rapid City, SD, to meet expected growing demand. Meanwhile, companies such as EnZinc are working to develop specialized porous Zn anodes that are initially targeting Zn-Ni battery applications but could ultimately enable a wider variety of Zn-based batteries, including Zn-MnO_2 or Zn-air.

Baseline Costs

Although there are several Zn batteries in active commercial development and in the early stages of deployment, market penetration today remains relatively immature, with significant opportunity for growth as the technical and economic landscapes for Zn-battery storage evolve. In order to understand this landscape and identify potentially impactful investment opportunities to advance Zn battery development, it is necessary to assess the current research and development (R&D) trajectory and project performance and cost parameters out to 2030, assuming no marginal increase in R&D investment over currently planned levels. These values, presented in Table 1, represent the baseline against which all future impacts can be measured. The cost and performance values are derived exclusively from the 2022 *Grid Energy Storage Technical Cost and Performance Assessment* by V. Viswanathan et al. [13], as defined for a 100 MW, 10-hour Zn battery system. Note that capital cost values differ in terms of their unit of measurement, with some (e.g., controls and communication, power equipment) tied to the power capacity of the system and others (e.g., storage block capital costs) tied to energy capacity. The 2030 levelized cost of storage (LCOS) estimate from V. Viswanathan et al. [13] is $0.17/kWh; however, that estimate includes approximately $0.02/kWh in energy costs. The 2030 LCOS estimates presented in the next section exclude energy costs, except those associated with losses, and are based on a slightly different methodology, which results in a baseline LCOS of $0.15/kWh.

Table 1. Zn battery cost and performance (2030 estimates)

Parameter	Value	Description
Storage Block Calendar Life	17	Deployment life (in years)
Cycle Life	6,508	Base total number of cycles
Round-trip Efficiency (RTE)	74%	Base RTE

Storage Block Costs	212.58	Base storage block costs ($/kWh)
Balance of Plant Costs	27.90	Base balance of plant costs ($/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	Base fixed O&M costs ($/kW-year)

Pathways to $0.05/kWh

Having established baseline costs for 2030, the Framework Team worked with industry and Zn battery technical experts to assess the gaps in R&D investments that might establish a pathway to an LCOS of $0.05/kWh for Zn batteries. A group of 29 subject matter experts (SMEs) were identified and contacted (see Appendix A). These SMEs represented 19 organizations, ranging from industry groups incorporating various aqueous Zn technologies (from neutral/mildly acidic to alkaline battery manufacturers) to vendors (additive suppliers), universities, and National Laboratories. All but two of the identified groups participated in interviews where the Framework Team solicited information regarding pathways to innovation and associated cost reductions and performance improvements. For all SMEs, *long-duration energy storage* (LDES) was defined as 10 hours of storage. The innovations defined by the SMEs are presented in Table 2. Definitions of each innovation are presented in Appendix B. The Monte Carlo analysis below is based on feedback from ten of these groups (including the two that were not interviewed).

Table 2. Taxonomy of innovations

Innovation Category	Innovation
Raw materials sourcing	Mining and metallurgy innovations for battery-grade Zn metal
Supply chain	Supply chain analytics for sustainable sourcing
	Inactive materials cost reduction
Technology components	Separator innovation
	Pack/System-level design
Manufacturing	Implementation of manufacturing best practices
	Developing a manufacturing ecosystem
Advanced materials development	Improved Zn metal performance
	Cathode materials optimization and new materials discovery
	Advanced electrolyte/additive development
Deployment	Standardization of testing and safety requirements
	Demonstration projects
End of life	Enhancing domestic recycling

Input from SMEs was used to define the investment requirements and timelines for investment, the potential impacts on performance (e.g., RTE, cycle life), and the cost (e.g., storage block, balance of plant, operations and maintenance) for each innovation. The Monte Carlo simulation tool then combined each innovation in portfolios containing three to seven other innovations and, based on the range of impacts estimated by the industry, the tool produced the distribution of achievable outcomes by 2030 with respect to LCOS (Figure 1). The LCOS range with the highest concentration of simulated outcomes is in the $0.08/kWh to $0.10/kWh range, with the highest impact portfolios (greatest LCOS reduction) resulting in an LCOS between $0.079/kWh and $0.085/kWh (the top 10% are indicated by the marked region). The narrow distribution of outcomes broadly suggests that almost all interventions identified will result in impactful reductions to the LCOS of Zn battery technologies (relative to the $0.17/kWh baseline projected cost), although no subset of the interventions identified result in an LCOS less than the DOE target of $0.05/kWh.

