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Technology Strategy Assessment

Findings from Storage Innovations 2030
Lead-Acid Batteries
July 2023

About Storage Innovations 2030

This technology strategy assessment on lead acid 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 can be found in Appendix B.

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Background

Introduction

The lead-acid (PbA) battery was invented by Gaston Planté more than 160 years ago and it was the first ever rechargeable battery. In the charged state, the positive electrode is lead dioxide (PbO_2) and the negative electrode is metallic lead (Pb); upon discharge in the sulfuric acid electrolyte, both electrodes convert to lead sulfate ($PbSO_4$). The storage of electricity occurs when the electrodes transition between these chemical states. The energy density of a PbA battery is relatively low at 25 to 100 kWh/m^3 when compared with a Li-ion battery at 150 to 500 kWh/m^3; however, it has excellent low-temperature stability [1]. Its many advantages include low-cost and globally abundant raw materials, fundamental safety due to its aqueous electrolyte, and a 99% recycling rate, which minimizes the health and environmental risks. The PbA battery has a strong history of market impact in automotive starting, lighting, and ignition (SLI), but also is used in forklifts and data center backup [2].

Architectures

To support automotive SLI market needs, PbA batteries have transitioned from the conventional flooded to recombinant (valve-regulated) designs, and from prismatic to tubular. To support long-duration energy storage (LDES) needs, battery engineering can increase lifespan, optimize for energy instead of power, and reduce cost requires several significant innovations, including advanced bipolar electrode designs and balance of plant optimizations.

Market size

The 2020 global market for PbA batteries was ~500 GWh (70% of global energy storage) and $40 billion [3]. The U.S. PbA batteries industry supports nearly 25,000 direct jobs in 38 states and has a total combined economic impact estimated to be $32 billion (manufacturing, recycling, transport, distribution, and mining) [4].

Stationary storage and PbA batteries

Grid energy storage is a relatively new opportunity for PbA batteries; it is driven largely by the rise of solar and wind renewable energy and the need to address their intermittency issues. As grid renewable content increases to a level that is characteristic of deep decarbonization, durations greater than 10 hours will be required (LDES). LDES markets require exceptionally low-cost technology solutions and the only potentially viable storage chemistries are those derived from super-low-cost and abundant raw materials, such as lead. Unfortunately, PbA battery designs that are appropriate for today's SLI and backup power applications cannot meet LDES performance requirements. In SLI, the battery infrequently delivers brief, high-power, shallow discharges and is maintained at a high state of charge—energy efficiency is irrelevant—and the cell is significantly overdesigned to ensure longevity. In contrast, stationary markets require deep charge/discharge cycles; high-capacity utilization for low-cost, high-coulombic efficiency (round-trip efficiency); daily cycling in many cases; and approximately a 20-year lifetime. It is anticipated that significant re-design may be required to meet LDES metrics; estimating the magnitude of this challenge and gauging the industry's perception of it is the topic of this report.

Baseline Performance and Cost Estimates

This section references the comprehensive 2022 Pacific Northwest National Laboratory energy storage cost and performance report; it is sponsored by DOE and updated regularly [3]. While it is critical to offer a baseline cost, it also is important to understand that the values cover a range and are subject to assumptions. This consideration is especially important for PbA batteries; its challenges with regard to chemical stability and electrochemical reversibility are often compensated for by the overdesign of active materials, and methods used to quantify energy capacity often vary. Another important point is that cycle life, which is a key stationary storage performance metric, increases significantly when the depth of discharge is lowered. Figure 1 depicts the critical relationship between cycle life and depth of discharge. This tradeoff is one of the most significant technical challenges for meeting the levelized cost of storage (LCOS) target and is mentioned often in both the Framework and Flight Paths discussions.

