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Technology Strategy Assessment

Findings from Storage Innovations 2030
Sodium Batteries
July 2023

About Storage Innovations 2030

This technology strategy assessment on sodium 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.

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Authors

Erik D. Spoerke, Sandia National Laboratories

Venkat Durvasulu, Idaho National Laboratory

Hill Balliet, Idaho National Laboratory

Partners in Content Collection

Jagjit Nanda, SLAC National Accelerator Laboratory; Flight Paths

Jakob P. Meng, Idaho National Laboratory; Framework Study

Reviewers

Rebecca Glaser, Office of Clean Energy Demonstrations, DOE

Xiaolin Li, Pacific Northwest National Laboratory

Benjamin Shrager, Office of Electricity, DOE

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Background

High-Level History

Much of the attraction to sodium (Na) batteries as candidates for large-scale energy storage stems from the fact that as the sixth most abundant element in the Earth's crust and the fourth most abundant element in the ocean, it is an inexpensive and globally accessible commodity. Significant research and development of Na batteries date back more than 50 years. Molten Na batteries began with the sodium-sulfur (NaS) battery as a potential high-temperature power source for vehicle electrification in the late 1960s [1]. The NaS battery was followed in the 1970s by the sodium-metal halide battery (NaMH: e.g., sodium-nickel chloride), also known as the ZEBRA battery (Zeolite Battery Research Africa Project or, more recently, Zero Emission Battery Research Activities), also with transportation applications in mind [2]. Sodium-ion batteries (NaIBs) were initially developed at roughly the same time as lithium-ion batteries (LIBs) in the 1980s; however, the limitations of charge/discharge rate, cyclability, energy density, and stable voltage profiles made them historically less competitive than their lithium-based counterparts [3]. More recently, solid-state sodium batteries (SSSBs) have begun to emerge as candidate commercial products, although their applicability to large-scale, long-duration storage is not well established at this time [4].

Chemistries

Molten Na batteries, including both NaS and NaMH chemistries, employ a molten Na anode and a ceramic sodium-ion conducting solid-state separator, most commonly β"-alumina (or beta-alumina solid electrolyte [BASE]), but the molten cathode chemistries differ [5], [6]. Both chemistries typically operate at elevated temperatures (near 300°C) to ensure the molten state of the active materials and the high conductivity of the BASE. Descriptions of each class of molten Na battery are below, and a summary of key attributes is presented in Table 1.

Sodium-Sulfur (NaS) Batteries

During electrochemical cycling, traditional NaS batteries oxidize (discharge) and reduce (charge) Na at the anode and reversibly reduce (discharge) and oxidize (charge) molten sulfur (S) at the cathode. To balance these reactions, oxidized Na^+ shuttles between the electrodes through an ion-conducting ceramic separator and participates in the reversible formation of sodium polysulfides [6].

$$xS + 2Na \leftrightarrow Na_2S_x \ (3 \leq x \leq 5) \qquad E_{cell} \sim 2.08V \text{ at } 350°C$$

In recent years, a lower temperature (< 150°C) NaS system that employs dissolved, rather than molten, polysulfides has also been developed (Enlighten Innovations Inc., Calgary, Alberta, Canada, and Denver, CO) in a flow-cell configuration. This technology takes advantage of commercial NaSICON (Na Super Ion CONductor, nominally $Na_3Zr_2PSi_2O_{12}$) solid electrolyte manufacturing at scale, and although still in development, is targeting pilot-scale demonstrations in the near future.

Sodium Metal Halide (NaMH) Molten Salt Batteries

NaMH batteries (e.g., Sodium-Nickel Chloride [Na-$NiCl_2$ or ZEBRA]), like the NaS battery, rely on the oxidation and reduction of Na at the anode and utilize an ion-conducting ceramic separator; however, they rely on the reduction and oxidation of a nickel chloride/nickel-based cathode ($NiCl_2$/Ni). The Ni cathode typically takes the form of powders, suspended in a supporting metal halide molten salt "catholyte," traditionally $NaAlCl_4$ (sodium tetrachloroaluminate). These batteries

The range of LCOS for the top 10% performing portfolios (producing the lowest LCOS) is $0.23 to $0.28/kWh-cycle, representing 49% to 59% reductions. These portfolio LCOS values were constructed using the means of the distribution of Monte Carlo simulation results for the given portfolio. Therefore, if the realized innovation impacts are ultimately larger than the mean of the output, the LCOS reductions could be even larger than shown here. Figure 1 shows the histogram of LCOS for all portfolios from the simulation with the marked region representing the top 10% of best performing portfolios (lowest LCOS). More than 80% of the portfolios result in a 25% reduction of LCOS (versus the initial baseline estimates), which corresponds to $0.42/kWh.

