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FINAL PROJECT REPORT

California Zn-ion Energy Storage Development and Validation Project

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Specifically, extending gratitude to the California team of Salient Energy for its commitment and development for Salient's Residential Demonstration System.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

California Zn-ion Energy Storage Development and Validation Project is the final report for the EPC-19-040 conducted by Salient Energy. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Salient Energy (Salient) was awarded California Energy Commission grant EPC-19-040 (project) to bring its Zinc-ion (Zn-ion) cell technology from component demonstration in a laboratory environment to the technology demonstration stage. The project included installing and testing the Zn-ion cell technology in a 10-kilowatt-hour residential energy storage system.

While not without its challenges, this project advanced Salient's Zn-ion cell technology closer to commercialization. Salient's technology is the first Zn-based battery to utilize Zn-ions on both the cathode and anode sides of the cell in a non-toxic, near-neutral, aqueous electrolyte, thus eliminating the possibility of thermal runaway. The project enabled Salient to increase cell capacity, improve production capability, and both develop and test a 10-kilowatt-hour residential energy storage system using Salient's Zn-ion cell technology.

With the advances made in this project and further research and development going forward, Salient Energy plans to introduce a lower cost, safer, and more sustainable alternative to current Lithium-ion energy storage.

Keywords: Energy storage, battery energy storage, Zinc-ion, zinc battery, zinc aqueous electrolyte, technology demonstration

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Executive Summary

California is projected to need 52,000 MW of grid-connected energy storage capacity to reach the ambitious mandates of Senate Bill (SB) 100, which requires that 100 percent of electricity retail sales and state agency electricity needs be met with renewable and zero-carbon resources by 2045.[1] The need for longer-duration storage, in particular, has also increased due to climate change, greater use of renewable energy sources, and growing electric load. In this context, the development of advanced battery technologies is critical to establishing a robust portfolio of energy storage to enable a more reliable electric grid and accelerate deployment of renewables as California transitions to 100 percent clean energy.

To date, the most common battery technology for energy storage is lithium-ion (Li-ion) due to key attributes including fast response time, long cycle life, and high-energy density. Aside from its performance capabilities, however, Li-ion technology also presents challenges for large-scale energy storage installations including potential thermal runaway, which can result in generation of toxic gases and fire risks; capacity degradation over many charge and discharge cycles, and dependence on unstable supply chains based outside of North America. These issues are likely to worsen as current installations age, further exacerbating the need for viable alternative technologies.

As an alternative option to Li-ion technology, Salient Energy, Inc. (Salient) has developed a rechargeable zinc-ion (Zn-ion) battery for the stationary energy-storage market that is lower cost, safer, and more sustainably produced than existing Li-ion battery technologies. Salient's technology uses zinc-ions on both the positive and negative sides of the cell in a safe, near-neutral, non-toxic, aqueous electrolyte. In addition to competing with the energy efficiency of Li-ion cells, this system uses materials that are readily available across North America, mitigating potential supply chain issues. Its inherent safety, non-toxicity, affordability, and supply chain stability mean that Salient's technology is well-suited for stationary energy storage applications.

In this context, Salient was awarded a grant by the California Energy Commission (EPC-19-040) to advance its Zn-ion technology and further demonstrate its potential to provide ratepayer benefits in California. The goals of this agreement were to:

1. Advance the development of a new Zn-ion battery storage solution for the customer side of meter deployment, focused on safety.
2. Validate a cost-effective and high-performing energy storage solution to support higher levels of renewable resources and a carbon-free future by 2045.
3. Scale Salient's Zn-ion battery storage solution from laboratory demonstration to prototype testing for the customer side of the meter applications.

[1] California Energy Commission. 2023. California Sees Unprecedented Growth in Energy Storage, A Key Component in the State's Clean Energy Transition October 2023.

4. Provide greater reliability, lower costs, and increased safety for California's millions of investment-owned utility ratepayers.
5. Enable technological advancement to overcome barriers to achieving the state's statutory energy mandates, including SB 350 and SB 100.
6. Demonstrate improved energy density, increased cycle performance, improved reliability and safety, better lifecycle performance, and lower costs when compared with current fielded systems.
7. Replace fossil-fuel powered generators in response to public safety power shutoffs (PSPS) and other emergency shutoffs due to infrastructure failures, natural disasters, and severe weather events.

To achieve these goals, the primary objectives of this project included:

- Advancing Zn-ion battery technology from the pre-commercial stage (technology readiness level 4) to the technology demonstration stage (technology readiness level 6).
- Completing third-party validation of the Zn-ion battery technology.
- Designing and building a residential Zn-ion energy storage system that can provide low-cost and safe energy storage to California ratepayers.
- Demonstrating the performance of a 10-kilowatt-hour (kWh) residential Zn-ion energy storage system at a third-party system testing facility.

In working to meet these objectives, the project team initially intended to scale an original 1 ampere-hour (Ah) prismatic cell design to a 20-Ah prismatic cell, based on the proven design and performance of a 1-Ah prismatic cell developed prior to this project. However, issues surfaced relating to pressure application and electrolyte leakage. These were addressed by reconfiguring the cell design to large-format pouch cells. Initial redesigns targeted a 5-Ah Zn-ion pouch cell that utilized the same electrode format and footprint as the 20-Ah prismatic cell. This modification enabled more robust cell sealing, ensured that it would follow industrial norms in cell manufacturing (without significant capital cost), allowed stack pressure to be applied externally, and ultimately resulted in a decrease in cell failure rates from 70 percent to <1 percent.

A 20-Ah Zn-ion pouch cell was then designed, incorporating advancements to the core Zn-ion technology, which had been developed in parallel. Through cathode slurry, electrolyte development, and separator improvements, both higher-rate capability and specific capacity of the active material were achieved. Beyond capacity improvements, the new electrolyte effectively eliminated the impact of short circuits in Zn-ion cells, significantly extending cycle life.

Substantial performance improvements also amplified a failure mode within the core Zn-ion cell technology known as *active material dissolution*. This failure mode was expected to occur during discharge since zinc ions were intercalated into the active material; soluble active material ions were ejected from the cathode and diffused through the aqueous electrolyte. A critical direction for further research was thus identified for future projects. However, cell design and system development continued.

The project team subsequently focused on increasing the throughput of Salient's electrode-production capabilities. This was mainly pursued through external contract manufacturers to minimize capital costs. Multiple production issues were encountered in both the cathode and anode production processes, including:

- Quality issues with electrode coating processes.
- Issues with pressure distribution and a variation of up to approximately 25 percent of the thickness and loading across the width of the coated electrodes.
- Quality issues due to aging, poorly maintained or worn production equipment and machinery.
- Quality issues including significant folds or bends in the electrodes, bubbling between layers, and tab bending or creases.

These issues were addressed by a combination of identifying new contract manufacturers with more advanced equipment and by making key process improvements to improve the uniformity of the electrodes. Ultimately, the issues encountered in the manufacturing and production processes delivered important lessons learned for the production readiness of the technology as the company scales.

Despite these challenges, Salient successfully designed, produced, assembled, and tested a 10-kWh residential demonstration system composed of 272 Zn-ion cells. However, due to the lower-than-target capacity (approximately 7.4 Ah per cell) and some cell degradation, the system only achieved a peak capacity of 2.5 kWh during the demonstration. Testing validated critical aspects of Zn-ion cell performance, however, while also highlighting the impact of cell variability on overall system capabilities. This provided valuable baseline data for the next phase of development, which will focus on improving cell quality and identifying the root causes of premature degradation.

Importantly, the project also demonstrated the critical safety advantages of Zn-ion chemistry and obtained third party validation from UL Solutions. Their UL9540A testing showed no thermal runaway or flammable gas emissions even under extreme conditions. This safety certification, along with the improved manufacturability and performance insights gained, positions Zn-ion technology for broader adoption in residential and grid-scale energy storage applications in future iterations.

Going forward, technology development efforts at Salient will focus on refining the 10-kWh residential system for in-field deployments to facilitate enhanced testing. Production of Zn-ion cells will additionally continue to scale to meet demands of additional demonstration system testing in the residential space. Finally, development of larger Zn-ion modules for use in commercial, industrial, and grid-scale applications will be pursued.

The outcomes of this grant agreement represent a substantial step forward in the commercialization of Salient's Zn-ion cell technology. In advancing research into Zn-ion's technical and economic competitiveness, the results of this project further highlight the technology's potential to play a role in the state's growing energy-storage portfolio.

The knowledge acquired in the development of this technology was transferred throughout the project via the participation of Salient's staff in multiple industry conferences (both as attendees and presenters) and by submitting key research findings to peer-reviewed journals for publication.

CHAPTER 1: Introduction

As energy markets transition from fossil fuels to intermittent renewable resources, battery storage is increasingly vital to maintain the reliability and resilience of the state's power grid. This is particularly true in the Western United States, where California, Oregon, and Washington have enacted ambitious decarbonization policies. To meet its 2045 greenhouse gas (GHG) reduction goals, California alone is projected to require 79 gigawatts (GW) of new renewable generation and approximately 52 GW (200 gigawatt-hours [GWh] when considering 4-hour systems) of battery storage.[2]

The large-scale integration of battery storage presents both challenges and opportunities. Currently, most operational large-scale battery storage systems rely on lithium-ion (Li-ion) cell technology, which remains the preferred choice due to its fast response times, high cycle-life and energy efficiency. Other energy storage technologies are also undergoing pilot and demonstration testing in collaboration with the California Energy Commission (CEC).

While batteries do not generate electricity they provide flexibility, allowing energy to be stored so its consumption can be shifted across different times of the day. This capability enables a strategy known as arbitrage, where batteries store electricity during midday — when solar energy is abundant and prices are low — and sell it back to the grid in the evening when demand is higher, solar output decreases, and prices rise. Beyond providing flexible generating capacity during critical peak hours, the growing fleet of battery storage resources also helps manage the increase in electricity demand during other parts of the day and can ultimately support higher renewable energy penetration while reducing curtailment.

Despite being the leading technology of today's large-scale energy storage systems, Li-ion batteries still face several challenges. For instance, the supply chain for Li-ion cells poses significant risks to developers. The supply of raw materials required for Li-ion batteries is limited and projected to lead to a shortfall in global production of between 30 percent and 40 percent for electric vehicles and stationary energy storage by 2050.[3] Significant global Li-ion battery material reserves are limited to South America (lithium), the Democratic Republic of the Congo (cobalt) and Indonesia, Russia, and the Philippines (nickel). The supply of these materials is volatile, influenced by geopolitical factors, trade policies, and ethical concerns, particularly regarding mining practices and China's significant role in processing and refining materials. As demand for batteries continues to rise, efforts are being made to diversify supply chains, invest in alternative materials, and develop more sustainable sourcing and refining methods.