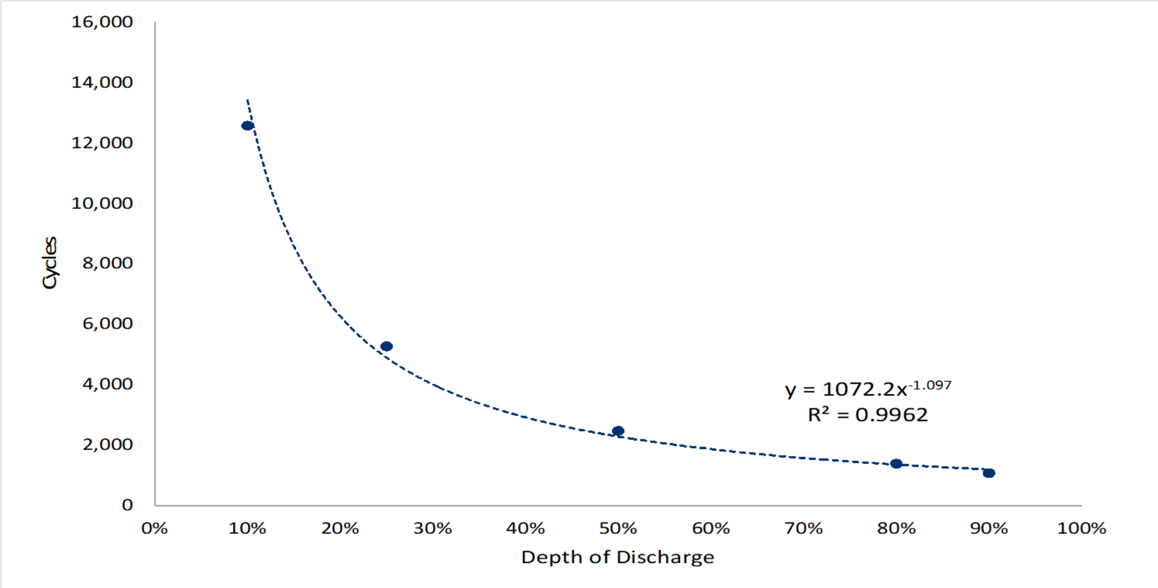

Figure 1. PbA cycle life versus depth of discharge

Table 1 summarizes the cost/performance values for 2021 and those for 2030, given no marginal increase in industry research and development (R&D) investment over currently planned levels. These 2030 values represent the baseline against which all future impacts are measured, with the 2021 values offered for comparative purposes. The cost and performance values in the table are those of a 100-MW, 10-hour PbA system and are derived exclusively from V. Viswanathan et al. (2022) [5]. LCOS is calculated using the approach outlined in the SI 2030 Methodology Report, which was released alongside the ten technology reports. The 2030 baseline LCOS estimate for a PbA battery is $0.38/kWh-cycle, which is a slight decrease from the 2021 value of $0.42/kWh-cycle. The LCOS methodology presented in V. Viswanathan et al. (2022) [5] differs slightly, resulting in a 2030 LCOS value of $0.32/kWh-cycle.

Table 1. 2021 and 2030 performance and cost values for 100-MW, 10-hour PbA battery storage

Parameter	2021	2030	Description
Storage Block Calendar Life	12	12	Deployment life (years)
Cycle Life	1,370	1,370	Base total number of cycles
Round-trip Efficiency (RTE)	78	78	Base RTE (%)
Storage Block Costs	219.00	206.01	Base storage block costs ($/kWh)
Balance of Plant Costs	43.80	32.71	Base balance of plant costs ($/kWh)
Controls and Communication Costs	1.50	1.12	Controls and communication costs ($/kW)
Power Equipment Costs	114.78	101.54	Power equipment costs ($/kW)
System Integration Costs	37.87	32.13	System integration costs ($/kWh)

Parameter	2021	2030	Description
Project Development Costs	53.10	45.05	Project development costs ($/kWh)
Engineering, Procurement, and Construction (EPC) Costs	41.71	35.39	EPC costs ($/kWh)
Grid Integration Costs	19.89	16.88	Grid integration costs ($/kWh)
Fixed Operations and Maintenance (O&M) Costs	12.67	10.78	Base fixed O&M costs ($/kW-year)
Variable O&M Costs	0.0005125	0.0005125	Base variable O&M costs ($/kWh)
LCOS	$0.42	$0.38	Levelized cost of storage ($/kWh-cycle)

Pathways to $0.05/kWh-cycle

Once the baseline costs for 2030 had been established, the research team worked with industry to assess the gaps in R&D investment. Thirty-nine subject matter experts (SMEs) were identified and contacted. These SMEs represented 24 organizations, ranging from industry groups (e.g., Battery Council International, Consortium for Battery Innovation) to vendors (e.g., Gridtential Energy, EAI Grid Storage, U.S. Battery Manufacturing Company) and universities (e.g., University of North Texas, University of California at Los Angeles). All 24 of the identified groups participated in interviews where the Framework Team solicited information regarding pathways to innovation and the associated cost reductions and performance improvements. The innovations, as defined by the SMEs, are presented in Table 2. The definitions of each innovation are presented in Appendix A. SMEs who contributed information to the Framework Study are acknowledged in Appendix B.

Table 2. Taxonomy of innovations

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

Input from SMEs was used to estimate the investment requirements and their timelines, the potential impacts on performance (e.g., round-trip efficiency, cycle life), and the cost (e.g., storage block, balance of plant, operations and maintenance) impacts of each innovation. The Monte Carlo simulation tool then combined each suggested innovation with two to seven other innovations, based on the range of impacts estimated by industry, and produced a distribution of achievable outcomes by 2030 with respect to LCOS (Figure 2). *The LCOS range with the highest concentration of simulated outcomes is in the $0.09 to $0.11/kWh range in life cycle.* However, some portfolios substantially reduce LCOS, with the highest impact portfolios (the top 10%) resulting in an LCOS of between $0.075 and $0.097/kWh-cycle.