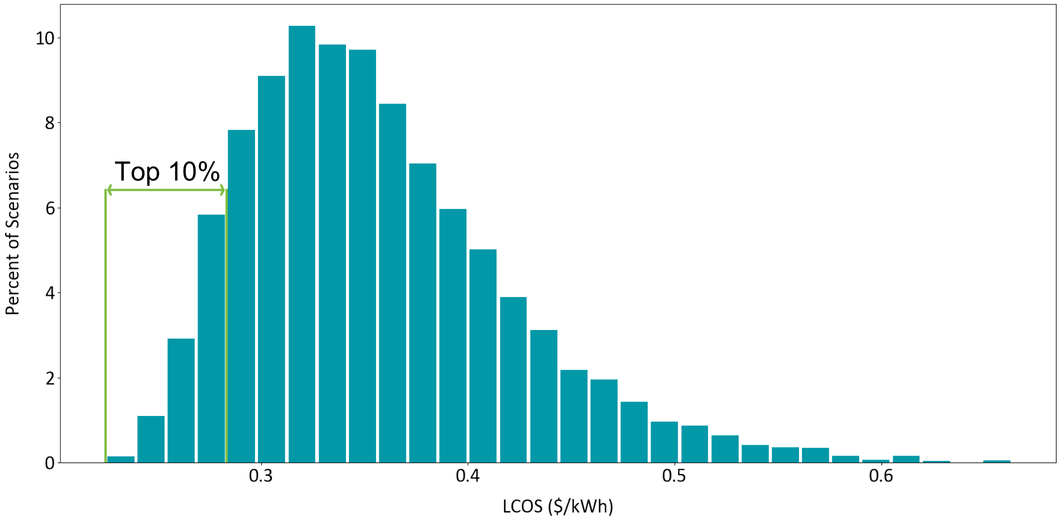

Figure 1. Distribution of effective LCOS based on the impact of all portfolios containing two to eight innovations per portfolio

The industry expenditure required by a top-performing portfolio would fall between $125 million and $362 million (Figure 2). The distribution of these portfolios suggests that the median would be around $273 million. Based on the simulation, we estimate that the top 10% of portfolios would take anywhere from 9 to 13 years to realize their potential. SMEs suggest that the technology is in an early stage and would require significant time and large financial investments to achieve the impacts suggested earlier.

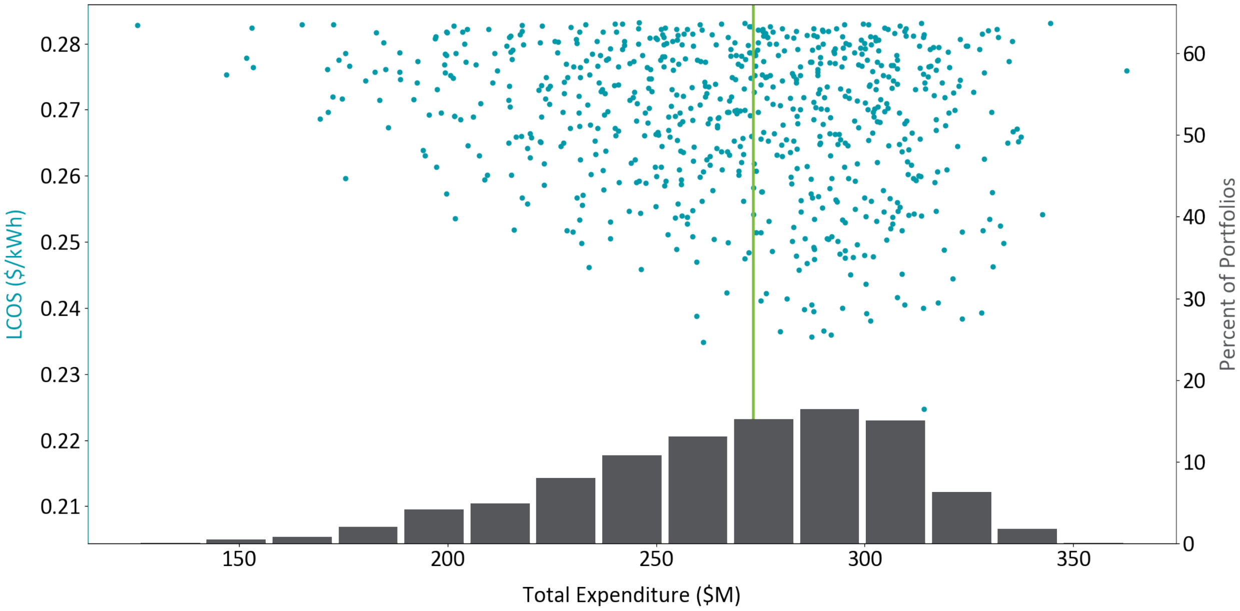

Figure 2. Scatterplot where each dot represents LCOS with respect to the industry expenditure of a portfolio from the top 10% performing portfolios aligned with the histogram representing the percentage of the top-performing portfolios (left y-axis) and the portion of portfolios within an expenditure bin (right y-axis)

The Framework Study SMEs were also asked which support mechanisms they believed to be most suitable or impactful. A summary is presented in Table 4. The cells with asterisks (*) indicate the most preferred investment mechanism.