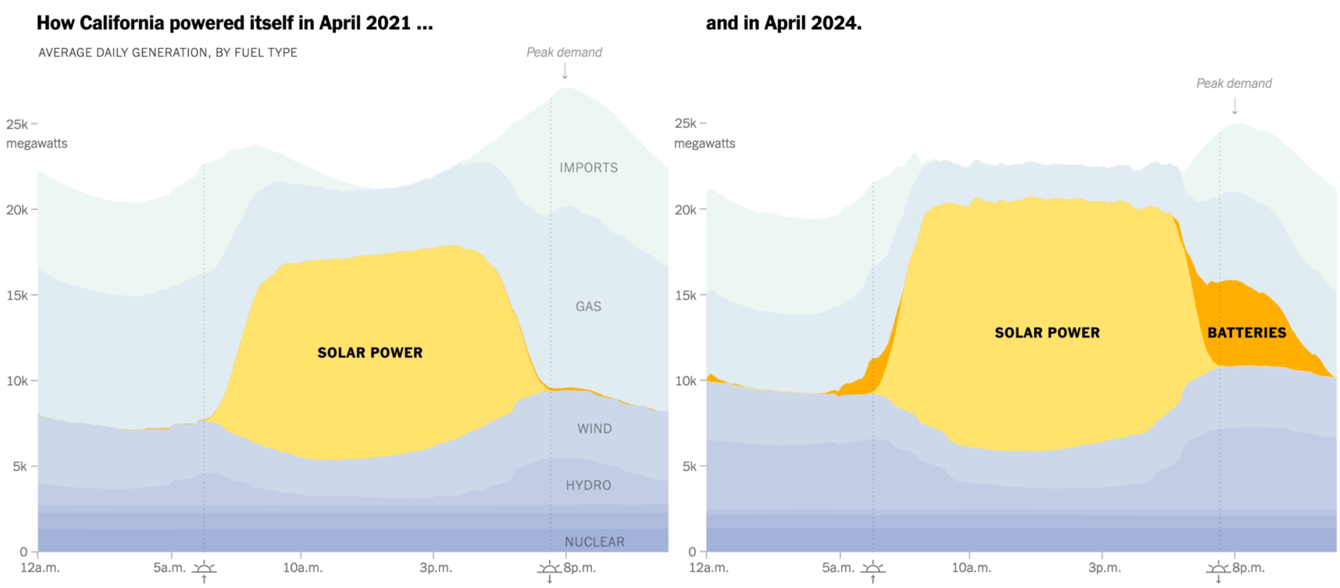
[2] Department of Market Monitoring. 2024. 2023 Special Report on Battery Storage. California Independent System Operator. https://www.caiso.com/documents/2023-special-report-on-battery-storage-jul-16-2024.pdf.

[3] Valckx, Nico, Martin Stuermer, Dulani Seneviratne, and Prasad Ananthakrishnan. 2021. "Metals Demand From Energy Transition May Top Current Global Supply." IMF Blog, International Monetary Fund. Available online: https://www.imf.org/en/Blogs/Articles/2021/12/08/metals-demand-from-energy-transition-may-top-current-global-supply.

Furthermore, much of California's current energy-storage infrastructure was installed in recent years and will therefore require upgrades or replacements within the next 7 to 15 years as these installations approach the end of their product lifetimes.[4] California has also experienced multiple battery-storage facility fires in recent years, highlighting safety concerns. At the Moss Landing Energy Storage Facility on the Central California coast, overheating issues in September 2021 and February 2022 led to shutdowns, and in January 2025, a major fire forced the evacuation of 1,200 residents and caused significant damage. The Gateway Energy Storage facility (Otay Mesa, California) in May 2024 also experienced a fire that burned for five days — with persistent reignition challenges — while the Elkhorn Battery Storage facility (Moss Landing, California) suffered a Tesla Megapack fire in September 2022, though it was contained without injuries. Finally, following the Moss Landing Energy Storage Facility fire in January 2025, the California Public Utilities Commission (CPUC) issued a proposal to increase the safety of battery energy-storage facilities.[5]

Meanwhile, as the state transitions to a carbon-free electric grid by 2045 and integrates higher levels of both renewable energy and battery use (Figure 1), the demand for cost-effective, high-performance storage solutions is expected to grow and diversify. Investing in the development of new storage systems will allow emerging technology developers to capitalize on these significant market opportunities going forward.

Figure 1: California Power Comparison by Source Type: 2021 Versus 2024



Source: Plumer, Brad, Nadja Popovich. 2024. "Giant Batteries Are Transforming the Way the U.S. Uses Electricity." The *New York Times*, May 7, 2024. Available online: https://www.nytimes.com/interactive/2024/05/07/climate/battery-electricity-solar-california-texas.html.

[4] California Energy Commission 2025. California Energy Commission "California Energy Storage System Survey." Data last updated April 3, 2025. Retrieved June 2, 2025 from https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/california-energy-storage-system-survey.

[5] California Public Utilities Commission. 2025. "CPUC Issues Proposal to Enhance Safety of Battery Energy Storage Facilities." California Public Utilities Commission, January 27, 2025. Available online: https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-issues-proposal-to-enhance-safety-of-battery-energy-storage-facilities.

In response to these multi-dimensional concerns, Salient Energy (Salient) developed a rechargeable zinc-ion (Zn-ion) battery for the stationary energy-storage market that is cheaper, safer, and more sustainably produced than existing Li-ion battery technologies, using raw materials found throughout North America. The Zn-ion battery energy-storage system combines high-energy density, long cycle-life and high-rate capability, making this technology a competitive solution for all stationary energy-storage needs. Over the course of this project, the project team advanced the Zn-ion battery technology from technology readiness level (TRL) 4 to TRL 6, improved production capabilities, and developed and laboratory tested a 10 kilowatt-hour (kWh) Zn-ion residential energy-storage system.

Due to aging infrastructure and more frequent extreme climate events, Californians are increasingly vulnerable to power outages from electrical equipment and infrastructure failures, brownouts, severe storms, earthquakes, landslides, and wildfires. To minimize the threat of wildfires caused by electrical infrastructure, California utilities have begun shutting off power to hundreds of thousands of customers during dangerous weather conditions and natural disasters.[6] With the development of Zn-ion cell technology, California residents would benefit from increased safety, energy-cost reductions, peak-load reduction and shifting, infrastructure resilience and reliability, as well as GHG and other harmful emission reductions. Non-lithium Zn-ion rechargeable-battery energy storage will create greater energy reliability and safety during both planned and unplanned power outages and peak grid hours, reducing the need for diesel or gas-fueled generators. Its aqueous electrolyte and domestically sourced materials directly address the safety and environmental impact concerns raised by Li-ion.

State of Development of Zn-ion

Salient developed and designed a unique rechargeable Zn-ion energy-storage battery built entirely of non-toxic components that is cheaper, safer, and as long-lasting as a Li-ion battery, which will help overcome barriers to achieving California's ambitious energy mandates in SB 100 and SB 350. A core part of Salient's innovation is the development of a special class of materials used at the positive electrode that can reversibly intercalate[7] Zn^{2+} into their crystal structure. Salient also developed unique designs and formulations for the negative electrode, electrolyte, and separator, which allow the battery to be recharged thousands of times before it needs to be recycled. Developing a battery based on Zn^{2+} intercalation is a technological advancement that improves energy density, daily-cycle capability, longevity, safety, and ultimately reduces costs when compared with conventional Li-ion technology.

This project advanced the cell technology from the pre-commercial stage (TRL 4) to the technology demonstration stage (TRL 6). Prior to this project, Salient developed its Zn-ion battery from basic research (TRL 1) to a component demonstration in a laboratory environment (TRL 4). Salient began with research conducted at the University of Waterloo,

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[6] Wolfe, Sean. 2025. "California Utility Weighs More Power Shutoffs for Thousands Amid Santa Ana Wind Resurgence." Renewable Energy World, January 21, 2025. Available online: https://www.renewableenergyworld.com/power-grid/outage-management/california-utility-weighs-more-power-shutoffs-for-thousands-amid-santa-ana-wind-resurgence

[7] Intercalation is the process where ions or molecules are reversibly inserted into the structure of a host material without significantly altering its framework.

which was summarized in a 2016 paper published by Salient in *Nature Energy*.[8] The work concluded that the material set in laboratory results could potentially become a lower-cost, longer-lasting, and safer alternative to Li-ion. Innovation continued and its development resulted in an active material to improve cycle life.[9]

Throughout 2019, the Salient team focused on modifications to electrode design that reduce Zn-ion cell costs and improve performance. The team developed an entirely novel electrode formulation for incorporating this intercalation material into a positive electrode. The Zn-ion cell technology has been successfully demonstrated in hundreds of 100 milliampere-hour (mAh)[10] prototypes. These prototypes, consisting of 25 cm^2 of the negative electrode, separator, and positive electrode, when stacked together to form a cell serve as component testing cells that are cycled accordingly to test performance parameters.

The following agreement goals were set in accordance with the technology development stages required for producing and testing a commercially viable, large-format Zn-ion cell for use in module- and energy-storage system development.

Project Goals

The goals of this project were to:

- Advance development of a new Zn-ion battery storage solution for the customer side of meter deployment, focused on safety.
- Validate a cost-effective and high-performing energy storage solution to support higher levels of renewable resources and a carbon-free future by 2045.
- Scale Salient's Zn-ion battery storage solution from laboratory demonstration to prototype testing for the customer side of meter applications.
- Provide greater reliability, lower costs, and increased safety for California's investor-owned utility (IOU) ratepayers.
- Enable technological advancement to overcome barriers to achieve the state's statutory energy mandates, including SB 350 and SB 100.
- Demonstrate improved energy density, increased cycle performance, improved reliability and safety, better lifecycle performance, and lower costs when compared with current fielded systems.
- Replace fossil-fuel powered generators in response to public safety power shutoffs (PSPS) and other emergency shutoffs due to infrastructure failures, natural disasters, and severe weather events.

[8] Kundu, D., Adams, B., Duffort, V. et al. A high-capacity and long-life aqueous rechargeable zinc battery using a metal oxide intercalation cathode. Nat Energy 1, 16119 (2016)

[9] Adams, Brian D., Ryan D. Brown, Marine Cuisinier, Susi Jin, 2024, Layered Electrode Materials and Methods for Rechargeable Zinc Batteries, US12170364, CA, Granted: 2024-12-17

[10] A unit for a measure of a battery cell's capacity (to store and deliver energy)

Project Objectives

The objectives of this project were to:

- Advance Zn-ion battery technology from the pre-commercial stage (TRL 4) to the technology demonstration stage (TRL 6).
- Help move Salient's testing, validation, and eventual manufacturing to California.
- Complete third-party validation of the Zn-ion battery technology.
- Design and build a residential Zn-ion energy storage system that can provide low-cost and safe energy storage to California ratepayers.
- Demonstrate the performance of a 10-kWh residential Zn-ion energy storage system at a third-party testing facility.
- Create four new, living-wage jobs in California by the end of the project.
- Develop a production readiness plan to manufacture Salient's energy storage technology in California.

Beyond the objectives of the project's initial parameters, a summary of project metrics and results appears in Appendix A: Project Metrics.

CHAPTER 2: Project Approach

While the general flow of the project proceeded as follows, many activities were carried out simultaneously. The Salient team developed a commercially viable Zn-ion cell (20 Ah) based on components developed on smaller 100 mAh test cells. The larger cells were tested to demonstrate improvements in the performance and capacity of Zn-ion cells. These were integrated with a battery management system into a 48-V Zn-ion battery module. The Zn-ion modules were then integrated into a residential energy-storage system, which included system control electronics and a commercially available inverter. The Zn-ion residential energy storage system was then tested at the third-party energy-engineering firm AKA Energy Systems, to evaluate the initial performance of the complete system.

Table 1 lists both the partners that worked with Salient throughout the project and their contributions to the project.