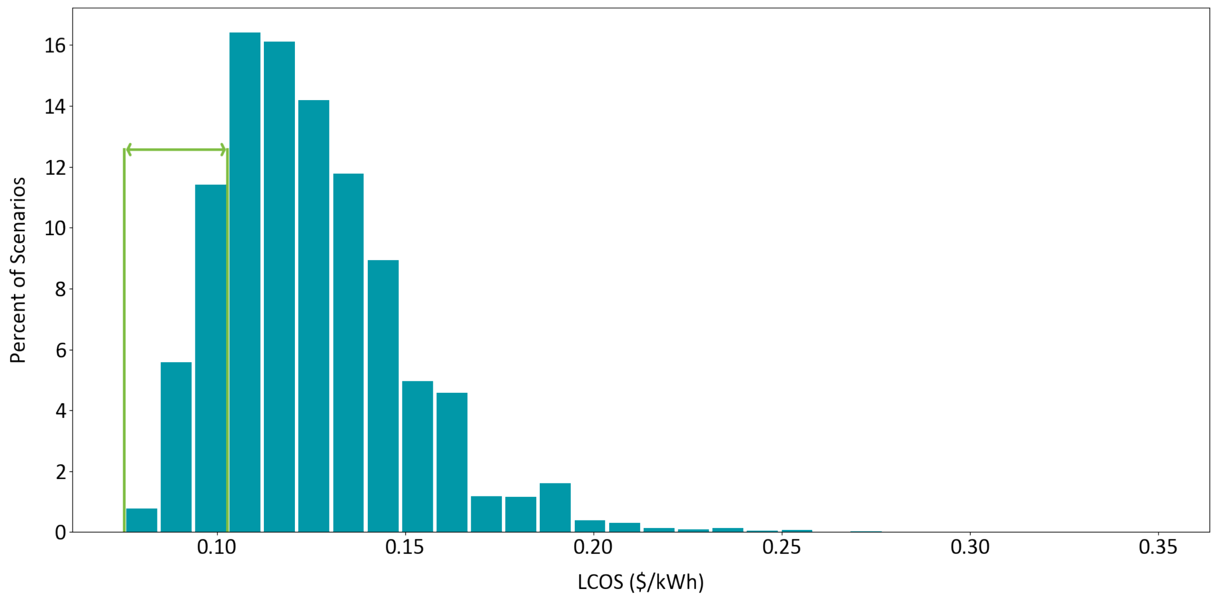

Figure 2. Portfolio frequency distribution across LCOS

The results of the Monte Carlo simulation for the thousands of portfolios that fall within the top 10% in terms of LCOS impact are presented in Figure 3. The vertical line indicates that the mean portfolio cost is $176 million in total expenditures, which is a value representing the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements. Total industry expenditure levels with the highest portfolio densities in the top 10% are in the $120 million to $200 million range, and the timeline required to achieve these LCOS levels is estimated at 5 to 9 years.

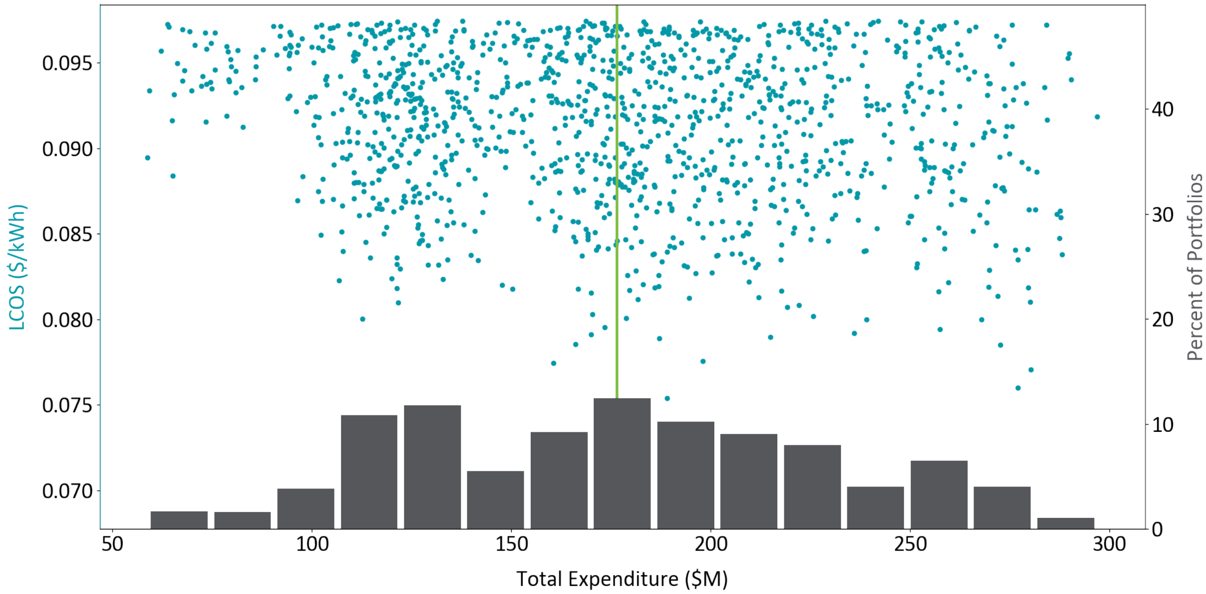

Figure 3. LCOS and expenditures for 10% of the portfolios

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

SMEs also were asked for their preferences regarding the investment mechanism, selecting among National Laboratory research, R&D grants, loans, and technical assistance. Table 3 presents the preference for each mechanism. National Laboratory research, typically with collaboration from universities and industry, was favored for most basic research efforts, including novel electrolytes, novel active materials, alloying in lead sources, and improving paste additives – carbon. R&D grants were supported for larger industry-focused efforts (e.g., enhanced domestic recycling, demonstration projects), while loans were selected for innovations involving industrial processes and demonstration projects that would require significant industry investment. Note that cells with asterisks (*) indicate that it was the preferred mechanism.

[a] To demonstrate how innovation coefficients work, the innovation coefficient for the combined investment in mining/metallurgy innovations and enhanced domestic recycling is 0.13, which means that the Monte Carlo simulation tool would only include 13% of the defined impact of the second innovation (e.g., enhanced domestic recycling) when added to the first innovation (e.g., mining/metallurgy innovations). The reason for the low coefficient for these innovations 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 innovation, while a coefficient of 0 means that the second investment would add no additional value.

Table 3. SME preferences for investment mechanisms. Cells with asterisks (*) indicate the most 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
Enhancing domestic recycling	22%	31%	25% *	22%
Demonstration projects	16%	47%	32% *	5%
Scaling and managing the energy storage system	23%	41%	32% *	5%
Novel electrolytes	60%	27% *	0%	13%
Improved paste additives – expanders or other	37%	37%	7%	20% *
Improving paste additives – carbon	48%	29% *	5%	19%
Novel active materials	47%	30% *	7%	17%
Manufacturing advanced PbA batteries	26% *	32%	18%	24%
Minimizing water loss from the battery	43%	39% *	0%	17%
AGM-type separator	37%	37%	5%	21%
Re-design of standard current collectors	25% *	46%	4%	25% *
Supply chain analytics	35%	29% *	12%	24%
Alloying in lead sources	40%	40%	7%	13%
Mining and metallurgy innovations	13%	33%	33%	20% *

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 4. As discussed in the next section of this report, while there are several basic research-focused innovations that appear to hold great promise for producing cost and performance improvements at modest investment levels (e.g., re-design of standard current collectors, novel active materials), these investments alone will not enable the deep reductions in LCOS targeted by the Energy Storage Grand Challenge.