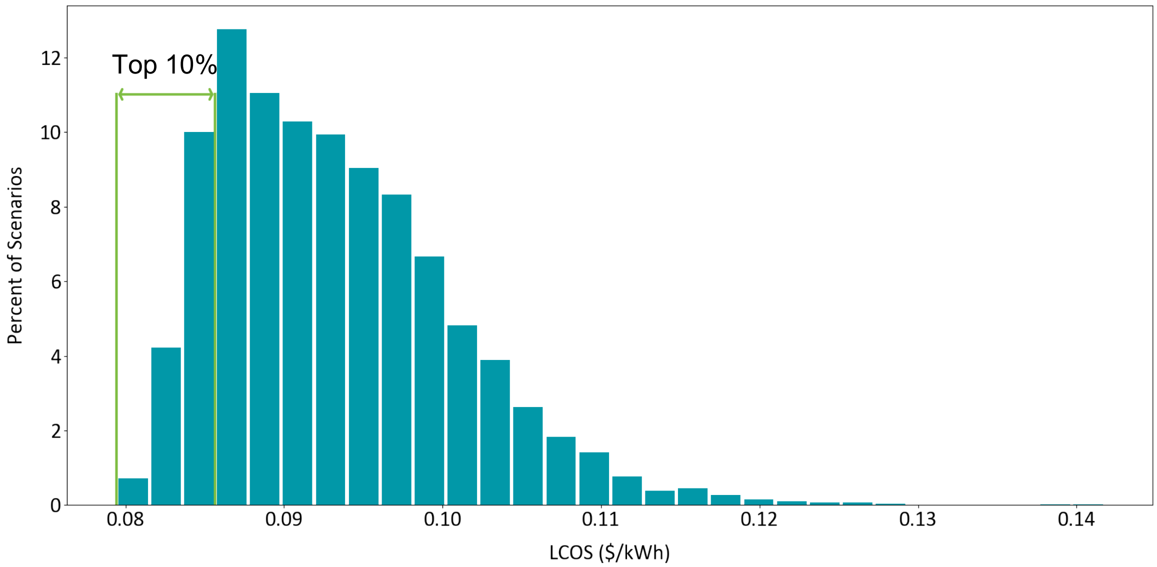

Figure 1. Portfolio frequency distribution across LCOS with the green rectangle indicating the top 10% of the portfolios

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 2. This plot correlates the simulated highest LCOS impact portfolios with the total investment needed to realize that impact. The dots at the top of the chart demonstrate that the top 10% of the portfolios reach their lowest level at an LCOS of roughly $0.08/kWh. The vertical green line demonstrates that the mean investment level required for these portfolios is $155 million. This value represents the marginal investment over currently planned levels required to achieve the corresponding LCOS improvements. The highest density of portfolios in the top 10% are in the $120 million to $150 million range. Not shown on the plot, but indicated in the simulations, is that the estimated timeline required to achieve these LCOS improvements is 5 to 7 years.

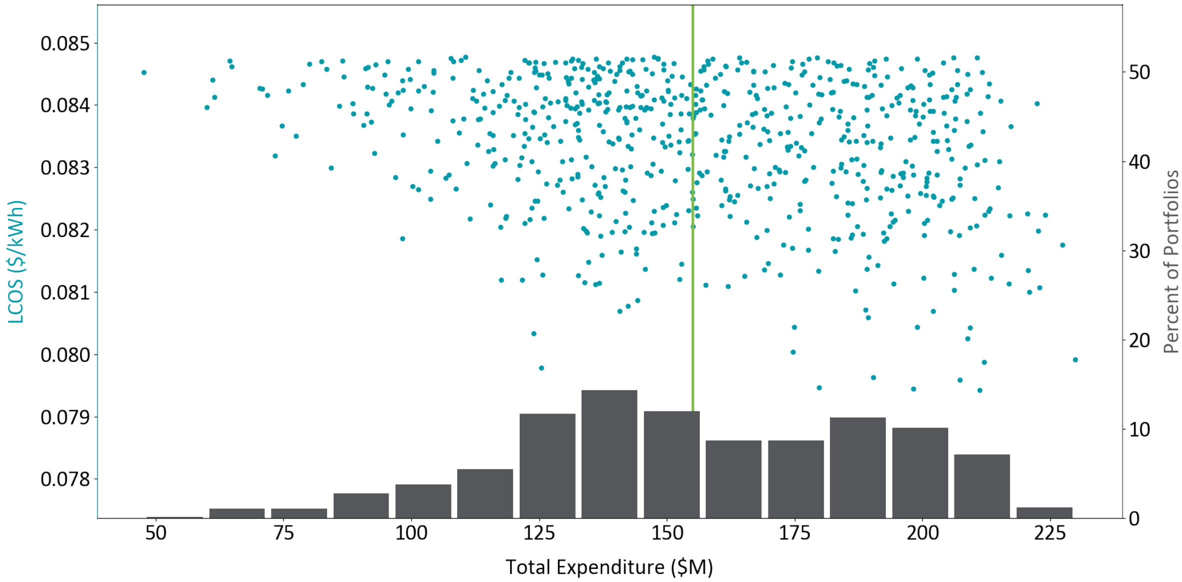

Figure 2. LCOS and estimated industry expenditures for the top 10% of the portfolios. The vertical green line shows the mean portfolio cost.