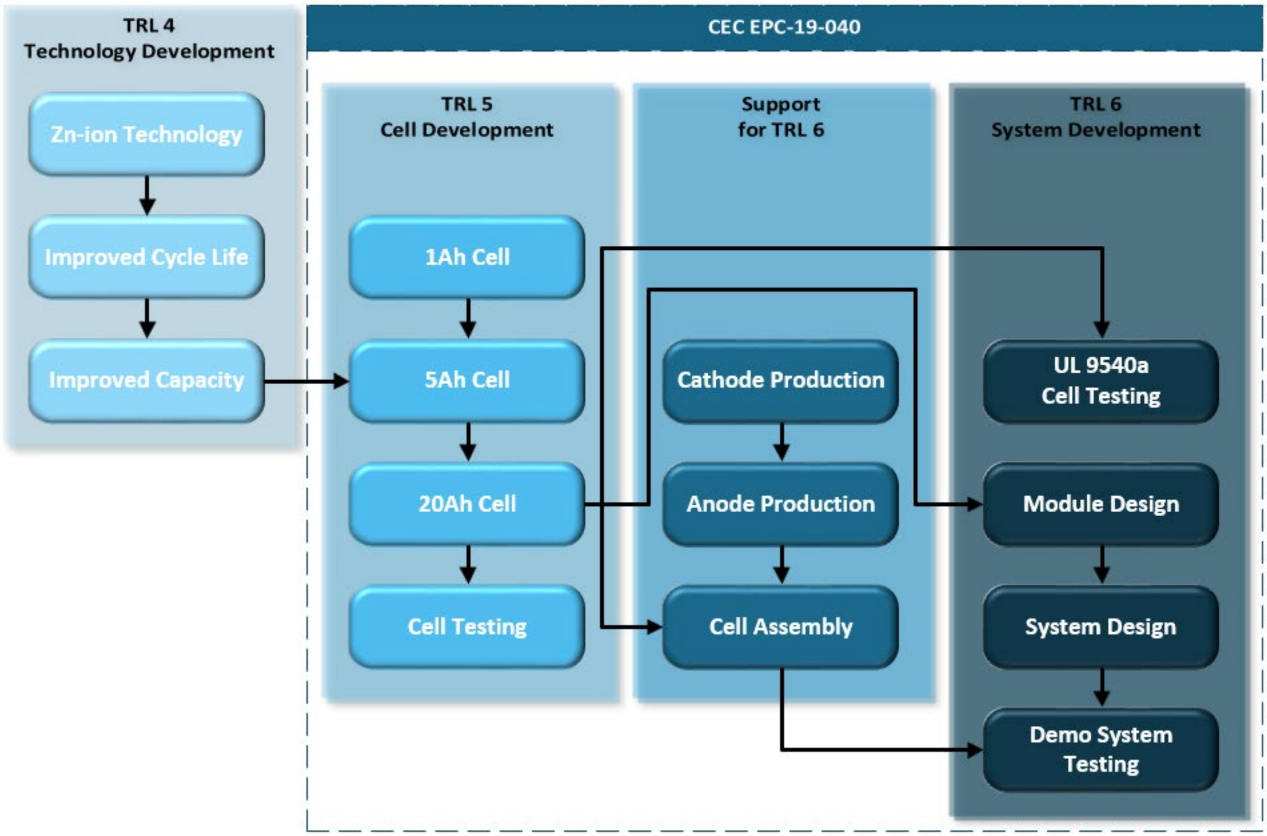
Table 1: Project Partners

Partner	Involvement
CEC, Private Investors, VCs	Project funding, both EPIC grant funding and associated match funding
Salient Energy	Prime recipient, carried out Zn-ion cell and system development
Technical Advisory Committee	Aided in technology direction and provided advice throughout the project
UL Solutions Northbrook	Carried out UL9540A safety testing on Zn-ion cells
AKA Energy Systems	Carried out Zn-ion residential demonstration system testing
Contract Manufacturers	Manufactured electrodes for Zn-ion cell production

Overall Project Approach

Outside this CEC project, research continues to further develop the core Zn-ion cell technology to improve cycle life and specific capacity for commercialization. Through this research project, targets to meet TRL 5 and TRL 6 were identified and project pathways developed to support those targets (shown in Figure 2), which illustrate the cascading, parallel development pathways for Zn-ion large-format cell development, cell production, and system development.

Figure 2: Zn-ion Parallel Development Pathways



Source: Salient Energy, Inc.

The tasks completed as part of this project are described in Table 2.

Table 2: Project Task Breakdown

#	Title	Description
1	General Project Tasks	General project administration, including initial and final meetings, reporting requirements, invoicing, permitting, and technical advisory committee initialization
2	Large-Format Cell Design and Validation	Designed a large format 20-Ah Zn-ion cell based on previously validated cell components. In later tasks, this large format cell was incorporated into a module with a battery management system (BMS) for the demonstration system.
3	Cell Production	Produced application-ready cells for long-term testing, certification, systems development, and, ultimately, inclusion in the final demonstration system
4	Long-Term Performance Testing	Demonstrated the long-term cycling potential of the Zn-ion battery through accelerated life-cycle testing

#	Title	Description
5	Energy Storage System Development	Designed and built a 10-kWh energy storage system with Zn-ion cells, a standard inverter, integrated control, and data-collection electronics
6	Safety Demonstration of Zn-ion Cell	Completed UL9540A testing of Zn-ion cells to demonstrate their safety
7	Installation and Operation of Demonstration Units	Delivered a 10-kWh Zn-ion energy storage demonstration system to AKA Energy Systems to measure system performance in a simulated environment
8	Evaluation of Project Benefits	Reported the benefits resulting from this project
9	Technology/Knowledge Transfer Activities	Developed a plan to make the knowledge gained, experimental results, and lessons learned available to both the public and key decision makers
10	Production Readiness Plan	Determined steps that will lead to the manufacture of technologies developed in this project and the ultimate commercialization of project results

Key Project Milestones

Given these project tasks, the milestones in Table 3 were developed to track project progress.

Table 3: Key Project Milestones

Task #	Title	Description
Technical Milestones		
2	Cell Development	• Design and prototype 20-Ah Zn-ion cells • Complete testing of 20-Ah Zn-ion cells
3	Cell Production	• Develop roll-to-roll processes to produce the positive and negative electrodes of Zn-ion cells • Develop quality control procedures for electrode and cell quality • Develop assembly processes for 20-Ah cells • Produce 100 x 20 Ah cells per month • Implement quality control procedures and develop the *Quality Control Procedure Report*
4	Long-Term Performance Testing	• Develop accelerated life-cycle testing protocol • Complete testing for accelerated life-cycle testing
5	Energy Storage System Development	• Develop Zn-ion module with integrated BMS • Conduct testing of Zn-ion module prototypes

Task #	Title	Description
		• Design a 10-kWh Zn-ion energy storage system, including commercially available inverter, Zn-ion modules, thermal controls, and electronic control unit
6	Safety Certification of Zn-ion Cells	• Deliver cells to subcontractor (IL LLC) to perform safety certification testing • Receive certification report
7	10 kWh Demonstra-tion System Testing	• Complete system validation testing of 10-kWh Zn-ion demonstration system
Administrative Milestones		
1	General Project Administration	• CPR meetings • Technical advisory committee development • Final reporting
8	Evaluation of Project Benefits	• Project benefits surveys • Project fact sheets
9	Technology Transfer and Knowledge Activities	• *Technology/Knowledge Transfer Plan* • *Technology/Knowledge Transfer Report*
10	Production Readiness Plan	• *Production Readiness Plan*

Overview of Zn-ion Technology

Salient's Zn-ion batteries represent a novel rechargeable cell technology with metallic zinc (Zn) negative electrodes, which undergo reversible plating and stripping[11] ($Zn \leftrightarrow Zn^{2+} + 2e^-$), and positive electrodes where Zn-ions (Zn^{2+}) (de-)intercalate[12] into during charge and discharge. This is completed in a near-neutral, non-toxic, thermally stable, safe, and aqueous electrolyte.

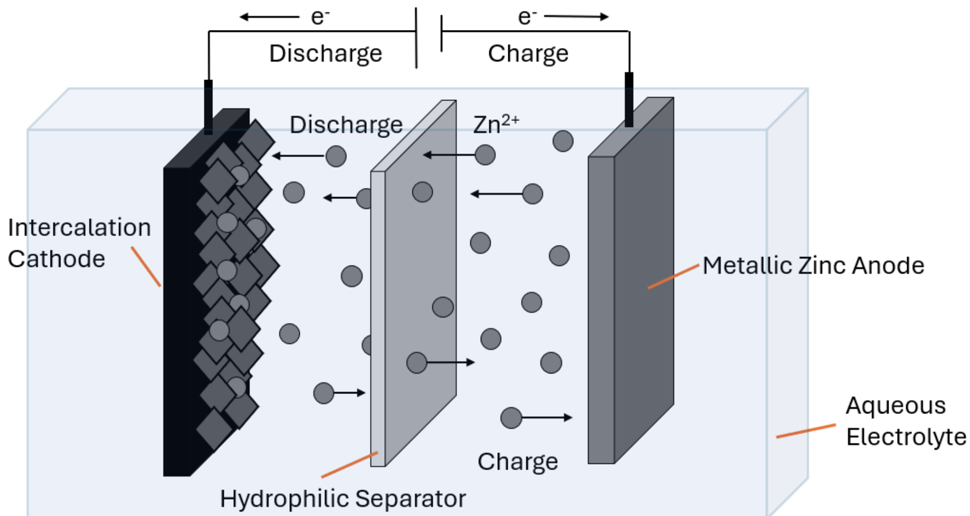
Salient is the first to incorporate zinc intercalation in the design of rechargeable zinc batteries, where Zn-ions are directly inserted into the active material at the positive electrode, sharing the same reaction mechanism as Li-ion batteries. Through this mechanism, Salient's core Zn-ion technology is functionally analogous to Li-ion cell technology, which enables high-power capabilities (how quickly energy can be stored and delivered) and high-energy efficiency (how much energy is returned on discharge following a full charge). Other emerging rechargeable zinc batteries (for example, zinc-air, nickel-zinc, zinc-bromine) are conversion batteries in which two different ions react at the surface of both electrodes while hydroxide ions (OH^-) or other anions (Cl^-, SO_4^{2-}) are transferred across the separator to enable conversion reactions.

[11] Physical plating of Zn onto the metallic Zn anode, and the reverse of removing Zn from the metallic Zn anode into the aqueous electrolyte in the form of Zn-ions.

[12] Intercalation is the process where ions or molecules are reversibly inserted into the structure of a host material without significantly altering its framework.

Figure 3 shows the basic schematic of a Zn-ion battery, showing the movement of stripped Zn-ions (Zn^{2+}) through the aqueous electrolyte and hydrophilic separator on discharge, to be reversibly intercalated into the cathode active material. On charge, the reverse occurs, Zn-ions are de-intercalated from the cathode-active material, shuttled through the electrolyte and separator, and finally re-plated on the metallic zinc anode to be re-used in subsequent cycles.

Figure 3: Diagram of Zn-ion Movement During Charge and Discharge



Source: Salient Energy, Inc.

As Zn-ion batteries are assembled with intercalation cathodes and metallic zinc anodes, cells are assembled in a charged state, eliminating the need for energy-intensive formation cycles[13] required for Li-ion, lithium iron phosphate (LFP) and sodium-ion (Na-ion) batteries.

Zn-ion batteries are produced from abundant, low-cost materials and feature a safe, non-toxic electrolyte, making them well-suited for all scales of stationary energy storage systems (ESS). The aqueous electrolyte and cathode active material eliminate risks such as thermal runaway, flammability, and toxicity—hazards commonly associated with Li-ion, LFP, and Na-ion batteries.[14,15]

Technology and Design Comparison

Zinc intercalation within Zn-ion cells enables higher energy density and delivers both higher power and higher energy efficiency when compared with other rechargeable zinc batteries.