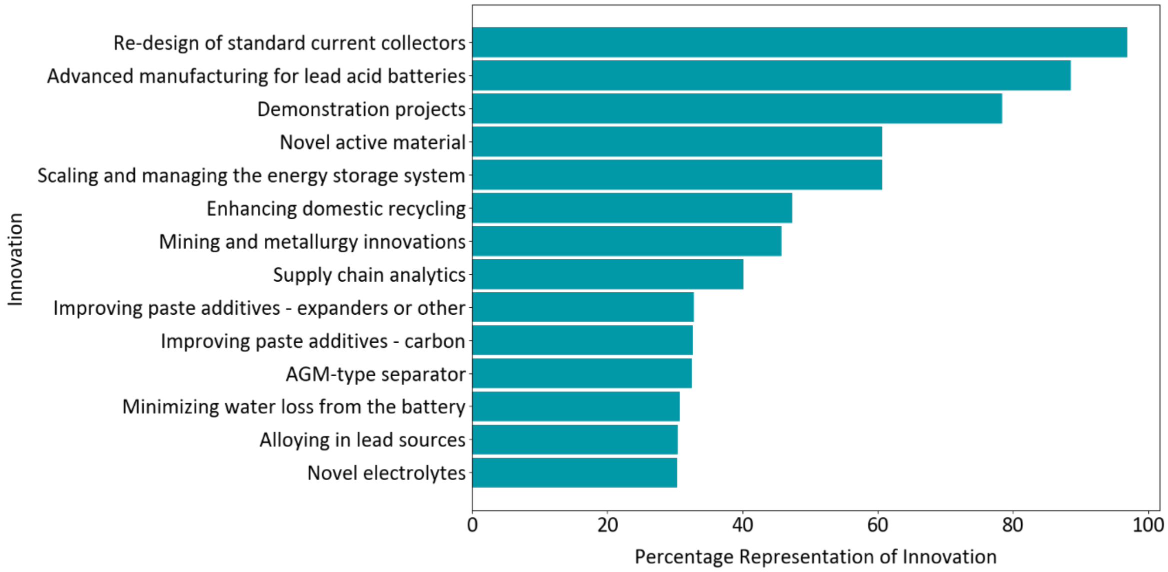

Figure 4. Representation of innovations in portfolios performing in the top 10%

Table 4 focuses on specific innovations where the design of standard current collectors, novel active materials, demonstration projects, and advanced manufacturing for PbA batteries consistently yield metrics in the top tier. Cycling improvements are the most significant contributor to reduced LCOS for PbA batteries and several innovations demonstrate particular strength in this metric. The Framework Team recognizes that some estimates are aggressive and optimistic yet remain worthy of attention as they demonstrate a strong directional cue from the industry, which believes that these innovations show great promise and have broad-based industry support. Enhanced domestic recycling, supply chain analytics, and mining/metallurgy were not viewed as promising by the industry. More detailed data, including minimum and maximum values and standard deviations for each metric, are presented in Appendix D.

Table 4. Impacts of proposed R&D investment levels, mean investments, and timelines. Cells with asterisks (*) indicate top-tier preferred mechanisms; daggers (†) represent mid-tier; and double daggers (‡) indicate the lowest tier.

Innovation	Storage Block Cost Impact (%)	Cycle Life Improvement (%)	Round-trip Efficiency Impact (%)	Mean Investment Requirement (million $)	Mean Timeline (years)
Enhancing domestic recycling	-15% *	0% ‡	0% ‡	37.8 ‡	3.8 ‡
Demonstration projects	-24% *	75% *	11% *	26.6 ‡	3.7 †
Scaling and managing the energy storage system	-12% *	53% †	10% *	9.0 †	2.8 *
Novel electrolytes	6% †	87% *	4% †	3.9 *	3.0 *
Improving paste additives – expanders or other	8% ‡	52% †	5% †	4.5 *	3.1 †
Improving paste additives – carbon	8% ‡	63% †	3% †	3.3 *	3.1 †
Novel active materials	-15% †	102% *	7% *	5.0 *	3.7 †
Advanced manufacturing for PbA batteries	-25% *	219% *	6% *	18.4 ‡	5.5 ‡
Minimizing water loss from the battery	8% ‡	56% †	5% †	5.4 *	3.0 *
AGM-type separator	9% ‡	78% †	6% *	5.7 †	3.2 †
Re-design of standard current collectors	-21% *	125% *	5% †	8.2 †	3.0 *
Supply chain analytics	-10% †	0% ‡	0% ‡	10.5 †	2.3 *
Alloying in lead sources	10% ‡	31% ‡	0% ‡	7.7 †	4.3 ‡
Mining and metallurgy innovations	-10% †	0% ‡	0% ‡	65.7 ‡	4.2 ‡

The recommended investment levels and timeline by innovation also are identified in Table 4. Most investments are in the $5 million to $20 million range and require investments over 3 to 5 years. Mining/metallurgy, manufacturing, demonstration projects, and enhanced recycling require significant investments in industrial processes and project development and, therefore, require a greater budget and more time. A pattern which emerges is that there are a number of innovations that yield fairly solid impacts at relatively low investment levels, including novel active materials, the re-design of standard current collectors, and novel electrolytes. However, to achieve levels at or near the $0.05/kWh-cycle target, deep investment in advanced manufacturing for PbA batteries, scaling and management techniques, and demonstration projects that involve development and validation of advanced controls and management systems are required.

R&D Opportunities

Highest Impact Opportunity Areas

The combined insights from the PbA battery industry's Framework Study and Flight Paths listening session identified critical research and development needs and opportunities to advance the commercialization and widespread deployment of this chemistry, with a significant focus on stationary storage. While both groups identified key issues whose solutions can provide a high impact, the Framework group primarily consisted of PbA battery technical experts, and the Flight Paths participants were high-level PbA battery industry executives. The subtle differences in perspective between them and rapidly evolving market sentiment may reflect the identified needs. Suggestions from the two groups did not always overlap. For example, the Flight Paths interactive session enabled participants to connect strategic issues to a variety of potential solutions, while the Framework interviewing process identifies more singular solutions. This section identifies key areas and how improvements will decrease the time to market.