Table 4. SMEs' preferences for investment mechanisms[b] (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). (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
Controllers to improve cycle life	44% *	33%	11%	11%
Cathode-electrolyte interface	50% *	50% *	0%	0%
Anode-less battery development	50% *	50% *	0%	0%
Aqueous Na-ion development	50% *	50% *	0%	0%
High-voltage cathode material development	40% *	40% *	10%	10%
Advanced materials discovery and development for anodes	50% *	50% *	0%	0%
In-operations materials science research	57% *	43%	0%	0%
Ceramic membranes	57% *	43%	0%	0%
Electrolyte development	36% *	36% *	9%	18%
Volume/Mass production for grid-scale deployment	9%	27%	36% *	27%
Pilot/Sub-pilot demonstrations	25%	25%	33% *	17%
Grid-scale Na-ion pilot testing	8%	33% *	33% *	25%
Lifetime/Lifecycle modeling and prediction	50% *	13%	13%	25%

Figure 3 presents the relative representation of each of the innovations across the top-performing (lowest LCOS) innovations for NaIBs. As mentioned earlier in this report, each portfolio consists of two to eight innovations. The data reveal a strong emphasis on materials and chemistry research, prioritizing cathode and electrolyte research, as well as in-operations materials science research, among all of the top-performing portfolios. Anode development, ceramic membrane innovation, and

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[b] Values sum all responses available and total ~100%. Slight deviations from 100% reflect rounding errors from the small sample size.

aqueous chemistry were other, less significant materials-related innovations in this population. These results indicate a need for more fundamental research, although it should be noted that this result reflects the perspectives of a pool of SMEs primarily comprising National Laboratories or universities. Nevertheless, there was also some significant emphasis on commercialization-relevant innovations, related to manufacturing and mass production, grid-scale testing or pilot-scale demonstrations, controller development, and lifecycle analyses. Ultimately, however, the more dominant emphasis on technology development over technology manufacture/deployment is consistent with the recognition that NaIBs are a relatively immature commercial technology at this time. The distribution of priorities would be expected to change as commercial, large-scale manufacturing matures.

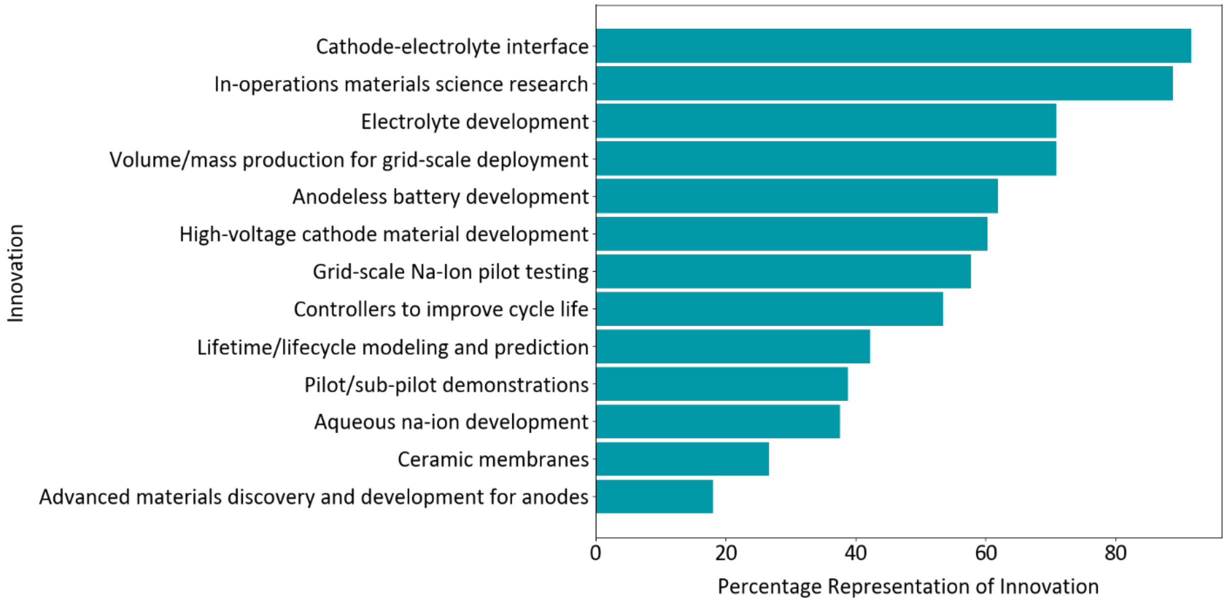

Figure 3. Representation of innovations in portfolios performing in the top 10% (resulting in the least LCOS)

R&D Opportunities

The input collected from both the FPLS and the Framework Study reflects expert insights from both industry and non-industry researchers into key R&D gaps and opportunities, which are central to the advancement of diverse Na battery technologies aimed at stationary storage. It should be noted, however, that because NaIBs, in particular, have potential applicability to electric mobility, there would be some expected overlap with development for complementary, mobility-driven use cases.

Contributor Backgrounds

As discussed above, FPLS collected insights from industry participants in NaS, Na-NiCl$_2$, NaIBs, PBA-NaIBs, and SSSBs, as well as the Na Battery Supply Chain and Battery Recycling. It also included representatives from both current battery manufacturers and U.S. companies whose Na batteries did not succeed domestically. In descending order of share, participants represented molten Na batteries (e.g., NaS, NaMH), NaIBs, and SSSBs. These participants represented a mix of U.S. and international companies (many with a U.S. presence). The technologies they represented spanned technology readiness levels (TRLs) from ~4 to 9, with an approximate average TRL of 7. The approximate average manufacturing readiness level (MRL) was also 7, indicating a fairly mature technical space among the diverse technologies and an international presence among those participating in the FPLS.