[13] A battery formation cycle is an initial charging and discharging process conducted after assembly, which allows a protective solid electrolyte interphase layer to form on the anode. For more information, see: Schomburg, Felix, Bastian Heidrich, Sarah Wennemar, Robin Drees, Thomas Roth, Michael Kurrat, Heiner Heimes, et al. "Lithium-Ion Battery Cell Formation: Status and Future Directions towards a Knowledge-Based Process Design." *Energy & Environmental Science* 17, no. 8 (2024): 2686–2733. https://doi.org/10.1039/D3EE03559J.

[14] Qi, Changbao, Hewu Wang, Minghai Li, Cheng Li, Yalun Li, Chao Shi, Ningning Wei et al. 2025. "Research on the Thermal Runaway Behavior and Flammability Limits of Sodium-Ion and Lithium-Ion Batteries." Batteries 11(1): 24. Available online: https://www.mdpi.com/2313-0105/11/1/24.

[15] Larsson, Fredrik, Petra Andersson, Per Blomqvist and Bengt-Erik Mellander. 2017. "Toxic Fluoride Gas Emissions from Lithium-Ion Battery Fires." Scientific Reports 7: 10018. Available online: https://www.nature.com/articles/s41598-017-09784-z.

This core functionality enabled Salient to design and build its Zn-ion battery using the same thin-film cell design and component production processes as Li-ion batteries, which in turn allowed Zn-ion technology to benefit from the rapidly evolving manufacturing processes and equipment being developed for the Li-ion industry.

Unlike Li-ion cells, Salient's Zn-ion batteries use a zinc salt dissolved in water in a near-neutral aqueous electrolyte. The most used electrolytes for Li-ion/Na-ion batteries consist of hexafluorophosphate salt dissolved in an organic solvent (such as ethylene carbonate) and dimethyl carbonate, leading to thermal instability and toxicity issues.[16]

An overview of the comparison between Salient's Zn-ion, Li-ion, LFP and other emerging zinc technologies appears in Appendix B: Comparison of Zn-ion Cells to Other Cell Technologies**.**

Benefits of Zn-ion

Salient's Zn-ion cell technology for ESS is designed with four main value propositions: safety, affordability, sustainability, and a secure supply chain.

Safety

Due to the inherent safety and incapability of thermal propagation, Zn-ion ESS installations have minimal fire-spacing restrictions. This ultimately reduces land-use requirements and increases comparable volumetric energy density at the installation level (versus other technologies that may require higher system spacing due to thermal propagation). Each installed Zn-ion unit may also have higher total energy capacity, without requiring further fire spacing, increasing the comparable volumetric energy density at the installation level when compared with other battery technologies.

The Zn-ion cell's high safety level allows Zn-ion-based storage facilities to be installed inside homes, dwellings, and other high-traffic locations without concern — unlike Li-ion battery energy storage systems (BESS) systems that may require specific outbuildings, exterior installations, and fire-prevention measures (depending on the jurisdiction) due to potential thermal runaway fires. This reduces the barrier to entry in both infrastructure costs and space, to enable more accessible BESS installations compared with currently available cell technologies; this also reduces potential site management issues and installation costs due to ease of standardization.

To validate the safety of Salient's Zn-ion cell technology, Zn-ion cells were successfully tested against the testing standard that evaluates the fire and thermal runaway characteristics of a BESS (UL 9540A thermal propagation and hazardous gas generation). Refer to UL 9540A for detailed information.

Environmental and Cost Benefits

The environmental benefits of Zn-ion cells over incumbent and emerging energy storage technologies begin with the processing of the raw materials used to produce Zn-ion cells. The

[16] Qi, Changbao, Hewu Wang, Minghai Li, Cheng Li, Yalun Li, Chao Shi, Ningning Wei et al. 2025. "Research on the Thermal Runaway Behavior and Flammability Limits of Sodium-Ion and Lithium-Ion Batteries." Batteries 11(1): 24. Available online: https://www.mdpi.com/2313-0105/11/1/24.

abundantly available active materials in Zn-ion cells require significantly less raw material processing when compared with raw materials required for Li-ion. Using Argonne National Laboratory's Battery Performance and Cost Model (BatPac), these different material-processing requirements may result in an estimated 50 percent to 60 percent decrease in energy consumption in the raw material processing stage when compared with incumbent Li-ion nickel-manganese-cobalt cell technologies.[17]

Although Salient's Zn-ion cells borrow thin-film cell design and manufacturing from the Li-ion industry, there are notable changes from Li-ion manufacturing requirements that reduce production energy requirements for Zn-ion cells. The aqueous nature of Zn-ion cells eliminates the need for dry rooms, and Zn-ion cells are assembled in the charged state so that they do not require a formation process. These two processes alone may constitute up to 60 percent of the energy required to produce Li-ion cells.[18,19] Furthermore, as Zn-ion uses a metallic zinc anode, an anode coating line is not required, and recent developments in Zn-ion cathode use a water-based slurry slot-die coating,[20] which would eliminate future requirements for solvent recovery during cathode production.

Without requirements for dry-room conditions, formation-cycling, and simplified manufacturing processes, Zn-ion batteries could be manufactured at an estimated 60 percent lower cost than Li-ion batteries. This could lead to a reduction of up to $5 million USD/GWh in capital expenditure (CaPex) (out of an estimated $117 M USD/GWh) when compared with Li-ion giga-scale manufacturing facilities.[21]

Finally, research into the recyclability of Zn-ion batteries with primary alkaline Zn/MnO_2 cells shows that >80 percent of the Zn-ion cell may be recyclable through current recycling streams.[22]

Supply Chain Stability

The current surplus of lithium supply due to overestimated demand has temporarily driven prices down. However, there has been a reduction in material availability due to increasing mining disputes and political tensions in key lithium-producing regions. Lithium demand is also expected to increase significantly in coming years; market analysts anticipate an increase from

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[17] Knehr, Kevin W., et al. "Battery Performance and Cost Modeling for Electric-Drive Vehicles (A Manual for BatPaC v5.0)." Argonne National Laboratory, July 2022. https://doi.org/10.2172/1877590.

[18] Volta Foundation. 2023. 2023 Annual Battery Report. Volta Foundation. Available online: https://volta.foundation/battery-report-2023.

[19] Degen, Florian, Marius Schütte. (2022). Life Cycle Assessment of the Energy Consumption and GHG Emissions of State-of-the-Art Automotive Battery Cell Production. Journal of Cleaner Production, 330, 129798. https://doi.org/10.1016/j.jclepro.2021.129798.

[20] Slot-die coating is a high-precision technique used in battery production to apply a uniform layer of electrode material onto a substrate. This method enables consistent thickness, efficient material use, and scalable manufacturing, ensuring reliable performance and quality in energy storage applications.

[21] Degen, Florian, Marius Schütte. (2022). Life Cycle Assessment of the Energy Consumption and GHG Emissions of State-of-the-Art Automotive Battery Cell Production. Journal of Cleaner Production, 330, 129798. https://doi.org/10.1016/j.jclepro.2021.129798.

[22] Ciez, Rebecca E. 2021. Recycling Opportunities for Rechargeable Zinc Batteries. Purdue University.

2020 levels of less than 500,000 metric tons lithium carbonate equivalent[23] per year to an estimate of 2.4 million tons per year in 2030.[24] Therefore, the underlying issues surrounding resource availability and geopolitical dynamics present a strong case for anticipating future price hikes in lithium.

According to the *United States Geological Survey 2024*, over 20 times more zinc is mined per year, with global resources exceeding three additional orders of magnitude when compared with lithium.[25] Salient's technology and cell design allow for a complete North American supply chain utilizing domestic materials. A North American supply chain enables funding from the 2022 *Inflation Reduction Act* and increases material security by eliminating potential geopolitical risk.

[23] Lithium Carbonate equivalent is the industry standard used for comparison of quantities since lithium can be produced in a number of forms, including lithium carbonate and lithium hydroxide.

[24] Paz, Silvia (Chair), Ryan E. Kelley (Vice Chair), Steve Castaneda, Rod Colwell, Roderic Dolega, Miranda Flores, James C. Hanks, Arthur Lopez, Luis Olmedo, Alice Reynolds, Frank Ruiz, Manfred Scott, Tom Soto, Jonathan Weisgall. 2022. *Report of the Blue Ribbon Commission on Lithium Extraction in California.* California Energy Commission. Publication Number: CEC-300-2022-009-F.

[25] U.S. Geological Survey. 2025. Mineral Commodity Summaries 2025 (ver. 1.2, March 2025). U.S. Geological Survey, 212 p. Available online: https://pubs.usgs.gov/publication/mcs2025.

CHAPTER 3: Results

Cell Development

Building on the thin-film cell design borrowed from the Li-ion industry, increasing the capacity of Zn-ion cells requires increasing the active area in each cell, which can be achieved by designing multi-layer cell stacks and increasing the area of each electrode.

Milestone targets for cell development included:

- Design and testing of a 20-Ah Zn-ion large-format cell.
- Long-term accelerated testing.

A 1-Ah prismatic cell was designed to serve as a development test bed before increasing the size of the associated cell components to the targeted 20-Ah cell capacity. The 1-Ah cell had initial design issues in pressure application to the cell stack and electrolyte leakage, which were solved through implementation of a closed-cell foam within the cell case and improvements in the cell sealing using a material-addition hot-welding[26] technique to seal the plastic prismatic-case seams. After implementing these solutions, the 1-Ah cells performed as expected.

The original intent was to scale the 1-Ah prismatic cell design to a 20-Ah prismatic cell (seen in Figure 4), based on the proven design and performance of the 1-Ah prismatic cell. However, similar issues in pressure application and electrolyte leakage re-surfaced in the larger cell format.

Figure 4: 1-Ah Prismatic Zn-ion Cell Design (left): 20-Ah Prismatic Zn-Ion Cell Design (right)

Source: Salient Energy, Inc.

[26] Like traditional metallic welding where material is added to secure joints and seams, but with plastic as the working material, added to seal the joints.

The increase in active area and increase in electrolyte volume within the 20-Ah cell amplified the problems. The stack pressure application resulted in significant issues at the sealed seams of the 3D printed case, resulting in electrolyte leakage. The solution was to separate the pressure application and cell sealing requirements with large-format pouch cells.

Initial redesigns targeted a 5-Ah Zn-ion pouch cell that utilized the same electrode format and footprint as the 20-Ah prismatic cell. This enabled cell sealing to be more robust, following industrial norms in cell manufacturing (without significant capital cost) and to apply stack pressure externally (Figure 5). The 5-Ah Zn-ion pouch cells performed as expected.

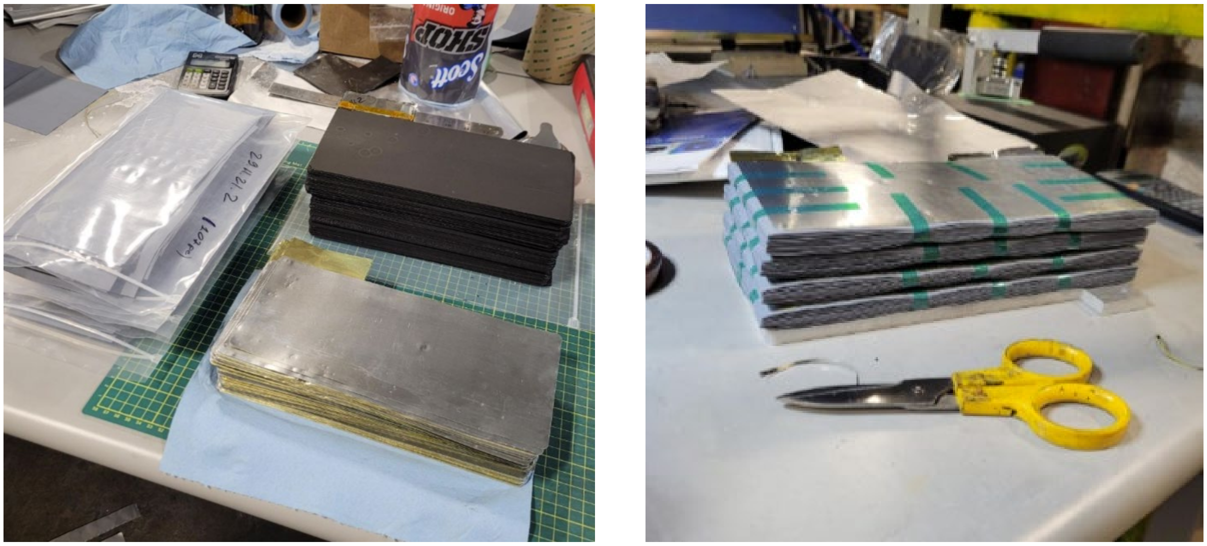
This substantial redesign resulted in a decrease in cell failure rates from 70 percent to <1 percent. Failures in the 20-Ah prismatic cell were ultimately attributed to inconsistency in the hardware connections within the cell, inconsistent pressure application from the internal pressure-application foam, and electrolyte leakage.