A significantly higher cycle life is the most direct route to lowering LCOS. A PbA battery has a well-documented behavior of cycle life degradation as more available energy is accessed (Figure 1), which is an interweaving of cycle life with cost in $/kWh of available energy. This performance issue is an area of great need that may require several innovations for an ultimate resolution. Its complexity is reflected in approaches to the identification of necessary innovations: (1) SMEs in the Framework Study identified demonstration projects (scaling aspects), novel electrolytes, novel active material, re-design of standard current collectors, and advanced manufacturing as innovations holding great promise for improving cycle life; and (2) Flight Path executive-level participants generally called for a better understanding of failure modes, which then holistically cascades to multiple solutions as the (strategic) approach to improvements. These two perspectives are mutually beneficial to one another.

Improved use-case definitions will support the development of effective test-cycling protocols and more accurate value propositions, which, in turn, enhance investment probability. Currently, definitions lack clarity and reliability, which hinder technical and commercial progress.

Lower cost manufacturing will *directly* impact LCOS (similar to cycle life). It will likely derive from reducing the manufacturing energy costs and improving device utilization of the energy available in the storage materials. This opportunity was stressed more in the Framework interviews with SMEs than in the Flight Paths discussion with company leaders.

Standardization of devices and protocols will improve the efficiency of the entire ecosystem—from discovery through scale-up and mass manufacturing. Currently, standards are nearly nonexistent.

Advanced control algorithms using state-of-the-art data science and sensor technologies can optimize the cycling of cells and systems during research and field deployment. This requires a large database of performance data to enable artificial intelligence/machine learning tool developments that improve the entire value chain from manufacturing to the optimization of cell design and fielded systems. This category of innovation, which includes both hardware and software, was mentioned in the Flight Paths listening session and was also raised by SMEs interviewed for the Framework Study. Advanced control algorithms are a component of the Scaling and Managing the Energy Storage System innovation category defined in the Framework Study.

Demonstration projects are believed by many to be an opportunity to address and resolve the multiple hardware and regulatory issues associated with scaling. Demonstration projects also would enable the industry to combine innovations in specific deployments for testing and validation, perhaps with analytical support provided by National Laboratories. This was mentioned frequently in the Framework interviews but less often in the Flight Paths discussion session. High capital cost and LCOS are the immediate barriers to widespread demonstrations.

Working groups that promote partnerships among public/private organizations, researchers, utilities, and so forth can speed deployment by supporting pre-competitive research, industry standardization, workforce development, and so on. They may be government-led in order to promote inclusivity.

Device energy density needs to be higher in order to address all markets (e.g., high population density locations where space is at a premium). Here, the PbA battery's nonflammability is very attractive.

The Most Promising Innovations

In the first section, high-level gaps as general battery attributes (in categorical context) were identified; these are key issues whose solutions can provide a high impact. In this section, specific technological improvements are offered. These are individual and specific improvements in a component, testing, or manufacturing, and may improve several battery attributes.

Improvements in current collectors are a high-priority innovation and focus area mentioned by both groups. Currently, corrosion limits calendar lifetime, material utilization, and cycle life. Solutions offered in the Flight Paths session include new corrosion-resistant, low-cost conductive materials; advanced analytics; and a deep understanding of failure mechanisms. The Framework SMEs referenced this primarily as the re-design of standard current collectors by changing the aspect ratios/current collector thickness, the design/placement of current collector tabs, and novel current collector materials (Pb alloys or non-Pb based) (see Appendix A). Additionally, this also could include alternative designs such as bipolar or tubular gel construction.

More effective electrode designs are needed to improve material utilization and cycle life. Two approaches mentioned in both efforts are improving active materials utilization and reducing inactive content (e.g., lead current collectors) by improved electrode formulations and porosity design. In Flight Paths discussions, this is an outcome resulting from the improved understanding of failure modes. Approaches for electrode innovations are expanded upon in "areas of need."

Lower manufacturing cost is considered to be potentially highly impactful because the cost of foundational materials is low for all components. Two general approaches to solutions are those related to the legacy manufacturing framework or those associated with an entirely new paradigm.

Cell architecture improvements is a broad category (some improvements are already listed individually at the component level [e.g., current collectors]) that can positively impact both cost and performance, preferably synergistically. Examples include "better" electrodes and components, new designs enabled by corrosion-resistant current collectors, bipolar electrodes, and cells. Additional improvements include materials, balance of plant on the cell level (e.g., geometry, shape, size), and system integration (e.g., thermal management, control circuit topology, power control strategy, hardware-firmware-software interface/communication). These innovations also generally improve reliability, resilience, and safety.

Reduced cell performance variability is key to success in large stationary systems. Issues are rooted in imprecise manufacturing, which creates a net higher cost because accessing a smaller fraction of available energy is a substitute for fundamental reliability. Current SLI single-cell products are more forgiving of variability than future stationary products that will require the balancing of large strings. Buried in this issue, then, is an opportunity not only for improved precision but also an improved battery management system that manages the variabilities efficiently.

Improved life testing can significantly reduce the time needed for product development, as life testing today is a key bottleneck. Tests need to be more rapid and represent authentic field use cases. This capability should be readily translatable to PbA batteries because it has already been demonstrated with lithium-ion batteries.

Improved materials are a broad category for all aspects of PbA batteries. The expected outcome is to provide more robust electrodes that will lower LCOS.