Note that the impact of each layered innovation is not additive. The impact of each additional innovation is weighted to determine the combined impact. Combinations of investments can be in conflict with or relate to alternative sub-chemistries, thus diminishing their combined impact. Working with SMEs, the research teams established innovation coefficients that are used to measure combined impact.[a] Innovation coefficients for each innovation pairing are presented in Appendix C.

SMEs were also asked for their preferences regarding the investment mechanism, choosing among National Laboratory research, R&D grants, loans, and technical assistance. Table 3 presents the SME preferences for each mechanism. In most cases, a mixture of R&D grants and National Laboratory research were supported, with R&D grants slightly preferred in most cases. There were also indications of support for loans for enhanced domestic recycling, technical assistance funding to support supply chain analytics for sustainable sourcing, and the development of a manufacturing ecosystem and the implementation of manufacturing best practices.

Table 3. SME preferences for investment mechanisms. Cells with asterisks (*) represent more preferred mechanisms. (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 for battery-grade Zn metal	30%	40% *	10%	20%
Supply chain analytics for sustainable sourcing	20%	30%	10%	40% *
Inactive materials cost reduction	25%	42% *	8%	25%
Separator innovation	29%	50% *	7%	14%
Pack/System-level design	20%	47% *	20%	13%

[a] To demonstrate how innovation coefficients work, the innovation coefficient for the combined investment in mining/metallurgy innovations for battery-grade Zn metal and enhanced domestic recycling is 0.15, which means that the Monte Carlo simulation tool would only include 15% of the defined impact of the second innovation (e.g., enhanced domestic recycling) when added to the first (e.g., mining/metallurgy innovations). The reason for the low coefficient for these innovations is 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, while a coefficient of 0 means that the second investment would add no additional value.

Implementation of manufacturing best practices	9%	27%	27%	36% *
Developing a manufacturing ecosystem	0%	33% *	33% *	33% *
Improved Zn metal performance	43%	57% *	0%	0%
Cathode materials optimization and new materials discovery	42%	58% *	0%	0%
Advanced electrolyte/additive development	50% *	50% *	0%	0%
Standardization of testing and safety requirements	38% *	23%	8%	31%
Demonstration projects	19%	44% *	19%	19%
Enhancing domestic recycling	19%	25%	31% *	25%

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 3. As discussed in the next section of this report, while there are some basic research-focused innovations that appear to hold great promise for reducing cost and improving performance at modest investment levels (e.g., cathode materials development and improved Zn metal performance), these investments alone will not reach the deep reductions in LCOS targeted by the Energy Storage Grand Challenge.