Figure 5: 5-Ah Zn-ion Pouch Cell (left): 5-Ah Zn-ion Pouch Cells in Pressure Rig (right)

Source: Salient Energy, Inc.

With successful testing of the 5-Ah Zn-ion pouch cells, scaling to the target 20-Ah cell capacity continued (Figure 6). This required increased throughput of Salient’s current electrode production capabilities (see “Cell Production” later in this chapter).

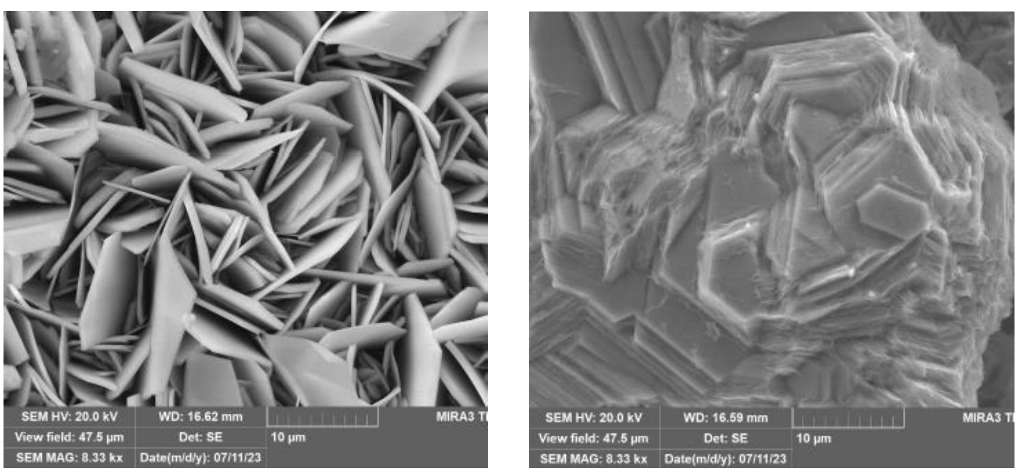
Figure 6: 20-Ah Zn-ion Pouch Cell Subcomponents Before Cell Stacking (left); 20-Ah Zn-Ion Cell Stacks (right)



Source: Salient Energy, Inc.

During development and testing of the new 20-Ah Zn-ion pouch cell, Salient's research and development staff continued to make significant improvements to the core Zn-ion technology. Through cathode slurry, electrolyte development, and separator improvements, both higher-rate capability and the specific capacity of the active material were achieved. Beyond capacity improvements, the new electrolyte effectively eliminated the impact of short circuits in Zn-ion cells by controlling the plating morphology of the replated zinc during charging, significantly extending cycle life before short circuiting occurred (Figure 7).

Figure 7: Zn Plating Morphology[27] and Platelet Formation with Previous Electrolyte (left), and Controlled Zn Plating Morphology Through Electrolyte Development (right)



Source: Salient Energy, Inc.

[27] The structural characteristics, including size, shape, and surface texture, of deposited Zn particles.

Substantial performance improvements also amplified a failure mode within the core Zn-ion cell technology: active material dissolution.[28] This failure mode was expected to occur during discharge as zinc ions were intercalated into the active material, soluble active material ions were ejected from the cathode and diffused through the aqueous electrolyte.

Due to the failure mechanism, the capacity fade was directly proportional to the increased capacity of the active material during cycling. As the specific capacity was increased in any cell format, the capacity fade also increased ─ consistently resulting in a stabilization region at ~40 percent of the initial specific capacity where cells could cycle hundreds to thousands of cycles with very little capacity fade.

A critical direction for further research was thus identified; however, cell design and system development continued. A milestone cell that balanced capacity and cycle life was locked in for the module and system design. This milestone cell will be referred to as Zn-ion LFC (large-format cell). Refer to "Ongoing Development" for more information on active material development since it is outside the scope of this CEC research project.

Zn-ion LFC Testing

The active material dissolution failure mode had a significant impact on the possible cycle life of Zn-ion cells. As a result, long-term life cycle testing of Zn-ion cells was reduced to in-house testing to learn more about the cyclability of Zn-ion cells (aside from total cycle life). Tests were performed to compare varying states-of-charge.

The active material dissolution failure mode was directly tied to specific capacity;[29] it was found that cells with lower specific capacity faded less. Limiting cell performance using the previous generation electrolyte and separator resulted in cyclability improvements when compared with higher-capacity cell configurations, including the new electrolyte (see Figure 8). After the capacity fade, until ~60 cycles, cell capacity continued to perform at ~40 percent of initial capacity following the capacity trend of the previous cell design.

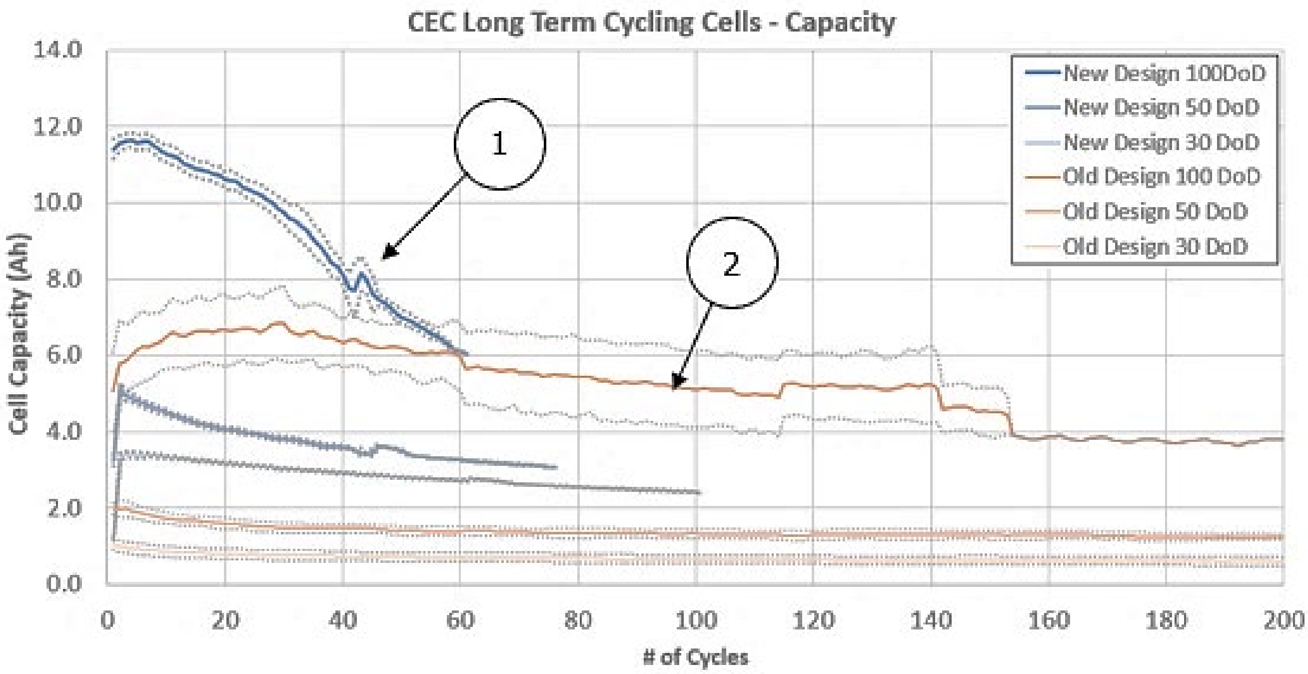
Accelerated life cycle testing of the Zn-Ion LFCs was completed with varying depths of discharge (DoD)[30]. Figure 9 shows the 30 percent DoD testing where cycling of the large-format Zn-ion cells underwent 3000 cycles, at which point capacity faded to ~40 percent of the original capacity, consistent with the active material dissolution failure mode.

[28] T. N. T. Tran, S. Jin, M. Cuisinier, B. D. Adams, D. G. Ivey, "Reaction Mechanisms for Electrolytic Manganese Dioxide in Rechargeable Aqueous Zn-ion Batteries", Scientific Reports, 11 (2021) 20777.

[29] Specific capacity refers to the charge stored per unit mass of active material in a battery

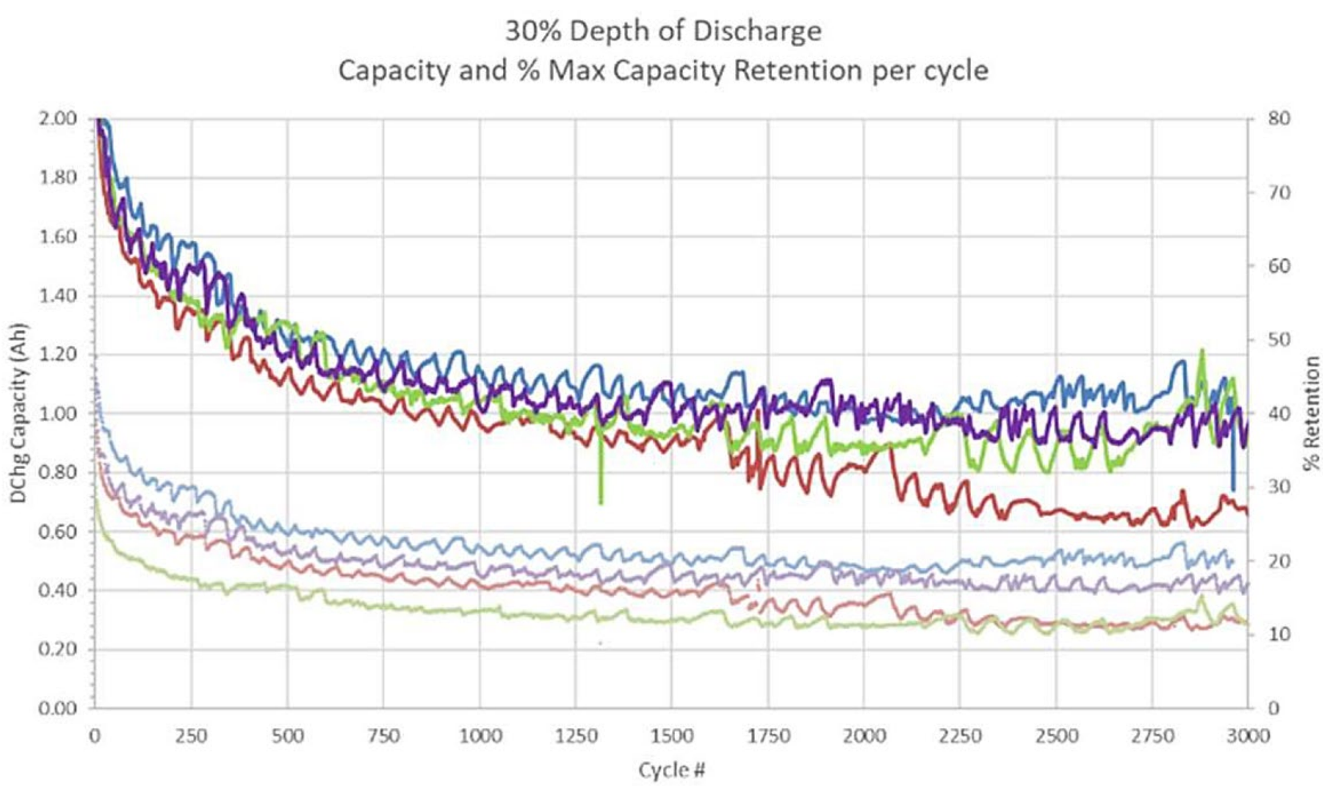
[30] As a property of a battery cycling regime, DoD quantifies the cycling depth, defined as the discharged Ah during a single cycle, divided by the nominal (rated) capacity of the battery (from Karden, In *Encyclopedia of Electrochemical Power Sources*, 2009).