Identification of Areas of Need – Pre-Competitive Research

The above two sections identified key attributes and specific innovations whose solutions can significantly impact the speed to market. In much of the current paradigm, the root causes that inhibit longevity remain unclear and cost-reduction solutions are incremental over time as the technical issues have not been resolved with an in-depth basic research approach. In this section, complex topics are synthesized into targeted efforts that require extensive research to provide high-impact solutions so the advantage of the PbA battery's low-cost raw material framework can accelerate the pace to meet the targeted LCOS. *These topics are directly from the Flight Paths conversation* and are important opportunities for pre-competitive research.

Use case and duty cycle definitions that represent the complex relationships between authentic energy storage activities and grid energy-power management strategies need better definitions to guide PbA device and system designs for LDES. To understand such complex relationships, it will require the acquisition of a substantial amount of "time-series" deployment data across many length scales (micro-grid, small to regional hubs, and then national transmission). This requires deep analysis of the performance requirements for devices, as well as for grid and device techno-economics. This knowledge gap is identified as a significant barrier that will likely require years of data collection and analysis efforts.

Effective understanding of performance degradation is a significant knowledge gap to meet LDES targets (e.g., how to achieve a much higher cycling ability compared to that of SLI). Deep understanding of degradation and failure mechanisms—from the atomic to the micron and beyond scales—is lacking. This gap limits the potential of innovative solutions. The PbA degradation and failure root from complexed electrochemical and speciation transport issues. The understanding of such root causes that lead to complicated failure mechanisms must be clearly established. Such understanding, if verified by effective cycling test protocols from well-defined use cases, will rapidly accelerate progress to meet LDES needs.

New testing methods that stem from a deep understanding of performance degradation under well-defined duty cycles will be required to accelerate deployments. Accelerated life testing and analyses (e.g., with artificial intelligence/machine learning) will be required to build more accurate predictive models than those currently derived from the existing data collected for SLI and backup power applications. Performance improvement and laboratory evaluation need to be concurrently integrated with new test data.

More efficient and robust electrodes. Improvements include (1) transport of protons and sulfate anions via more effective electrode architecture and pore structure, (2) the conduction of electrons by more efficient and robust current collectors, (3) novel active material formulations, and (4) reduction of inactive material's content. Synergistic improvements are needed (e.g., excess lead in current collectors is a long-standings issue that could be addressed through bipolar electrode innovations). However, more fundamental research is needed to achieve this goal.

Materials and energy utilization. Cells currently use a fraction of the available energy to compensate for poor performance—broad inefficiencies include both electrode design and cell operation (e.g., cycle life versus depth of discharge in Figure 1). This complex issue affects both the cost and the performance aspects of LCOS goals. Multiple innovations that span every aspect—from manufacturing through cell design, control of use, and improved system design—will be needed. Higher energy utilization relates to both electrode and cell design innovations.

Inadequate control algorithms are a broad gap that limits the ability to achieve high cycle life and high round-trip efficiency. This situation is somewhat of an SLI legacy, where significant overcharging preserves power density in an overdesigned device that tolerates low cycle life. Advanced control algorithms are considered by many to be a significant innovation for optimizing the performance of any design in any given use case. These improvements require better use cases, an understanding of failure mechanisms, and a large amount of data to support a state-of-the-art data science approach to innovation.

Additional Opportunities and Discussion

Additional opportunities were identified (and mentioned repeatedly) that are important but that do not fit the categories identified. These are discussed below.

Improved definitions of LDES market segments are critically needed and will provide broad impacts. For example, there are value streams, including those associated with resilience and reliability in several use cases (e.g., frequency response, voltage support) that yield value but are poorly compensated. The lack of full functional valuation inhibits adoption and innovation for LDES. Overcoming this barrier to fuel innovative technological concepts with refining value proposition in the markets should be highly encouraged with incentives.

Market activity and lackluster deployment was mentioned several times in the Flight Paths conversation. This was attributed, in part, to the overall weak value propositions.

Appendix A: Innovation Matrix and Definitions

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

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

Mining and metallurgy innovations: Includes innovations such as hydrometallurgical processes and extracting Pb as a byproduct of other mining processes. This category also includes innovations that would extend the lifetime and extraction efficiency of current domestic Pb mines.

Alloying in lead sources: Includes innovations related to the impurity or alloy composition of primary or secondary Pb. These innovations could remove harmful impurities from Pb sources or make those impurities less impactful on battery performance.

Supply chain analytics: Includes innovations and analysis that reduce risk in the supply of critical PbA battery materials (e.g., lead, plastics, additives). Examples could include lowering the fraction of valuable end-of-life PbA batteries that are exported or reducing the rising costs and lead times of critical materials. These analyses and innovations would support a domestic PbA battery circular economy.

Re-design of standard current collectors: Includes innovations that fundamentally alter the popular grid architecture of standard PbA battery current collectors. This could include changing the aspect ratios/current collector thickness, the design/placement of current collector tabs, and novel current collector materials (Pb alloys or non-Pb based). This also includes various designs of a PbA battery, such as bipolar or tubular gel construction, and the electrode materials necessary to improve those PbA battery designs.

AGM-type separator: Includes innovations for novel separator materials, coatings, and fabrication methods that have the potential to minimize stratification, aid diffusion, facilitate gas transfer, maintain stack compression over the lifetime of the battery, or be tailored to high performance on both the positive and negative sides [per electrodes] of the battery.

Minimizing water loss from the battery: Includes innovations that minimize the detrimental effects of water loss from the electrolyte or the need to add water to the battery to maintain performance. This could include controlling positive electrode corrosion and overcharging, water diffusion through the cell casing, water loss through the venting system, and catalysts for improving oxygen recombination. These innovations would be especially critical to battery performance for long calendar life and at higher temperatures.

Manufacturing for advanced PbA batteries: Includes innovations that would generate a manufacturing process for PbA batteries that is completely different from historically prominent methods. This would include the manufacturing of bipolar batteries, a Li-ion-like manufacturing process, or other processes designed to make PbA battery manufacturing greener. These innovations would reduce product variability, such as in paste mixing, curing, formation, and the manufacturing time and energy requirements, while increasing process automation.