Storage Application Focus

When asked about targeted battery discharge durations within the next 3 years, many participants indicated 4 to 8 hours of discharge duration, and a few targeted 2 to 4 hours. These shares were supported by discussions that current markets do not support batteries with a discharge duration much greater than 6 hours at this time. Particularly for smaller, emerging companies, the expense and risk of developing products beyond an existing market were recognized as unacceptably high at present. These participants indicated an expected timeframe of at least 5 years, possibly longer than 10 years, to develop a 10+ hour duration Na battery. Such timeframes are consistent with the Framework Study's estimates of 9 to 13 years for time to innovation impact for NaIBs. Many other participants indicated an 8- to 12-hour target within the next 3 years, and some indicated targets of greater than 12 hours, suggesting clear confidence in more near-term, long-duration-capable technologies. A very small share of participants indicated "other" high-power applications with durations of less than 1 hour. These distinctions highlight a significant dichotomy in the Na battery industry, with developing technologies such as NaIBs or SSSBs distinguished not just technically, but commercially, from more established technologies such as NaS or NaMH.

Impediments and Innovations

The most commonly raised challenge to widespread deployment and stationary system integration (and the persistent concerns of company leaders for Na batteries) was cost, including both the cost of the batteries themselves and the cost to establish, develop, and manufacture the batteries at scale. At the heart of these limitations were materials and performance metrics that can be tied to innovation opportunities. R&D to improve materials performance/efficiency or to identify replacements for existing costly materials was a significant priority, emphasized throughout both the FPLS and the Framework Study. Throughout the FPLS, several common innovation needs were specified as being potentially impactful, including direct material/component innovations, and, in terms of improved performance metrics, charging rates (time to charge) and component degradation were called out. For molten battery systems, a desire to reduce battery operating temperature without sacrificing performance was seen as an opportunity for pre-competitive innovation that could benefit multiple technologies. Such changes would likely involve multiple innovations across the battery assembly (possibly including significant changes to battery chemistry) to enable lower temperature performance.

In the FPLS, the discussions revealed components of batteries that would benefit not only from innovation but also from DOE/National Laboratory Technical Assistance, in particular. Trending priorities across technologies are expected to be reasonably consistent based on the discussions during the FPLS, correlation to the Framework Study, and the persistence of raised issues throughout the FPLS (across different discussions). Cathode and electrolyte development were the most common targets, together accounting for approximately half of the responses, and subsequent discussions revealed that cathode innovation not only included higher efficiency, lower resistance performance, but also understanding mechanisms for cathode-related degradation/failure. Notably, these potentially high-impact material innovations were also top innovations identified by participants in the Framework Study, as shown in Figure 3.

Many participants highlighted innovation in power electronics development. This focus on downstream integration was reiterated throughout the FPLS discussion, reflected as an impediment to both deployment and grid-scale integration. Note that "controllers" for battery management were also called out as a mid-level priority by the Framework Study looking at NaIBs. Support for power electronics and system integration was seen as a specific opportunity for DOE engagement, both in the development or implementation of power electronics and in the testing or validation of integrated battery systems. These integration challenges were particularly important for batteries designed and manufactured outside of the United States.

Anode, separator, current collector, and packaging were noted as well, showing that some level of innovation is desired across most of these batteries. The lower-level impact of anode development also parallels the Framework Study findings, although it is arguable that anodes were seen as more important for NaIBs. The emphasis on cell packaging and other manufacturing issues were not highlighted for NaIBs in the Framework Study. Particularly with regard to higher temperature battery manufacturers with more established chemistries, however, FPLS participants believed that packaging, including seals and insulation, were important as they relate to reducing costs.

R&D Approach

As described above, the Framework Study emphasized the need for basic, materials-focused research to advance the relatively less mature NaIBs. This trend was also seen in the FPLS, and funding for fundamental R&D was specifically called out, not only for emerging technologies but also for more mature molten Na batteries. These technologies have fundamentally changed relatively little since they were first explored more than 50 years ago. The lack of investment in R&D for lower TRL innovations has led to materials systems that are functional but that should be updated, adapted, or replaced to meet modern, evolving demands on the batteries and the lower costs required by a competitive stationary storage marketplace. For still-emerging NaIBs and SSSBs, significant innovation is still needed across the batteries to create the high-performance, cost-effective technologies that the industry will demand. Key to this requisite technical agility are a strong scientific foundation and technical basis, continually maintained and updated through quality, application-focused fundamental R&D.

Connecting DOE-directed, application-motivated basic R&D with industrial needs for innovation would be expected to enable the technology updates required to drive down costs and improve the performance of Na batteries across the board. The FPLS participants specifically indicated a desire to enable supported R&D (e.g., in the National Laboratories). This goal was further supported by the results of the Framework Study (consider Table 4 and Figure 3), which revealed the potential value in R&D innovation of virtually all significant NaIB components (including anodes, cathodes, separators, and electrolytes), with preferred support from DOE National Laboratories. (Please note, however, that many of the Framework Study participants were from National Laboratories.)