Figure 8: Long-Term Cycling of Target 20-Ah Cells, Comparing Cell Capacity and Capacity Fade of New and Old Electrolyte



Source: Salient Energy, Inc.

Figure 9: Accelerated Life-Cycle Testing of 30-Percent Depth-of-Discharge Testing of Target 20-Ah Zn-ion Cells



Source: Salient Energy, Inc.

Zn-ion Cell Production

Increasing throughput and quality of the production of Zn-ion cells was required to support the development of both LFCs and the Zn-ion modules and subsequent system. For example, 272 Zn-ion cells were required for a single 10-kWh Zn-ion residential demonstration system.

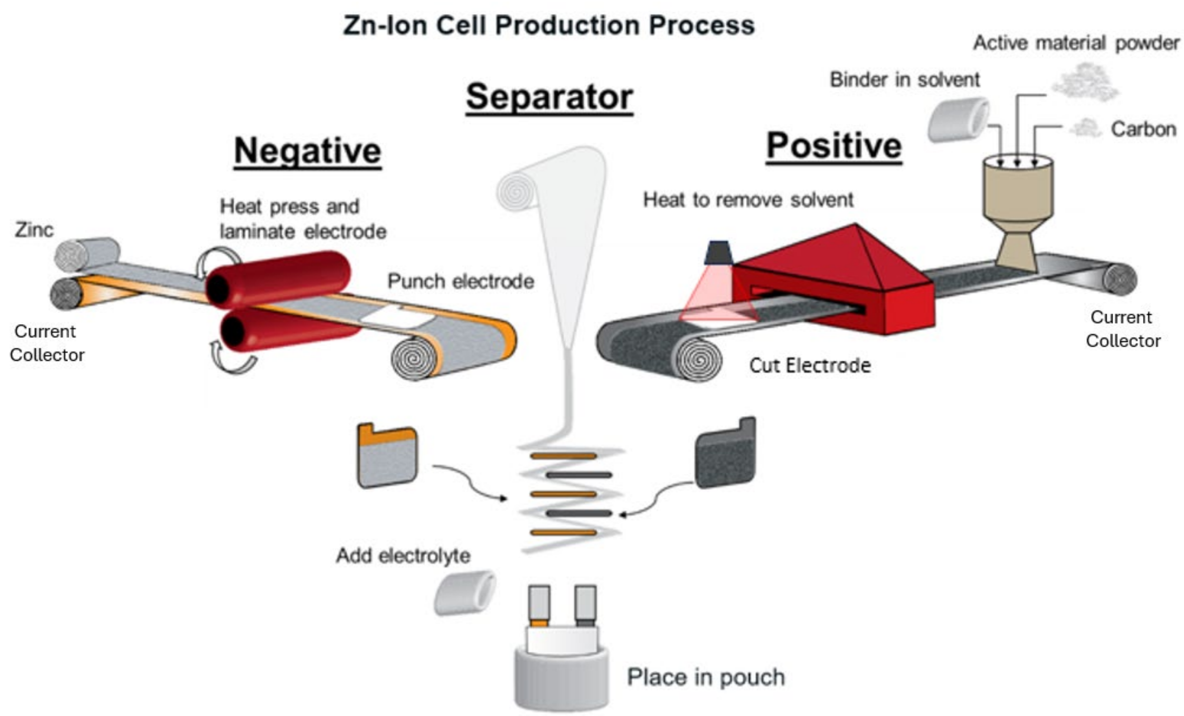
The target milestones for this set of tasks were to:

- Develop roll-to-roll processes to produce the positive and negative electrodes of Zn-ion LFC.
- Develop assembly processes for Zn-ion LFC.
- Implement quality control procedures.
- Produce 100 Zn-ion LFCs per month.

Through the industrial standard of thin-film cell design for Zn-ion cells, many production processes required to manufacture Zn-ion cells can be replicated from the existing Li-ion industry. This reduces the manufacturing technology development required to increase throughput of Zn-ion subcomponents.

The positive electrode consists of a thin-film metallic foil coated with a thin carbon primer layer, then coated with a matrix consisting of the active material, carbon, and binder. The negative electrode similarly consists of a thin film metallic foil laminated with zinc foil. The separator is received on rolls and Z-folded during cell-stack assemblies. After tab and terminal welding, the cell stack is then sealed into a pouch with the aqueous electrolyte (Figure 10).

Figure 10: Zn-ion Cell Production Process

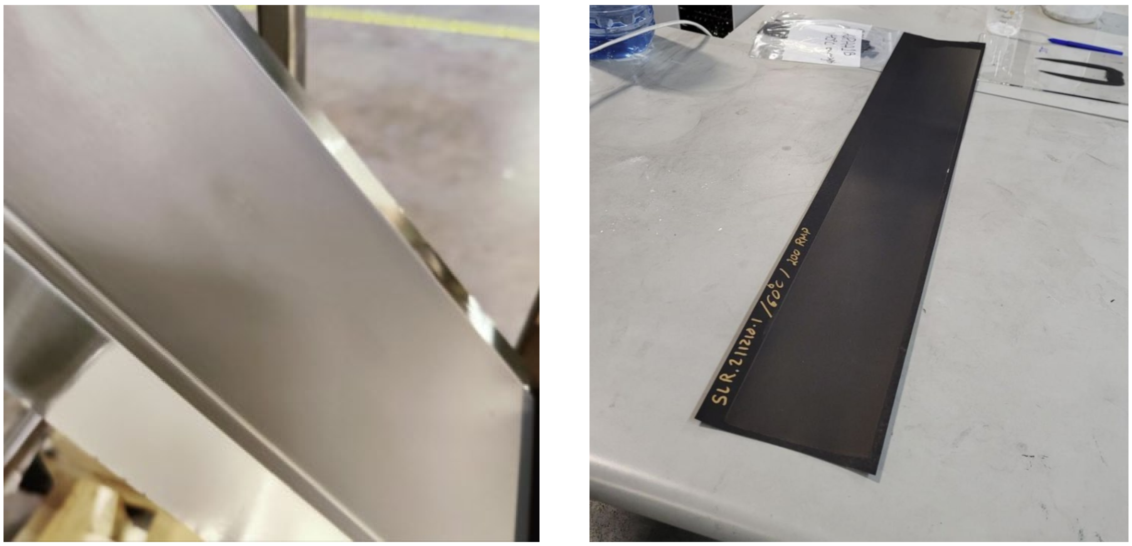


Source: Salient Energy, Inc.

Positive Electrode

The positive electrode production process was developed internally before working with an industry contract manufacturer to increase its throughput. In-house process development of the positive electrode resulted in very low throughput, equivalent to ~10 meter (m) positive electrode per day (Figure 11).

Figure 11: Dried Positive Electrode Following In-House Roll-to-Roll Process Development



Source: Salient Energy, Inc.

After establishing in-house roll-to-roll manufacturing capabilities of the Zn-ion positive electrode, it was determined that the in-house mixing capabilities and Doctor Blade coating[31] limited the overall quality of the positive electrode. Additionally, contract manufacturing was required to minimize capital cost.

While throughput of initial production runs with contract manufacturers was a substantial improvement over in-house coating methods, despite the use of higher quality equipment and industry-standard processing methods such as the use of planetary mixers[32] and slot-die[33] coatings, the quality of the electrode produced notably declined when compared with in-house production methods (Figure 12). Improving the quality of the produced positive electrode thus became an additional priority for these external contract manufacturers.

[31] Doctor Blade Coating is a technique used in battery cathode production where a slurry of active material, binder, and solvent is spread evenly onto a current collector using a precisely controlled blade to achieve a uniform thickness.

[32] A planetary mixer is a high-shear mixing device used in cathode slurry preparation, where multiple mixing blades rotate on their own axes while simultaneously orbiting around a central axis. This dual motion of high and low shear mixing ensures thorough dispersion of active materials, binders, and solvents.

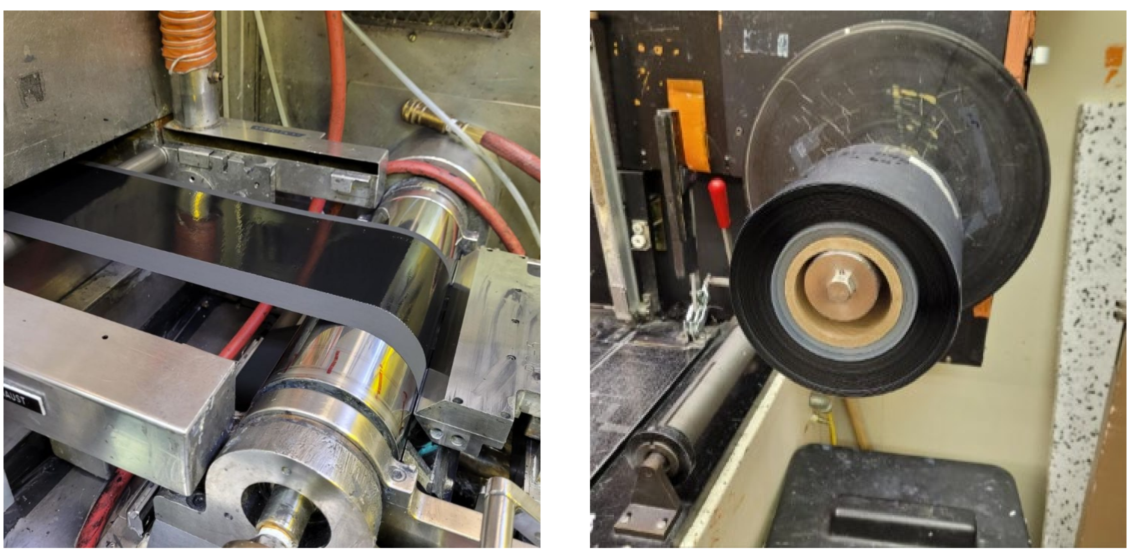
[33] Slot-die coating is a precise, high-throughput technique used in cathode manufacturing, where a controlled flow of slurry is dispensed through a narrow slit onto a moving substrate to form a uniform coating.

Figure 12: Initial Production Runs of Positive Electrode at Contract Manufacturers, Showing Poor Quality of the Coated Positive Electrode Material

Source: Salient Energy, Inc.

One of these contract manufacturers continued process development for the positive electrode of Salient's Zn-ion cells. They had the capability of mixing up to 20 liters of cathode slurry and coating onto substrate up to 150 millimeter (mm) width (Figure 13, left).