Novel active materials: Includes innovations that use a different lead-based material than what is currently mixed into pastes during PbA battery manufacturing. The innovation could improve uniformity, eliminate or simplify manufacturing steps such as curing and formation, incorporate novel dopants or alloying elements for enhanced properties, and provide active materials that are tailored to specific applications of the battery.

Improving paste additives – carbon: Includes innovations that use high surface area carbons to improve battery performance. In addition to innovations in the surface area, porosity, crystallinity, and conductivity of the carbon, it is important to further understand the role that carbon plays in the electrode, especially in deep-cycling applications.

Improving paste additives – expanders or other: Includes innovations that improve the performance of expanders added to the paste or develop novel synthetic additives that improve paste performance. This could include naturally occurring expanders (lignosulfonates), synthetic molecules, or inorganic materials. Targeted improvements include active materials utilization, expander stability, high-temperature performance, performance in deep-cycle stationary storage batteries, and optimizing the expander/carbon interaction and loading.

Novel electrolytes: Includes innovations that use a non-aqueous or other novel electrolyte composition. This approach would fundamentally alter the electrochemical processes in the PbA battery and attempt to avoid sulfation, which causes battery failure.

Scaling and managing the energy storage system: Includes innovations for integrating and managing a large number of low-voltage batteries in a stationary energy storage system. These innovations would lead to a turnkey energy storage system for multiple use cases, similar to the products offered in the Li-ion battery industry.

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

Appendix B: Industry Contributors

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

Participant	Institution
Jay Frankhouser	EnerSys
Grant Grunewald	EnerSys
Shawn Peng	C&D Technologies and Trojan Battery Company
Jon Anderson	C&D Technologies and Trojan Battery Company
Paul Mattaliano	Stryten Energy
Mike Berger	Stryten Energy
John Miller	Stryten Energy
Bruce Cole	East Penn Manufacturing
John Buchanan	East Penn Manufacturing
John Timmons	Crown Battery
Samira Fahrani	Crown Battery
Frank Fleming	EAI Grid Storage
Jay Lohrbach	EAI Grid Storage
John Barton	Gridtential Energy
Collin Mui	Gridtential Energy
Robert Biczek	Gridtential Energy
Reed Shick	Advanced Battery Concepts
Ed Shaeffer	Advanced Battery Concepts
Paolina Atanassova	Cabot Corporation
Terry Murphy	Hammond Group
Gordon Beckley	Hammond Group
Travis Hesterberg	Ecobat
Bruce Murray	Ecobat
Tammy Stankey	Doe Run Company
Matt Wohl	Doe Run Company
Joe Grogan	Gopher Resource
Matthew Raiford	Consortium for Battery Innovation
Don Karner	Electric Applications Incorporated
Tim Ellis	Battery Council International
Fred Wehmeyer	U.S. Battery Manufacturing Company
Marvin Ho	U.S. Battery Manufacturing Company
Eddie Reyes	GS Yuasa
Bill Cunningham	GS Yuasa
Tim McNally	Borregaard USA
Chris Regan	University of California at Los Angeles
Michael Moats	Missouri University of Science and Technology
Marcus Young	University of North Texas
John Howes	Redland Energy Group
Roger Miksad	Battery Council International

Appendix C: Innovation Coefficients

Table C.1. Innovation coefficients

Innovation	Mining and metallurgy innovations	Alloying in lead sources	Supply chain analytics	Re-design of standard current collectors	AGM-type separator	Minimizing water loss from the battery	Manufacturing for advanced PbA batteries	Novel active materials	Improving paste additives – carbon	Improving paste additives – expanders or other	Novel electrolytes	Scaling and managing the energy storage system	Demonstration projects	Enhancing domestic recycling
Mining and metallurgy innovations	–	0.25	No isolated benefit for supply chain analytics*	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	1.00	1.00	0.50
Alloying in lead sources	0.25	–		0.88	0.60	0.75	1.00	1.00	0.88	0.33	0.42	1.00	1.00	0.88
Supply chain analytics	0.01	0.08		0.16	0.09	–	0.19	0.16	0.10	0.09	0.11	–	–	0.02
Re-design of standard current collectors	1.00	0.88		–	1.00	1.00	0.88	1.00	1.00	0.55	0.75	1.00	1.00	1.00
AGM-type separator	1.00	0.60		1.00	–	1.00	0.75	1.00	0.88	0.42	0.75	1.00	1.00	0.75
Minimizing water loss from the battery	1.00	0.75		1.00	1.00	–	0.75	1.00	1.00	0.50	0.92	1.00	1.00	0.75
Manufacturing for advanced PbA batteries	1.00	1.00		1.00	0.75	0.75	–	1.00	1.00	0.58	0.83	1.00	1.00	0.75
Novel active materials	1.00	1.00		1.00	1.00	1.00	1.00	–	0.88	0.58	0.83	1.00	1.00	1.00
Improving paste additives – carbon	1.00	1.00		1.00	0.88	0.75	1.00	0.88	–	0.67	0.67	1.00	1.00	0.75
Improving paste additives – expanders or other	0.50	0.42		0.55	0.50	0.33	0.58	0.58	0.67	–	0.67	0.75	0.92	0.50
Novel electrolytes	0.50	0.42		0.75	0.75	0.75	0.83	0.83	0.67	0.67	–	0.75	0.92	0.75
Scaling and managing the energy storage system	1.00	1.00		1.00	1.00	0.75	1.00	1.00	1.00	0.58	0.75	–	0.63	1.00
Demonstration projects	1.00	1.00		1.00	1.00	1.00	1.00	1.00	1.00	0.75	0.92	0.63	–	1.00
Enhancing domestic recycling	0.13	0.75		1.00	0.75	0.75	0.75	1.00	0.75	0.50	0.75	1.00	1.00	–

* Supply chain analytics is treated as an impact enhancement mechanism with no isolated benefit.