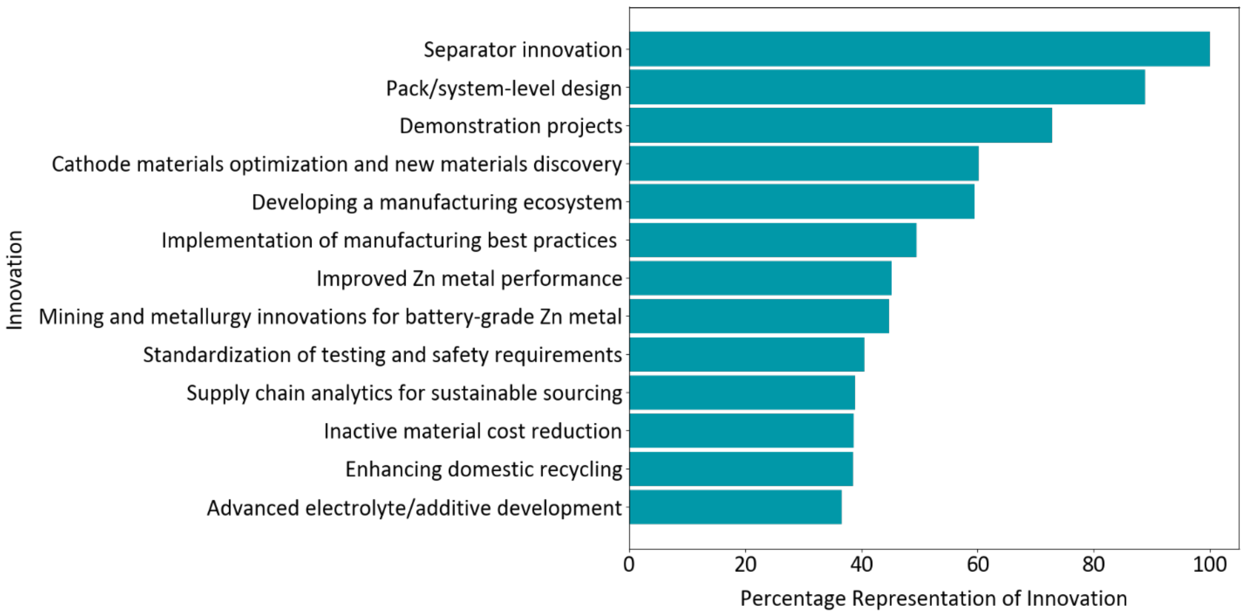

Figure 3. Innovation representation in the top 10% of the portfolios

R&D Opportunities

Together, the Framework Study and Flight Paths listening session with the Zn battery industry and industry-informed experts identified critical R&D needs and opportunities to advance the commercialization and widespread deployment of Zn-based batteries, particularly for stationary storage.

The Flight Paths listening session presented guiding questions around Zn battery challenges and opportunities to active representatives from the Zn-MnO_2, Zn-Air, Zn-Br (flow), Zn-Ni, Zn-ion, and Zn anode and supply chain industries. Technologies were rated with an average technology readiness level of 5.7/9 and an average manufacturing readiness level of 4.4/9, suggesting an intermediate level of commercial development for the field as a whole. These values, however, were a reflection of both the emerging technologies described above and those already in early deployment. These values are expected to shift, however, as battery scale, performance, and cycle life (metrics linked to deployability) grow through continued R&D. As mentioned above, some of these technologies are sufficiently mature to manufacture and deploy as commercial systems today, although continued technical advances will also accelerate their future deployability.

When discussing impediments limiting widespread Zn battery deployment, the most significant technical hurdle identified was battery cycle life and the material components that affect cycling efficiency and lifetime. Another concern was effective, safe management of evolving gas, which is an issue tied to many aqueous batteries.

Interestingly, participants also identified what *other* technology providers might say were the limitations of Zn-based batteries, which included technical issues around battery cycling performance, lifetime, and especially energy density. Energy density was identified as only a minor concern by the industry experts in the field, which reveals a disconnect between what the battery community and the Zn battery industry understand about these batteries. This disconnect highlights an opportunity for education and public relations regarding Zn-based batteries. Improved awareness and understanding of Zn batteries, including their virtues and limitations, were seen as a potentially valuable tool to improve market availability and motivate the development of more Zn-suitable and effective safety regulations, standards, and deployment policies.

When discussing the “pre-competitive” innovations that could advance Zn-based batteries, a mix of both technical and non-technical opportunities were identified. (Non-technical opportunities will be described in the next section.) The most desirable technical innovations included electrolytes, cathodes, and separators, which again correlate with the prioritized impact of the components that impact cycle life efficiency and lifetime, as mentioned above. Although the specific nature of these innovations varied by technology, (for example, Zn-Air has different cathode challenges than Zn-MnO_2), common themes arose around these battery material components. These three components (electrolytes, cathodes, and separators) were further highlighted when the group identified the components of Zn batteries that would benefit most from DOE/National Laboratory technical assistance. Curiously, in the Framework Study, Zn anode performance was recognized as a battery innovation element with “great promise for reducing cost and improving performance at modest investment levels” (see Figure 3 and Table 4). This potential impact does not align well with the Flight Paths findings, which indicated that anode development was not an area where DOE/National Laboratory involvement was prioritized. One interpretation of this apparent inconsistency could be that this community does not perceive this topic as pre-competitive, or that it is not a particularly limiting technical component of the battery today (i.e., other, more immediate concerns simply outweigh the importance of optimizing the anode, despite the potential impact of such innovations). As important as the anode may be, it is also conceivable that the battery innovators believe that challenges related to the anode can be handled internally, the technical challenges may have been addressed already, or the anode challenges may be addressed through complementary innovations in electrolyte and separators. It is recognized that any electrolyte innovation or advance would be intimately involved with the function of the Zn anode (and cathode). Thus, while the responses at the component level are informative, the full function of the battery is the ultimate objective and is reflected by the collective, potentially collaborative, impact of the component innovations.

These technical innovation elements, which represent the fundamental elements of a battery, reflect the reality that these companies are pressing forward with technologies as they stand today. *Importantly, there remains a clear NEED to prioritize continued R&D beyond basic engineering and minor technical optimization.* If they are to succeed in industry over the longer term, as markets change and demands on storage systems evolve, these technologies must be able to evolve and adapt. Absolutely central to that evolution is a robust technical, scientific foundation continually generated and updated by high-quality, application-focused fundamental research.