Figure 13: Slot-Die Coating Head Coating Zn-ion Cathode (left): ~40 m Roll of Dried Zn-ion Cathode (right)

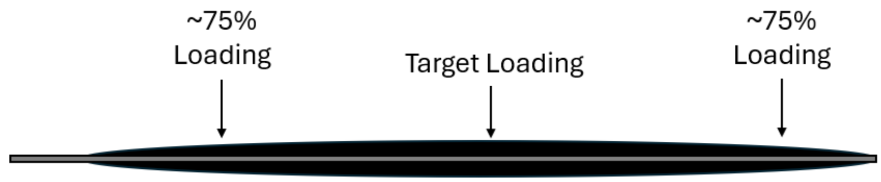


Source: Salient Energy, Inc.

Through continued process development, a production throughput of 40 m of double-sided electrode was achieved. This marked a significant milestone in the production of Zn-ion cells.

As Salient's production-quality measurement capabilities improved, the team identified issues with pressure distribution and limitations in performance of the Zn-ion LFC from the rolls of cathode from this contract manufacturer. Variation up to ~25 percent of the thickness and loading across the width of the coated electrodes was identified, using a fixed array of micrometers (Figure 14).

Figure 14: Variation of Loading Across the Width of the Coated Cathode



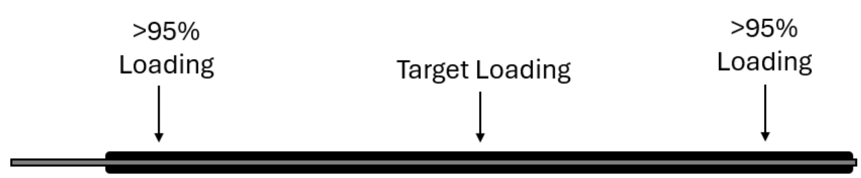
Source: Salient Energy, Inc.

Adjusting coating parameters including line speed, pump speed, slurry viscosity, slot-die shim heights, internal shim shape, and slot-die gap resulted in only marginal improvements in the coating's uniformity. It was determined that the slot-die heads used were worn from years of use without maintenance. The costs and timeline to correct this issue made continuing production with this manufacturer undesirable so Salient decided to change contractors for this part of the process.

This production challenge was used as an opportunity to introduce an improved Zn-ion cathode slurry to improve cathode performance and producibility. The new slurry increased active material content, which improved mass loading and decreased the drying time of the cathode.

Process development at the new contract manufacturer was more straightforward with its more advanced equipment. In combination with the new slurry composition, this resulted in a reduction in thickness variation from ~25 percent to <5 percent while improving electrochemical performance, marking a substantial increase in quality of the Zn-ion positive electrodes (Figure 15). The equipment at this manufacturer was capable of coating on substrate up to ~300 mm in width. This enabled two-lane coating capabilities, doubling the throughput. Following production optimization, this resulted in over 200 m of Zn-ion cathode produced per coating day, representing a 500-percent increase in production capability.

Figure 15: Reduced Variability in Loading and Thickness Across the Width of Zn-Ion Cathodes



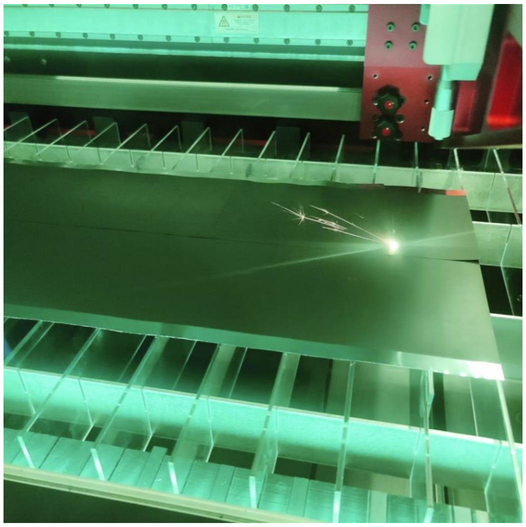
Source: Salient Energy, Inc.

Production with this contract manufacturer continued regularly throughout the remainder of the project.

Following cathode coating, the cathode must be processed for cell stacking. The roll of coated cathode was calendered[34] to increase density and improve conductivity, performance, and volumetric energy density. This is analogous to Li-ion cell electrodes and was carried out in-house at Salient. This process can produce electrode material at a rate of 3 meters per minute (m/min), or up to 1000 m of cathode material per day.

Once densified, the cathode material is laser-cut to size through a custom scanning-field gantry laser-cutting machine (Figure 16). The machine cuts 2 m of cathode material in 90 seconds, processing over 400 m of cathode per day.

Figure 16: Laser-Cutting Positive Electrodes to Size for 20-Ah Zn-ion Cells

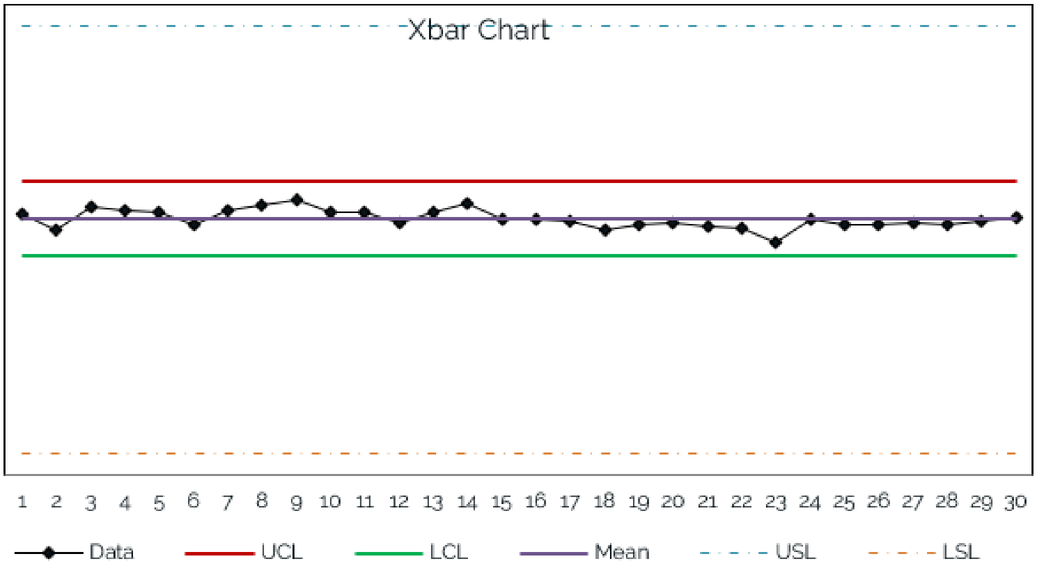


Source: Salient Energy, Inc.

Quality evaluation of the laser-cutting process determined that variation was less than ±0.08 percent in width and length of the electrodes produced, indicating a highly capable cathode-cutting process. The custom laser-cutter will continue to be a significant asset as production throughput increases. An example of the length measurements taken from laser-cut cathode samples is shown in Figure 17.

[34] Calendering or 'Compression Rolling' - this process involves passing the coated electrode material through precision rollers to increase density, improve adhesion, and enhance electrochemical performance.

Figure 17: Xbar Run Chart of Cathode Length Produced from Laser-Cutting



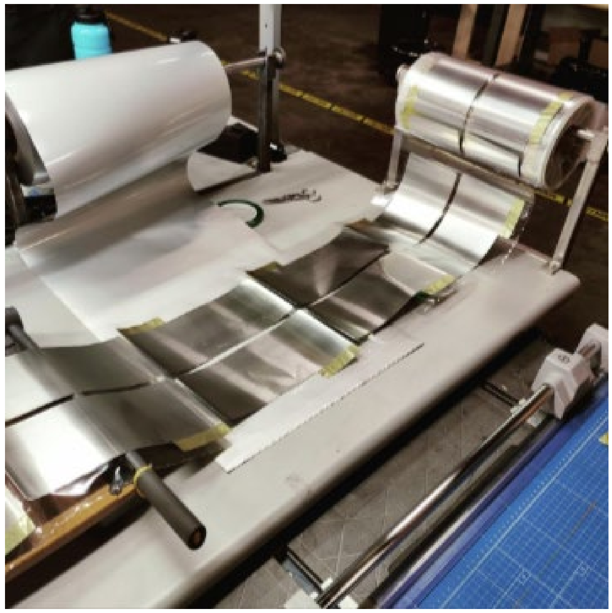
Source: Salient Energy, Inc.

Negative Electrode

Alongside the positive electrode, an equal amount of negative electrode is required to manufacture Zn-ion cells. The design of negative electrodes consists of two zinc foils laminated on either side of a metallic foil current collector. An internal process was developed to produce Zn-ion negative electrodes through hand-layup and calendering, which required significant effort. This process enabled production of up to 50 m of negative electrode per day with reasonably acceptable results in both quality and variability.

Many contract manufacturers exist in the laminating industry (often referred to as converters) and can produce significant amounts of roll-to-roll materials. A contract manufacturer was identified to produce negative electrodes for Salient, so process development was completed. The process included inline rotary-die cutting of the laminated roll of electrode, resulting in rolls of laminated electrodes ready for use (Figure 18).

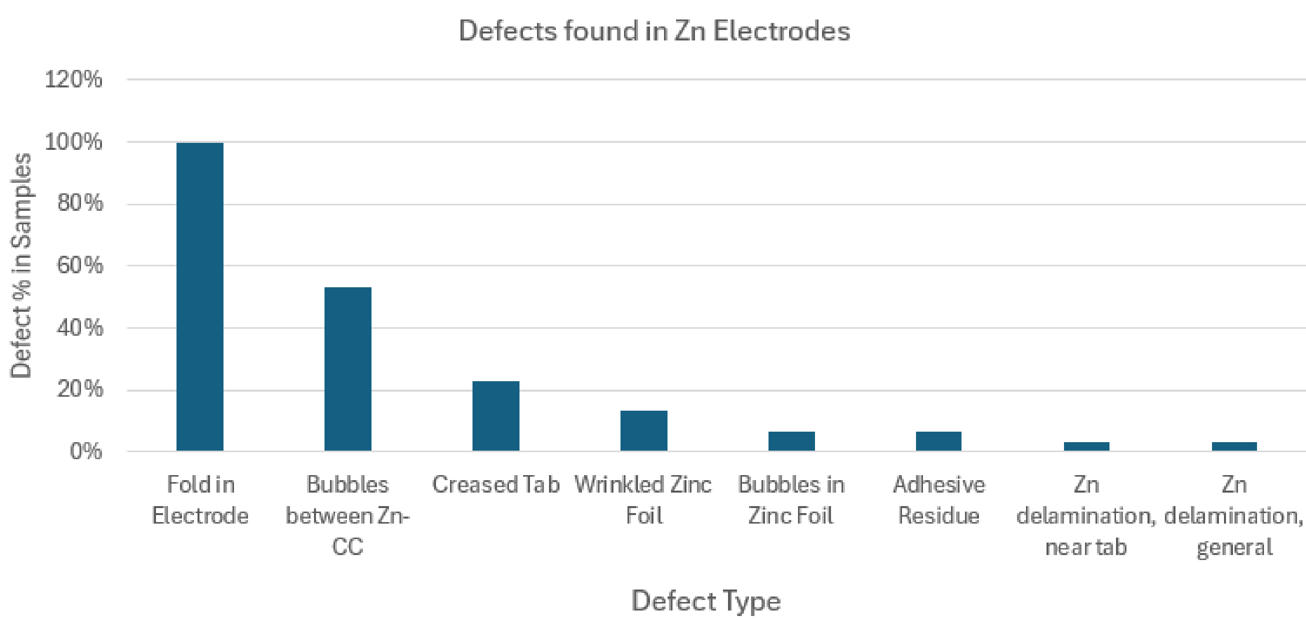
Figure 18: Roll of Rotary-Die Cut Zn-Ion Negative Electrodes Produced at Contract Manufacturer



Source: Salient Energy, Inc.