Manufacturing Innovations

In addition to being part of the “cost” impediment noted above, manufacturing was independently identified as another significant limitation of Na battery deployment and a topic that was raised throughout the FPLS. In particular, the ability to access large-scale, potentially automated manufacturing was seen as a significant gap in current industry. For some technologies, such as NaIBs, the manufacturing facilities and processes are sufficiently similar to LIB manufacturing that significant leveraging of existing industry expertise and resources may be feasible. For molten Na or other emerging batteries, innovations toward upgrading and accelerating manufacturing will be important. While manufacturing may not be seen as a traditional R&D topic, it was clear that scientific and engineering innovations are likely needed to enable the transformation of manufacturing capabilities. In this case, manufacturing not only included the complete battery but also key components, such as ceramic solid electrolytes, central to molten Na and SSSBs. It is notable, however, that ceramic separators also registered as a lower-priority target innovation in the NaIB Framework Study results. The issue of manufacturing, however important, presents significant cost challenges. Either strategies to repurpose existing manufacturing infrastructure should be identified that will allow for lower-cost manufacturing development or very large investments (> $100 million per facility) will be needed to develop new manufacturing infrastructure.

Additional Opportunities and Discussion

In addition to the technically oriented R&D challenges highlighted above, the FPLS and the Framework Study identified a significant number of non-technical challenges and opportunities.

Supply Chain

Supply chain was a repeated challenge for multiple Na battery types, particularly around electrolyte materials. For NaIBs and NaMH batteries, this concern included electrolyte salts, and NaMH also registered concerns over the volatile price of nickel. These concerns not only related to the availability of high-quality chemical manufacturers but also to the regulations for transport and handling of materials. The U.S. Environmental Protection Agency (EPA) Toxic Substances Control Act (TSCA) can create significant barriers for supply chains, especially for new materials. A suggestion was made that following “read across” practices, claimed to be common in Europe, may provide a route to streamlining the safe and efficient handling of materials without unnecessarily disrupting new materials supply chains. For technologies that use solid electrolytes, these (typically) ceramic materials themselves were seen as a potential commodity. Unlike NaIBs or LIBs, which use independently manufactured, commodity-scale polymer membranes, companies seeking to use solid electrolytes are currently challenged with having to manufacture their own solid electrolytes in addition to the balance of the battery. The development of a solid-electrolyte industry capable of supplying manufactured materials (such as β”-alumina, NaSICON, or other high-performance materials) as part of a mature supply chain was seen as a route to streamlining the industry and enabling multiple current and emerging Na battery technologies. Challenging the resolution of all these material issues, however, is the immaturity and small scale of the manufacturing and supply chain ecosystem. In a negatively self-reinforcing commercial cycle, because of the limited Na battery manufacturing volume, material suppliers are not incentivized to invest in larger volume materials supply; however, the insufficient supply chains increase costs and limit Na battery manufacturing.

There may be opportunities for intervention to break this cycle, potentially through support or incentivization of Na battery supply chain priorities. Public intervention has been key to the success of commercial entities in Europe and Asia and could provide some models for successful engagement. Timely support to improve supply chain issues could prove to be particularly relevant to domestic supply chains associated with Na batteries, where the United States may have a unique strategic interest in supply chain development. Key material sources needed to make the electrode (typically cathode) and electrolyte materials for NaIBs and LIBs are sodium carbonate (soda ash) and lithium carbonate, respectively. The distribution of these critical resources is shown in Figure 4, which highlights the fact that the United States has relatively poor lithium mineral reserves, with the most significant amount of natural resources coming from overseas. In contrast, the figure clearly shows that the United States sits on the world’s largest natural repository of soda ash (93% of known reserves), providing a key opportunity to establish and maintain control over an emerging globally important supply chain [27].

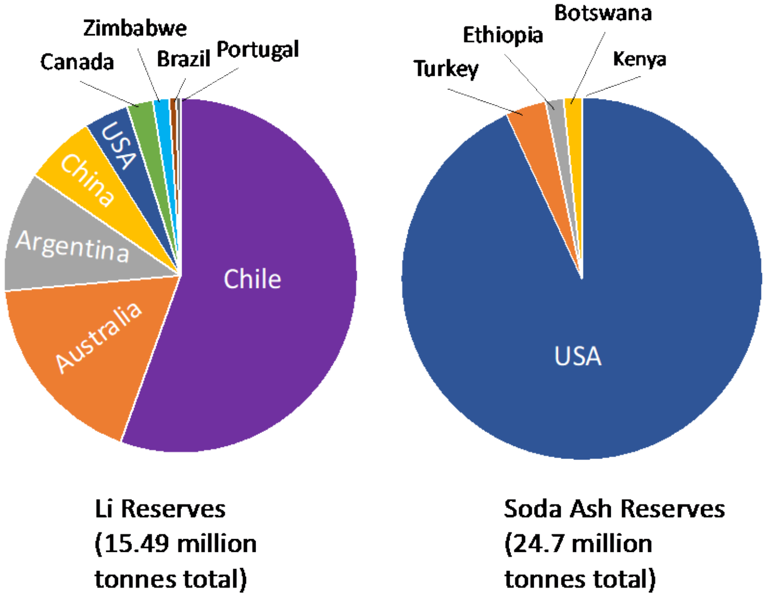

Figure 4. Global distributions of lithium and soda ash reserves. The United States is home to the largest soda ash deposit in the world. Figure content adapted from Hirsh et al. [27].