Additional Opportunities and Discussion

Beyond the specific technical challenges and opportunities, numerous non-technical challenges concerned the industry team and were raised in both the Framework and Flight Paths engagements. In the Flight Paths listening session, during the initial discussions around significant impediments that are limiting Zn battery deployment, non-technical hurdles, such as funding (particularly around capital investments), were a priority. In fact, this point was reiterated as a major concern because the group identified capital investment at a level of $25 million to $100 million as one of the most significant issues that "keeps the [chief technology officer and chief executive officer] up at night." Notably, these values bridge the large-scale investments from Figure 2 above ($120 million to $150 million) and the activity-specific investments from Table 4 below ($5 million to $20 million). These agreeable values collectively show that large investments (possibly from multiple sources) will be essential for advancing Zn battery commercialization.

Many of the other non-technical issues, such as manufacturing, demonstrations, regulations and safety, supply chain, and end-of-life considerations, have already been called out in the Framework discussion; however, these issues were also raised in the Flight Paths listening session, and there were numerous parallels between the two efforts.

With respect to safety regulations, standards, and policies, many participants noted that these aspects of battery development are disproportionately designed and implemented with a nearly exclusive focus on lithium-ion batteries. Because Zn-based batteries present inherently different chemistries and performance metrics, forcing Zn-based batteries into the Li-ion requirements matrix was seen as limiting, expensive, and ineffective. Some of the key needs identified included a standardized set of cycling protocols, performance requirements, and installation guidelines for different *long-duration storage use cases* (e.g., few versus tens of hours versus 100-hour storage, relevant charge/discharge rates, temperature ranges) rather than imposing short-duration standards and protocols on non-Li-ion, LDES-targeted chemistries. This challenge applied not only to developed batteries but also material supply chain and associated Toxic Substances Control Act (TSCA) requirements. In addition to Li-ion incumbency in the industry, another concern over long interconnect application queues was raised. The current wait time, which is on the order of years, is recognized as a major limiting factor for implementing all emerging technologies.

The discussions about supply chain extended beyond the Li-ion constraints, although there was a mixed response from participants as to whether there was a supply chain concern for Zn batteries. It was recognized that although Zn metal is a globally abundant and inexpensive material, "battery-grade" Zn is not always seen as readily and domestically available, or current supply chains are consumed/dominated by other industries (Zn primary batteries or steel) and many of these supply chains currently are not domestic. There was also some recognition that supply chain and end of life or recycling should be considered as part of a more comprehensive manufacturing ecosystem that remains immature today. There was agreement, however, that as markets grow and the scale of manufacturing increases, this ecosystem is likely to mature. Identifying strategies to repurpose or leverage existing battery manufacturing infrastructure/expertise and to introduce greater automation to manufacturing as that ecosystem matures would help to increase efficiency, limit waste, and reduce timelines to large-scale manufacturing and deployment.

Access to crucial workforce capacity, along with manufacturing, were identified as challenges central to both developed and emerging manufacturing. Many of the workers with expertise in batteries and related technology production are not located in the United States, even if they were trained in the United States (e.g., foreign graduate students). For the remaining domestic workforce, there is competition for workers from both established (Li-ion, Pb-acid) and emerging battery technologies. Prioritizing increased training and education for battery storage (on the whole) would help meet Zn battery workforce needs.

Beyond engaging DOE or National Laboratories with R&D opportunities, there was significant interest in cooperation with DOE to enable demonstration projects and validation/testing sites or to develop cost-modeling tools, analogous to Li-ion resources, such as BatPac. There was additional desire to form Zn-centric consortia or increase engagement with existing consortia like those in development by organizations such as NAATBatt. Public investment in Zn battery science and technology has been modest compared with the scale of the investments in Li-ion batteries. Thus, even modest incremental investments—ranging from fundamental science, as noted above, to tools for those interested in moving technologies to products—would be useful. These activities could be enabled through consortia with multiple companies participating, appropriate academic partners, and taking advantage of DOE and National Laboratory technical and analytics expertise. A small minority of the companies could speak to successful DOE relationships; however, the majority of the respondents were unaware of what DOE resources were available to them, indicating an opportunity to improve community awareness of existing capabilities and expertise available throughout DOE. For those who had tried to work with DOE, there was some concern that the processes for contracting were cumbersome and often prohibitive. Finding pathways to streamline and incentivize collaboration between industry and DOE/National Laboratories would be desirable.

Regarding Zn potential for LDES applications, most participants indicated that a Zn battery technology capable of 10+ hours discharge duration would be produced within 3 years. Moreover, participants indicated that, within the next 3 years, many companies were targeting 4 hours to 12 hours of storage and a few others indicated that they were targeting more than 12 hours of storage. Other participants indicated that they were working toward applications that would compete with other current markets, such as 2 hours to 4 hours of storage, currently dominated by Li-ion. These trends reflected a significant, articulated belief that Zn-based batteries are well suited to LDES, provided they can meet key long-duration performance metrics, such as cycle life on a large scale. The 3-year target for LDES deployment is slightly lower than innovation impact timelines indicated in Table 4. This difference suggests that many of the innovations and improvements proposed may be aimed at later generations or evolving technologies.