Appendix D: Descriptive Statistics for Individual Innovations

Table D.1. Descriptive statistics for individual innovations

Innovation_cat	Innovation	Budget_low	Budget_high	Budget_mean	Budget_std	Timeline_low	Timeline_high	Timeline_mean	Timeline_std	sbc_low	sbc_high	sbc_mean	sbc_std	cyc_low	cyc_high	cyc_mean	cyc_std
Raw materials sourcing	Mining and metallurgy innovations	1.0	250.0	65.7	85.2	1.0	10.0	4.2	2.4	(0.10)	(0.10)	(0.10)	–	–	–	–	–
	Alloying in lead sources	0.5	30.0	7.7	7.5	0.5	8.0	4.3	2.0	0.10	0.10	0.10	–	0.10	1.00	0.31	0.34
Supply chain	Supply chain analytics	0.5	50.0	10.5	17.2	0.5	5.0	2.3	1.4	(0.10)	(0.10)	(0.10)	–	–	–	–	–
Technology components	Re-design of standard current collectors	1.0	30.0	8.2	8.3	0.5	10.0	3.0	2.1	(0.80)	0.10	(0.21)	0.30	0.25	4.00	1.25	1.23
	AGM-type separator	1.0	15.0	5.7	3.6	1.0	7.0	3.2	1.7	0.01	0.15	0.09	0.05	0.05	2.00	0.78	0.72
	Minimizing water loss from the battery	0.3	20.0	5.4	4.5	1.0	5.0	3.0	1.4	0.05	0.10	0.08	0.04	0.10	2.00	0.56	0.62
Manufacturing	Manufacturing for advanced PbA batteries	1.0	100.0	18.4	25.8	2.0	20.0	5.5	3.9	(0.88)	0.10	(0.25)	0.19	0.15	9.00	2.19	2.73
Advanced materials development	Novel active materials	0.3	15.0	5.0	3.6	1.0	10.0	3.7	1.9	(0.25)	(0.05)	(0.15)	0.08	0.05	9.00	1.02	2.04
	Improving paste additives – carbon	0.3	10.0	3.3	2.3	1.0	6.0	3.1	1.5	–	0.15	0.08	0.08	0.10	2.00	0.63	0.65
	Improving paste additives – expanders or other	0.3	15.0	4.5	4.1	1.0	5.0	3.1	1.5	–	0.15	0.08	0.06	0.10	2.00	0.52	0.59
	Novel electrolytes	1.0	10.0	3.9	2.2	1.0	5.0	3.0	1.2	–	0.15	0.06	0.06	0.10	3.00	0.87	1.08
Deployment	Scaling and managing the energy storage system	1.0	25.0	9.0	7.2	1.0	7.0	2.8	1.6	(0.40)	(0.02)	(0.12)	0.13	0.40	0.80	0.53	0.15
	Demonstration projects	1.0	200.0	26.6	46.6	1.0	10.0	3.7	2.3	(0.50)	(0.05)	(0.24)	0.16	0.50	1.00	0.75	0.25
End of life	Enhancing domestic recycling	1.0	200.0	37.8	55.1	1.0	10.0	3.8	2.1	(0.20)	(0.10)	(0.15)	0.05	–	–	–	–

sbc = storage block cost, cyc = lifetime cycles

Innovation_cat	Innovation	rte_low	rte_high	rte_mean	rte_std	bpc_low	bpc_high	bpc_mean	bpc_std	fom_low	fom_high	fom_mean	fom_std	vom_low	vom_high	vom_mean	vom_std
Raw materials sourcing	Mining and metallurgy innovations	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Alloying in lead sources	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Supply chain	Supply chain analytics	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Technology components	Re-design of standard current collectors	–	0.10	0.05	0.04	-0.50	(0.35)	(0.20)	0.21	(0.50)	(0.05)	(0.32)	0.24	(0.75)	(0.05)	(0.40)	0.49
	AGM-type separator	0.02	0.10	0.06	0.06	–	–	–	–	(0.50)	(0.25)	(0.38)	0.18	–	–	–	–
	Minimizing water loss from the battery	–	0.10	0.05	0.04	–	–	–	–	(0.50)	(0.25)	(0.38)	0.18	–	–	–	–
Manufacturing	Manufacturing for advanced PbA batteries	0.03	0.10	0.06	0.03	-0.35	(0.10)	(0.23)	0.18	(0.50)	(0.05)	(0.18)	0.19	(0.75)	(0.05)	(0.32)	0.24
Advanced materials development	Novel active materials	–	0.15	0.07	0.05	–	–	–	–	(0.50)	(0.25)	(0.38)	0.18	(0.30)	(0.10)	(0.22)	0.10
	Improving paste additives – carbon	–	0.10	0.03	0.03	–	–	–	–	(0.50)	(0.50)	(0.50)	–	–	–	–	–
	Improving paste additives – expanders or other	–	0.15	0.05	0.05	–	–	–	–	(0.50)	(0.50)	(0.50)	–	–	–	–	–
	Novel electrolytes	–	0.10	0.04	0.04	–	–	–	–	(0.50)	(0.50)	(0.50)	–	–	–	–	–
Deployment	Scaling and managing the energy storage system	0.10	0.10	0.10	–	-0.20	(0.10)	(0.14)	0.05	(0.20)	(0.10)	(0.17)	0.06	(0.80)	(0.10)	(0.30)	0.27
	Demonstration projects	0.11	0.11	0.11	–	-0.10	(0.10)	(0.10)	–	(0.15)	(0.05)	(0.10)	0.04	(0.10)	(0.05)	(0.09)	0.03
End of life	Enhancing domestic recycling	–	–	–	–	–	–	–	–	(0.20)	(0.20)	(0.20)	–	(0.30)	(0.20)	(0.27)	0.06

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

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