End-of-Life Management

Part of developing the mature materials ecosystem for Na batteries is considering the “end of life” disposition of the batteries and their material components. While one of the virtues of many Na batteries is that they use low-cost, earth-abundant materials, these cost-effective materials *limit* their recycling value, decreasing the economic incentive to dispose of batteries. Moreover, in the case of molten Na batteries, safely handling metallic Na during battery disposal/recycling requires special expertise/capabilities that could be expensive. (Notably, similar challenges will confront the end-of-life management of lithium metal batteries currently in development, so a collaborative, cooperative approach to handling multiple air-sensitive material sets may be appropriate.) While Japanese NaS manufacturer NGK has shown the feasibility of safe and effective Na battery disposition capabilities overseas, the infrastructure for managing battery disposition in the United States is not yet well established, and the value proposition outside of Ni-rich NaMH batteries is sufficiently limited to prevent independent, exclusively market-driven development of these capabilities domestically. Finally, both federal (EPA) and local regulators and insurers have tremendous influence over these materials handling activities. Possible restrictions or limitations associated with these entities are increasingly seen as potential deterrents to end-users and stakeholders in the United States. Certainly, increased education for regulators, end-users, and developers about the needs, opportunities, and safe handling practices for Na battery disposition would be productive in the United States. Cooperative international engagement with experts in Na battery disposition could help accelerate the resolution of these end-of-life challenges.

Workforce

Another key element of this development and manufacturing ecosystem is the workforce needed to support Na batteries—from basic R&D to the manufacturing and maintenance of deployed systems. In the case of NaIBs, similarities to LIB manufacturing and installation may afford opportunities to leverage existing LIB workforce and workforce training. For other technologies, such technology similarities may not be as obvious, necessitating more specialized workforce development. For example, because many of the molten Na battery technologies in commercially advanced stages today are technically distinct from other batteries, much of this workforce often has to be trained specifically by each manufacturer. As with streamlined supply chains, streamlining and finding common areas of technical training for the workforce (even bridging completely different battery types beyond Na) would help reduce this burden on current Na technology developers. In addition, the restrictions and complications of importing a trained workforce from overseas are complicated by immigration policies, leaving domestic battery companies searching for a limited U.S.-trained workforce.

Collectively, the impacts of improvements to this ecosystem composed of supply chain, manufacturing, disposition, and workforce could all be captured through a comprehensive lifecycle analysis. Both the Framework Study and the FPLS participants indicated the need for effective lifecycle analysis, recommending DOE tools as potential resources to make such pre-competitive insights available to the Na battery community.

Market Development

Market opportunity space represents a challenge and an opportunity that encompassed several recognized issues for Na batteries. First, industry experts noted that the dominant position LIBs have established in the current energy storage market, even when LIBs are not the best technology for a given application, is clearly a barrier to market entry for Na batteries. There were some suggestions from participants that subsidizing (currently) more expensive Na batteries could help balance the impact that electric vehicle (EV) subsidies have had supporting the growth of more well-known LIBs in stationary storage. Not only have LIBs become a common household name that stakeholders and end-users recognize more than Na batteries, but, in part because stationary LIBs grew out of a robust EV marketplace, the commercialization and deployment ecosystem, as a whole, has evolved with a focus on LIBs. This ecosystem includes policies and standards related to performance requirements, safety certifications, supply chain, and demonstration prioritization. While LIBs are clearly an important component of current and anticipated storage portfolios, forcing other (Na) technologies with different optimal use cases into the LIB policy and standards framework does not allow the storage community to effectively evaluate the diverse performance virtues and challenges of these alternatives. Working toward certification or validation of a technology is a time-consuming and expensive series of processes. Therefore, refining standards and policies to (1) be more agile as both storage needs and technologies evolve, and (2) better account for batteries developed with different storage durations (especially long durations), power ratings, safety concerns, and anticipated lifetimes will help end-users identify the best technologies for their respective application and grow Na batteries (as appropriate) as part of an inclusive storage marketplace.

In addition to the actual input provided by the FPLS and Framework Study contributors, the process of engaging with the Na battery industry revealed several key points. First, the Na battery market is growing aggressively. Although mostly limited to only a few established companies at this time, the molten Na battery industry is expanding globally with manufacturing and/or deployments on every continent but Antarctica, and increasingly large deployments being introduced regularly (see the Current Commercial Usage section above). Meanwhile, market analyses in January 2023 by Wood Mackenzie [22] suggests an anticipated growth of approximately 40 GWh of NaIBs alone by 2030, but up to an additional 100 GWh of manufacturing capacity is projected if the market is successful by 2025 (Table 5). These projections indicate an impending boom in the NaIB industry, which is dependent upon commercial commitment within the next few years.

Table 5. Summary of current and projected NaIB manufacturing capacity globally. Data adapted from Wood Mackenzie, “Sodium-ion update: A make-or-break year for the battery market disruptor,” January 2023 [22].

Manufacturer	Year	Current Production (GWh)	Base Pipeline Capacity expected by 2030 (GWh)	Possible Projected *Additional* Pipeline Capacity by 2030 (GWh)	Notes
HiNa Battery	2022	1–5	5	5	Initial GWh-scale NaIB production in 2022
CATL	2023	> 10	10	20	Planned GWh-scale production in 2023
Zoolnasm	2023	5	5	6	Building factory (Jiangsu, China)
Farasis Energy	2023	–	–	10	Teaming with JMEV for NaIB electric vehicle in 2023
BYD	2023	–	–	20	Aiming for NaIB electric vehicle in 2023
SVolt	2023	–	–	10	Planning NaIBs in 2023
Natron Energy	2023	0.6	~1	5	With Clarios, manufacturing in 2023
Li-Fun Tech	2023	–	–	5	Planning NaIBs in 2023
TIAMAT	2020s	6	6	–	With Neogy, will produce high-volume NaIB
AMTE	2020s	0.5	0.5	3	Building factory (Scotland)
EVE Energy	2020s	–	–	10	NaIBs in development
Godi Energy	2020s	–	–	5	NaIBs will follow LIB factory
Faradion	2020s	> 10	10	5	With Reliance, planning high-volume production