Among the significant challenges to realizing the deployment of LDES goals was a poorly defined, immature stationary storage market space that is currently dominated by the Li-ion industry. Some of this market is defined by market policies, which, again, are largely geared toward shorter-duration Li-ion technologies at present. Future revisions to market rules and policies could take full advantage of the capabilities in new technologies. The degree of renewable energy deployment was also identified as an expected market driver for larger-scale, longer-duration storage. Integrating renewables with the storage during this market evolution may help to achieve more efficient and optimal mating of storage capabilities with market needs. Consideration of "the total system" could factor in all of the benefits, challenges, lifecycle, manufacturing, and evolving application needs of a system as priorities and strategies for storage integration are developed. Finally, recognizing that the markets, storage needs, and demands on technology change, it is once again clear that the fundamental R&D underpinning anticipated responsive, adaptive technological solutions must remain a priority.

As presented in Table 4, the Framework Study revealed that separator innovations, cathode materials optimization, improved Zn metal performance, and pack/system-level design for Zn batteries consistently yielded metrics in the top tier, which is designated with asterisks (*). Daggers (†) represent mid-tier metrics and double daggers (‡) represent the lowest tier. Separator innovations were the largest contributor to a reduced LCOS for Zn 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 promising innovations have broad 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 4. Impacts of proposed R&D investment levels, investment requirements, and timelines. Cells with asterisks (*) represent top-tier effects, cells with daggers (†) represent mid-tier metrics, and double daggers (‡) represent the lowest tier.

Innovation	Storage Block Cost Impact (%)	Cycle Life Improvement (%)	Round-trip Efficiency Impact (%)	Mean Investment Requirement (in million $)	Mean Timeline (years)
Mining and metallurgy innovations for battery-grade Zn metal	-20.3% ‡	0.0% ‡	0.0% ‡	16.3 ‡	4.4 †
Supply chain analytics for sustainable sourcing	-16.3% ‡	0.0% ‡	0.0% ‡	11.4 †	2.6 *
Inactive materials cost reduction	-27.5% †	50.0% †	0.0% ‡	7.7	2.7 *
Separator innovation	-51.7% *	195.7% *	20.0% †	11.7 †	4.2 †
Pack/System-level design	-28.0% *	35.0% †	12.5% †	16.0 †	3.5 *
Implementation of manufacturing best practices	-21.5% †	110.0% *	2.0% ‡	24.4 ‡	3.4 *
Developing a manufacturing ecosystem	-24.1% †	50.0% †	0.0% ‡	64.2 ‡	5.6 ‡
Improved Zn metal performance	-30.0% *	242.1% *	30.0% *	8.4 *	4.4 †
Cathode materials optimization and new materials discovery	-28.3% *	430.0% *	6.7% †	9.0 †	4.8 ‡
Advanced electrolyte/additive development	-5.0% ‡	217.1% *	26.7% *	7.8 *	4.4 †
Standardization of testing and safety requirements	-5.0% ‡	0.0% ‡	0.0% ‡	3.9 *	3.6 †
Demonstration projects	-27.5% †	100.0% †	60.0% *	57.4 ‡	4.9 ‡
Enhancing domestic recycling	-4.0% ‡	0.0% ‡	0.0% ‡	23.6 ‡	4.4 †

The recommended investment levels and timeline by innovation are also identified in Table 4. Most investments required are in the $5 million to $20 million range over a period of 3 to 5 years. Developing a manufacturing ecosystem, establishing demonstration projects, implementation of best practices, and enhanced recycling require significant investments in industrial processes and project development, and therefore require more capital and time. A pattern that emerges is that there are several innovations that yield impactful outcomes at relatively low investment levels, including improved Zn metal (anode) performance, cathode materials optimization, separator innovation, pack/system-level design, and inactive materials cost reductions. Investment in these innovations, along with those in electrolyte/additive development and the standardization of safety requirements, would yield solid reductions in LCOS at a modest required investment level. Activities that could help reach the $0.05/kWh target include demonstration projects that involve the development and validation of advanced controls and management systems, as well as the development of a manufacturing ecosystem to support the deployment of technologies at scale.