Despite this clear window into a future multi-billion-dollar industry, and despite the potential technical and environmental advantages of Na batteries, there is a lack of mature domestic Na battery manufacturers (of any battery type). There are several small companies in the United States, each focused on either PBA-NaIBs, SSSBs, or NaMH. These small companies are likely to confront significant challenges from larger, established international competitors (especially for molten sodium and emerging NaIB systems). Aside from the potential opportunity to establish a robust manufacturing capability in the United States, the unique, overwhelming domestic Na resources (e.g., soda ash) in the United States (Figure 4 above) are an opportunity for global market leadership.

Education and Awareness

One of the other keys to advancing Na battery domestic development and manufacturing and improving Na battery selection/acceptance by end-users is to increase community awareness of Na battery technologies. The FPLS participants mentioned throughout the session a lack of awareness around the current state of Na battery technologies. Many industry stakeholders are simply unaware that (1) there are multiple different types of Na batteries, (2) some of these technologies are already at high technology and manufacturing readiness, and (3) these technologies offer potential cost and performance benefits that are not accessible with LIB or Pb-acid batteries they may already recognize. This lack of familiarity with Na batteries is not only evident in the limited number of demonstrations or deployments, but also in the number of RD&D awards and incentives that preferentially go to the more familiar LIB technologies, even when it is not the ideal technology for a particular application. Even more “upstream” education around supply chain or manufacturing opportunities would benefit from increased education.

Part of the solution to addressing the challenges of community education could be addressed through greater visibility and dissemination of both technical data and commercial successes. There is a potential role for DOE/National Laboratories to provide and maintain educational resources to help both users and policymakers understand the landscape of Na batteries more comprehensively. In addition, however, the FPLS discussion recognized that a key tool to generating the content needed to make this message clear and compelling could be increased demonstrations and the validation of system *performance and safety*. DOE and the National Laboratories, in particular, were recognized as potentially important resources that not only could enable *demonstrations, testing,* *and validation* at scale, but also could provide the compelling, credible, objective third-party validation needed to inform and reassure risk-averse stakeholders and end-users. The Framework Study also clearly highlighted the potential value of demonstrations both for pilot-scale and grid-scale testing. Particularly where validation can take up to 10 years for grid-scale systems, DOE engagement to accelerate confidence in successful technologies will be important.

Summary

Together, the Framework and FPLS have identified several potentially impactful technical and non-technical opportunities to address limited U.S. participation (industry and government) and realize pending opportunities in Na battery commercialization. Table 6 provides a non-comprehensive summary of some of the most prominent needs and opportunities, broken down by strategic effort and either technical or non-technical innovation.

Table 6. Summary of key opportunities identified from both the SI Framework and Flight Paths

	R&D Technical Innovations	Non-Technical Advances
Flight Paths Listening Session (NaS, NaMH, SSSB, NaIBs)	Cathodes Electrolytes Power Electronics/Integration Manufacturing Advances Lower Temperature	Battery Ecosystem Development (Supply Chain, Manufacturing, End of Life, Workforce) Education (Public Relations for Na Batteries) Na-Specific Codes, Standards, Requirements, and Validation (not force-fit to Li-ion) Demonstrations/Testing/Validation Resources Lifecycle Analyses
Framework Study (NaIBs only)	Cathodes Electrolytes In-Operations Materials R&D Anodes Controllers/Battery Management Systems	High-Volume Manufacturing Multi-Scale Demonstration Projects Lifecycle Analyses

On the R&D front, a strong emphasis on cathodes and electrolytes was prominent in both the Framework and FPLS, along with varying levels of power electronics and integration development. Increased capacity and technology for advanced, large-scale manufacturing was seen as a significant cross-cutting priority as well. As one might expect for technologies that are seeking to increase their stake in the U.S. marketplace, demonstrations, testing, and validation, along with the lifecycle analyses of these technologies, were highlighted in both initiatives as well. There is an arguably important opportunity space for the United States in Na batteries, but it will require a decisive and timely commitment across all stakeholders. This report summarizes potential action items that may be the basis for a commitment to realizing this opportunity. As the energy storage landscape continues to evolve, so will the needs and opportunities for Na batteries, and subsequent evaluated industrial engagements, such as those highlighted here, are likely to provide important insights into the necessary adaptations of the U.S. approach to Na battery research, development, and deployment.

Appendix A: Contributors

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

Subject Matter Expert	Affiliation
Marca Doeff	Lawrence Berkeley National Laboratory
Andrej Singer	Cornell University
Bin Li	Idaho National Laboratory
Claire Xiong	Boise State University
David Mitlin	University of Texas at Austin
Todd Mooney	Enlighten Innovations, Inc.
Erik Spoerke	Sandia National Laboratories

In addition to these contributors, the FPLS hosted participants from a wide range of Na battery technologies, including several international contributors. The expanded scope of the FPLS, relative to the NaIB-focused Framework, increased industry engagement.

Appendix B: Framework Details

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

Innovation Category	Innovation
Technology Component	Controllers to improve cycle life
	Cathode-electrolyte interface
	Anode-less battery development
	Aqueous Na-ion development
Advanced Materials Development	High-voltage cathode material development
	Advanced materials discovery and development for anodes
	In-operations materials science research
	Ceramic membranes
	Electrolyte development (general)
	Electrolyte development (solid state)
	Electrolyte development (organic)
Manufacturing	Volume/Large-scale manufacturing
	Volume/Mass production for grid-scale deployment
Deployment	Pilot/Sub-pilot demonstrations
	Grid-scale Na-ion pilot testing
End of Life	Lifetime/Lifecycle modeling and prediction

Controllers to improve cycle life: The use of materials science insights about in-operation Na-ion degradation to improve control systems to minimize degradation and maximize cycling performance.

Cathode-electrolyte interface (CEI): The instability of the CEI contributes to a rapid decrease in the cycling performance of NaIBs. Improvements to the CEI can lead to reduced electrolyte consumption and improved cycling performance.

Anode-less battery development: The development of NaIB technology that only utilizes a cathode, liquid or solid electrolyte, and a current collector without using an anode. This has been demonstrated previously on a very small scale using a copper foil current collector on the anode side.

Aqueous Na-ion development: These batteries would be low cost and very safe but are limited by a narrower thermodynamic voltage window (1.23V) and lower energy density compared with organic systems. Needs more stable aqueous electrolyte and new electrode materials of high capacity.

High-voltage cathode material development: Higher voltage, stable cathode materials.

Advanced materials discovery and development for anodes: Needs an anode that provides greater energy density; one such example is a sodium metal anode.

In-operations materials science research: Emphasizes why existing cathode materials degrade rapidly during cycling, also includes more general materials changes and degradation during operations.

Ceramic membranes: Na-based redox flow batteries, select NaIBs, and SSSBs have been hindered by the lack of suitable membranes.

Electrolyte development (general): The basic electrolyte physiochemical properties for NaIBs are not well understood or studied.

Electrolyte development (solid state): Solid-state electrolytes for NaIBs would improve thermal/chemical stability and durability, as well as reduce flammability and increase performance.

Electrolyte development (organic): Non-flammable organic electrolytes increase safety; however, research is needed to ensure that the organic electrolyte does not decrease the electrochemical performance of the cells.

Volume/Large-scale manufacturing: There were many comments about the challenges of manufacturing, especially at volume, the materials required for thin solid-state electrolytes. There also were comments about the challenges of manufacturing thin anodes at scale.

Volume/Mass production for grid-scale deployment: Converting existing battery manufacturing capacity to produce grid-scale Na-ion or create new manufacturing capacity for grid-scale Na-ion production.

Pilot/Sub-pilot demonstrations: Demonstrate new/novel NaIB configurations/materials (still in development).

Grid-scale Na-ion pilot testing: Demonstrate current Na-ion technology at grid scale. Cheap, readily available materials with minimal supply chain concerns can offset the low energy density. Need exists to demonstrate feasibility to de-risk the technology and its application.

Lifetime/Lifecycle modeling and prediction: New approaches are needed to model and predict the lifetime of NaIBs.

Appendix C: Innovation Coefficients for the Framework Study

Table C.1. Innovation coefficients for the Framework Study

	Controllers to improve cycle life	Cathode-electrolyte interface	Anode-less battery development	Aqueous Na-ion development	High-voltage cathode material development	Advanced materials discovery and development for anodes	In-operations materials science research	Ceramic membranes	Electrolyte development	Volume/Mass production for grid-scale deployment	Pilot/Sub-pilot demonstrations	Grid-scale Na-ion pilot testing	Lifetime/Lifecycle modeling and prediction
Controllers to improve cycle life	–	0.50	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	0.25
Cathode-electrolyte interface	0.50	–	1.00	0.50	0.75	1.00	1.00	0.75	0.50	1.00	1.00	1.00	1.00
Anode-less battery development	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.75	1.00	1.00
Aqueous Na-ion development	1.00	0.50	1.00	–	1.00	1.00	1.00	0.75	0.25	1.00	0.50	1.00	1.00
High-voltage cathode material development	1.00	0.75	1.00	1.00	–	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00
Advanced materials discovery and development for anodes	1.00	1.00	1.00	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00
In-operations materials science research	0.50	1.00	1.00	1.00	0.50	1.00	–	1.00	0.75	1.00	1.00	1.00	0.25
Ceramic membranes	1.00	0.75	1.00	0.75	1.00	1.00	1.00	–	0.25	1.00	1.00	1.00	1.00
Electrolyte development	1.00	0.50	1.00	0.25	1.00	1.00	0.75	0.25	–	1.00	1.00	1.00	1.00
Volume/Mass production for grid-scale deployment	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	–	0.75	1.00	1.00
Pilot/Sub-pilot demonstrations	1.00	1.00	0.75	0.50	1.00	1.00	1.00	1.00	1.00	0.75	–	0.50	1.00
Grid-scale Na-ion pilot testing	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	–	1.00
Lifetime/Lifecycle modeling and prediction	0.25	1.00	1.00	1.00	1.00	1.00	0.25	1.00	1.00	1.00	1.00	1.00	–

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