Although the needs, opportunities, and priorities of each Zn-based battery are unique and complex, there are some specific topics that emerged as *potential* priority focus areas in both the Framework Study and the Flight Paths listening session. Although it may be an overly broad prioritization, Flight Paths may be seen as providing a qualitative sense of where the industry sees needs and opportunities for collaborative advancement of technology, while the Framework Study provides a numerically-derived assessment of what innovations, advances, or developments may offer timely, cost-effective, and meaningful impact toward battery manufacturing and deployment. Summarized in Table 5, cathodes, separators, and electrolytes were seen as common R&D areas where there is both need (Flight Paths) and modeled impact (Framework) for innovation. The potentially significant impact of the anode registered in the Framework Study did not align with the Flight Paths input from industry. As mentioned above, anode development may be a potentially high-impact battery component, but it may not be an explicit pre-competitive area where industry is seeking assisted innovation. In the non-technical areas, the Flight Paths and Framework Study showed more distinction. Flight Paths participants voiced a greater emphasis on DOE-enabled education; improved relevance of codes, standards, and validation; greater access to demonstrations; and an emphasis on community engagement/collaboration. The Framework Study also identified demonstrations as a common source of impactful opportunity; however, other non-technical impact areas related to the practical production of batteries were highlighted. Topics such as manufacturing, system designs, and inactive materials cost reductions were emphasized priorities. These topics should not be taken as exclusive priorities because key issues around the supply chain and workforce were also highlighted as priorities, albeit less significant. Ultimately, these studies have provided key insights into what industry and other experts working in Zn batteries recognize as key gaps and opportunities to advance Zn-based batteries. These insights may prove to be valuable in identifying areas where DOE can engage and enable battery development—ranging from funding basic science to enabling agile, evolving technologies to supporting large-scale demonstrations and deployments as technologies mature.

Table 5. Summary of key opportunities identified from both the SI Framework and Flight Paths

	R&D Technical Innovations	Non-Technical Advances
Flight Paths	Cathodes Separators Electrolytes	Education (public relations for Zn batteries) Zn-Specific Codes, Standards, Requirements, and Validation (not force-fit to Li-ion) Demonstrations/Validation Resources Industry Cooperation (consortium/engagement with DOE/U.S. Department of Defense)
Framework	Separators Cathodes Zn Anodes Electrolytes	Improved/Supported Manufacturing Pack/System-Level Design Demonstration Projects Inactive Materials Cost Reductions

Appendix A: Industry Contributors

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

Participant	Institution
Erik Spoerke	Sandia National Laboratories
Tim Lambert	Sandia National Laboratories
Amy Marschilok	Stony Brook University
Dan Steingart	Columbia University
Debra Rolison	United States Naval Research Laboratory
Ryan DeBlock	United States Naval Research Laboratory
Jeffrey Long	United States Naval Research Laboratory
Xingbo Liu	West Virginia University
Rohan Akolkar	Case Western Reserve University
Kang Xu	United States Army Research Laboratory
Nian Liu	Georgia Institute of Technology
Chungsheng Wang	University of Maryland
Sanjoy Banerjee	Urban Electric Power
Jinchao Huang	Urban Electric Power
Gautam Yadav	Urban Electric Power
Onas Bolton	Octet Scientific
Josef Daniel-Ivad	International Zinc Association
Frank Goodwin	International Zinc Association
Francis Richey	Eos
Michael Burz	EnZinc
Meinrad Mahler	EnZinc
Michael Galluzzo	EnZinc
Philip Baker	EnZinc
Sasha Gorer	Zelos Energy
Simon Fan	Zinc8 Energy Solutions
Steve Edley	Zinc8 Energy Solutions
Brian Adams	Salient Energy
Feng Zhao	Storagenergy Technologies
Konstantin Tikhonov	Imprint Energy

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	Mining and metallurgy innovations for battery-grade Zn metal
Supply chain	Supply chain analytics for sustainable sourcing
Technology components	Inactive materials cost reduction
	Separator innovation
	Pack/System-level design
Manufacturing	Implementation of manufacturing best practices
	Developing a manufacturing ecosystem
Advanced materials development	Improved Zn metal performance
	Cathode materials optimization and new materials discovery
	Advanced electrolyte/additive development
Deployment	Standardization of testing and safety requirements
	Demonstration projects
End of life	Enhancing domestic recycling

Mining and metallurgy innovations for battery-grade Zn metal: Innovations such as hydrometallurgical processes and mining ores at sufficient scale for producing battery-grade Zn metal.

Supply chain analytics for sustainable sourcing: Supply chain analytics to identify opportunities for sourcing of precursor materials (custom salts, binders, etc.) for cell assembly and the chemicals required for developing next-generation electrolyte additives for improved performance.

Inactive materials cost reduction: System-level design or materials innovation to reduce the cost of inactive materials (e.g., current collectors, cell housing, battery management system, busing).

Separator innovation: Materials innovation to reduce the cost and/or improve the performance of separator technologies. This includes the integration of materials from other electrochemical systems (e.g., Pb-acid, fuel cells), the development of new separators with selective transport properties and improved conductivity, or other innovations that drive down the cost of materials.

Pack/System-level design: Optimization of cell architectures specific to Zn chemistries, rather than relying on existing architectures (e.g., Li-ion, Pb-acid) to reduce the required cell infrastructure (e.g., battery management system requirements) relative to existing systems.

Implementation of manufacturing best practices: Increased automation, waste reduction, adapting existing infrastructure (e.g., idled Pb-acid plants), and the integration of best practices from existing manufacturing modalities (e.g., Pb-acid, Li-ion).

Developing a manufacturing ecosystem: Supplier engagement for critical component manufacturing at relevant scales and overall standardization of critical system components to de-risk component development for suppliers and manufacturers.

Improved Zn metal performance: Electrode architecturing for improved morphology control, alloying concepts, and other innovations that suppress dendrite formation and improve the performance of the Zn metal anode. This does not include electrolyte design.

Cathode materials optimization and new materials discovery: Discoveries that enable improved performance of existing cathode materials (e.g., enabling two-electron transfer for

MnO_2), the discovery of new materials (e.g., reversible Zn intercalation cathodes for Zn-ion), and the discovery of new catalysts/electrode architectures that can enable improved performance (e.g., for Zn-air, Zn-Br).

Advanced electrolyte/additive development: New electrolyte chemistries/additives for improved electrode reversibility (anode and cathode), enhanced temperature stability, higher voltage operation, and other innovations that improve the performance or decrease the cost of the overall system.

Standardization of testing and safety requirements: Development of standardized cycling protocols for different long-duration storage use cases (e.g., few versus tens of hours versus 100-hour storage, relevant charge/discharge rates), the definition of other performance requirements (e.g., high/low temperature stability, acceptable self-discharge rates), and Zn-specific installation guidelines that are not derived from Li-ion best practices (e.g., battery management system requirements). This also includes expanded testing infrastructure, improved access, and a lower cost for testing capabilities.

Demonstration projects: 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.

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

Appendix C: Innovation Coefficients

Table C.1. Innovation coefficients

Innovation	Mining and metallurgy innovations for battery-grade Zn metal	Supply chain analytics for sustainable sourcing	Inactive materials 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 materials 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	–

Appendix D: Descriptive Statistics for Individual Innovations

Table D.1. Descriptive statistics for individual innovations

Innovation_cat	Innovation	Investment_low	Investment_high	Investment_mean	Investment_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 for battery-grade Zn metal	4.00	28.67	16.33	19.44	1.75	7.00	4.38	3.42	-0.05	-3.00	-0.67	1.30	0.00	0.00	0.00	0.00
Supply chain	Supply chain analytics for sustainable sourcing	3.00	19.75	11.38	16.21	1.60	3.60	2.60	1.51	-0.05	-3.00	-0.71	1.28	0.00	0.00	0.00	0.00
Technology components	Inactive materials cost reduction	1.30	14.00	7.65	15.15	1.67	3.67	2.67	1.37	-0.05	-2.00	-0.65	0.91	0.50	0.50	0.50	0.00
	Separator innovation	2.90	20.40	11.65	24.26	2.29	6.14	4.21	3.12	-0.25	-5.00	-1.92	2.67	0.20	5.00	1.96	1.85
	Pack/System-level design	3.20	28.80	16.00	30.12	1.86	5.14	3.50	2.41	-0.05	-5.00	-1.12	2.17	0.20	0.50	0.35	0.21
Manufacturing	Implementation of manufacturing best practices	5.30	43.40	24.35	40.04	1.79	5.00	3.39	2.42	-0.05	-3.00	-0.60	1.18	0.20	2.00	1.10	1.27
	Developing a manufacturing ecosystem	13.80	114.60	64.20	154.27	3.40	7.80	5.60	3.34	-0.01	-3.00	-0.63	1.18	0.50	0.50	0.50	0.00
Advanced materials development	Improved Zn metal performance	3.14	13.71	8.43	13.05	2.13	6.63	4.38	3.36	-0.30	-0.30	-0.30	0.00	0.20	10.00	2.42	3.76
	Cathode materials optimization and new materials discovery	4.00	14.00	9.00	12.97	2.25	7.25	4.75	3.61	-0.30	-0.50	-0.37	0.12	0.50	10.00	4.30	3.83
	Advanced electrolyte/additive development	2.43	13.14	7.79	13.31	2.13	6.63	4.38	3.36	-0.20	0.10	-0.05	0.21	0.20	5.00	2.17	2.00
Deployment	Standardization of testing and safety requirements	1.50	6.33	3.92	3.85	1.86	5.29	3.57	2.65	-0.05	-0.05	-0.05	0.00	0.00	0.00	0.00	0.00
	Demonstration projects	4.50	110.33	57.42	140.85	2.29	7.57	4.93	3.56	-0.05	-0.50	-0.28	0.32	1.00	1.00	1.00	0.00
End of life	Enhancing domestic recycling	3.83	43.33	23.58	3.8.16	2.29	6.57	4.43	3.37	-0.02	-0.05	-0.04	0.02	0.00	0.00	0.00	0.00

sbc = storage block cost, cyc = lifetime cycles

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