The first batches provided by the contract manufacturer initially met Salient's expectations, and the majority were ultimately used within cells without issue. However, a subset of these first batches had potential quality issues including significant folds and bends in the electrodes, bubbling between layers, bending and creases of the tab, and other general quality issues. A full breakdown of defects is shown in Figure 19. Photo examples of the types of defects are shown in in Figure 20.

Figure 19: Defects Identified in Negative Electrodes from Contract Manufacturing



Source: Salient Energy, Inc.

Figure 20: Examples of Defects Identified in Negative Electrode Production, Folds and Bends (left) and Creased Tab (right)

Source: Salient Energy, Inc.

It was confirmed that the folds and bends found in 100 percent of the negative electrodes had developed in the rewinding and packaging stage of the process. The solution was to cut the electrodes into sheets and ship the electrodes flat to reduce the impact of being re-rolled for extended periods of time. This greatly reduced the re-occurrence of this issue. At the same time, the contract manufacturer improved process control to reduce occurrences of other identified quality issues.

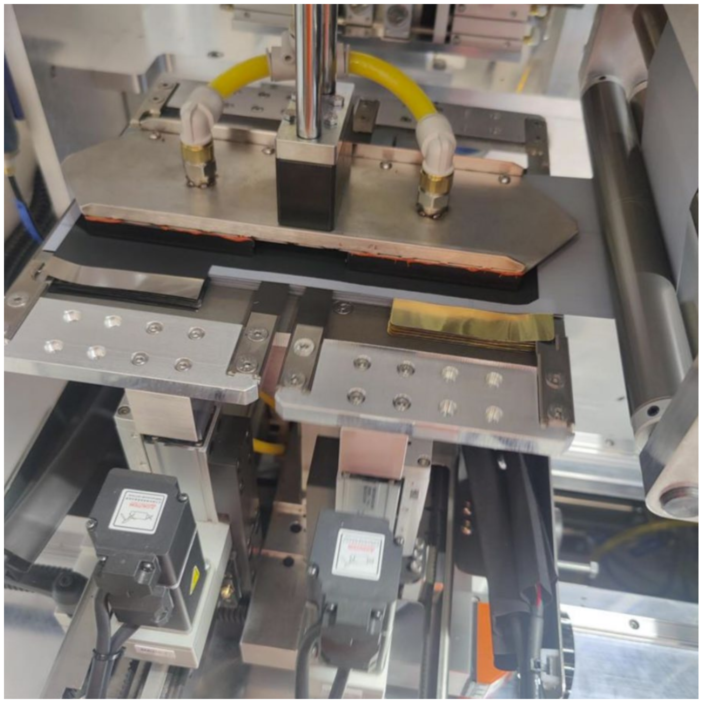
This process is highly scalable and capable of running at line speeds of over 3 m/min in a similar 2-lane configuration as the positive electrode (300 mm width substrate); this resulted in production throughputs of up to 2000 m of electrode per day. Thousands of ready-to-use negative electrodes were ordered throughout the project for use in testing, development, and cell production.

Cell Assembly

Salient processes both electrodes for quality, fit, and function for use in the Zn-ion LFC. Cell stacks are made of cathodes, anodes, and separators. This is completed by an automated z-fold stacking machine (Figure 21), capable of producing a Zn-ion cell in ~2 minutes. This enabled production of up to 180 Zn-ion cells per day.

Misalignment between the positive and negative electrodes was consistently <0.5 mm in all directions: an acceptable margin for the purposes of this project. Benefits in throughput and reduced variability can still be achieved, however, with additional process development and modifications. After cell stacking, electrode tabs and terminals are laser-welded together (see Figure 22).

Figure 21: Zn-ion Cell in the Middle of Stacking by Automated Z-Fold Stacker



Source: Salient Energy, Inc.

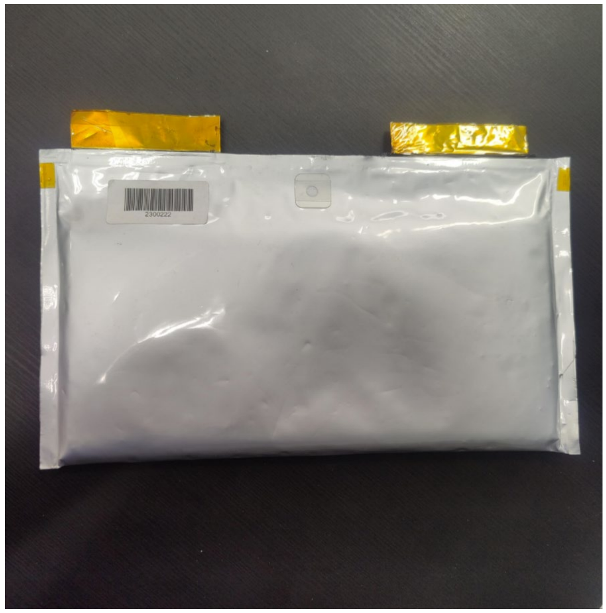
Figure 22: Example of Laser-Welding the Electrode Tabs/Terminal of a Zn-Ion Cell

Source: Salient Energy, Inc.

Once both welds were completed, the cell stacks were vacuum wetted with aqueous electrolyte in pouches and sealed (see Figure 23).

Following cell assembly, the cells completed end-of-line testing cycles to measure electrochemical quality metrics to batch cells for module assembly.

Figure 23: Example of a Zn-ion LFC, Terminals Taped to Prevent Short-Circuit During Handling



Source: Salient Energy, Inc.

UL 9540A Testing

A substantial value of Zn-ion cells for use in stationary energy storage systems is its significant safety improvement over both existing and emerging cell technologies. Due to the aqueous electrolyte and stable materials, Zn-ion cells have no possibility of thermal runaway. Originally, certification testing UL 2054[35] and/or UL 1973[36] was targeted to evaluate the safety of Zn-ion cells. However, that was changed to target thermal runaway and propagation testing through the standard testing directions of UL 9540A, "Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems."

The UL standard UL9540 "Energy Storage Systems and Equipment" is the primary standard used to determine safety and construction requirements for electrochemical or other energy storage systems used to both receive and store energy and provide electrical energy. UL9540A is the standard test method for evaluating thermal runaway under the UL9540 standard and was determined to be the most relevant standard to demonstrate the superior safety of Salient's Zn-ion battery chemistry.

UL9540A testing subjects cells, modules, and systems to external stresses that induce thermal runaway including overcharging, external heating, short-circuiting, and mechanical damage. Tests are performed incrementally for cells, modules, and systems. If the cells cannot be

[35] UL 2054 is a standard for household batteries. Its requirements "cover portable primary (non-rechargeable) and secondary (rechargeable) batteries for use as power sources in products". This standard does not apply to cells to be used in stationary energy storage systems.

[36] UL1973 is a Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications).

forced into thermal runaway through the described external stresses, further testing at higher levels is usually not required.

The intent of UL9540A testing is to make two primary determinations.

- The likelihood of inducing thermal runaway in the unit being tested
- The flammability of gases that may be released by the cell

Testing is typically conducted on the primary subcomponents. If the test can be passed at the cell level, for instance, it typically negates the need to test at the module or unit levels.

During UL9540A testing of Salient's Zn-ion cell, four distinct tests were used to induce thermal runaway and create off-gassing events. These included nail penetration of the cell, overcharge of the cell, over-discharge of the cell, and short-circuiting of the cell. None induced thermal runaway. In addition, the cell vent gas collected did not present a flammability hazard when mixed with any volume of air.

In meeting the performance criteria of the UL9540A tests, Salient demonstrated the superior safety of the Zn-ion technology at the cell level. The UL test report stated that "module level testing in accordance with UL 9540A need not be conducted" given that the performance criteria were met at the cell level.

For more information, please refer to the project deliverables.

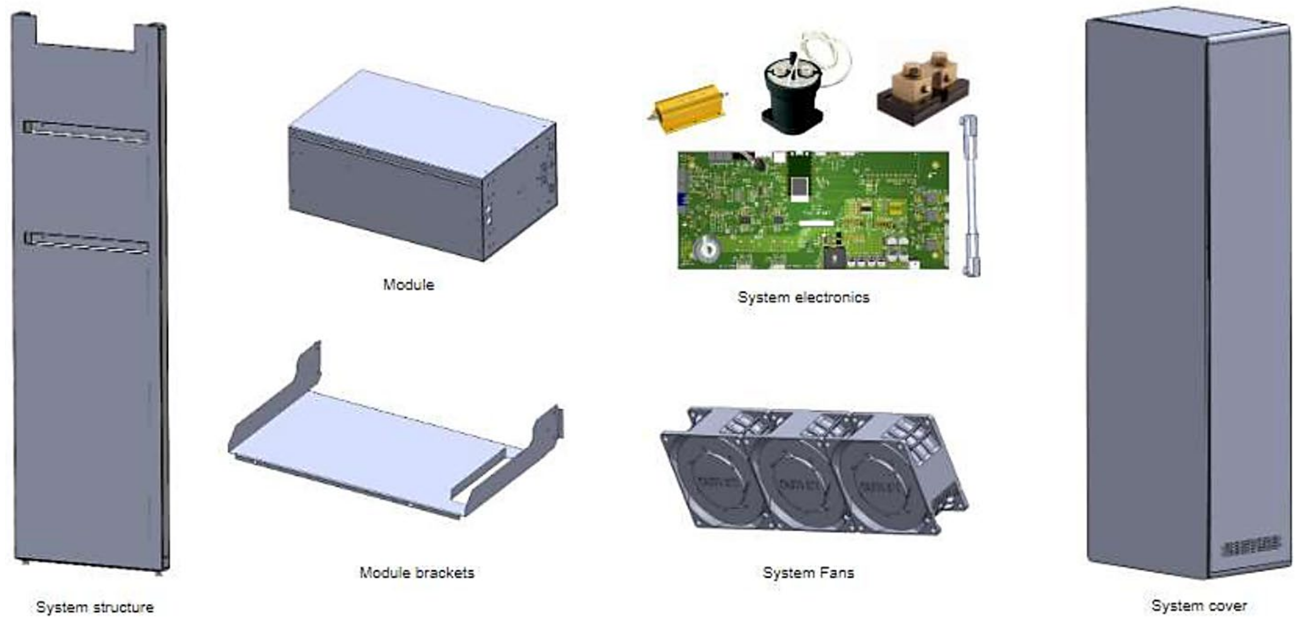
System Development

Throughout 2022 and 2023, Salient developed a 10-kWh Zn-ion residential demonstration system to demonstrate the performance of Zn-ion cells in a simulated environment. Cells were produced and modules assembled through Q2 2023 into Q1 2024.

The 10-kWh Zn-ion residential demonstration system consists of eight 48-V Zn-ion modules designed by the Salient team. Each 48-V Zn-ion module houses 34 Zn-ion cells in series (see Figure 24 for renderings of major subcomponents). The design capacity of the total system is between 7.68 kWh to ~11.0 kWh, depending on the charge/discharge rate[37] of the system, between C/3 and C/10.

[37] C-rate is a measure of the rate at which a battery charges or discharges relative to its maximum capacity, where 1C corresponds to a full charge or discharge in one hour. A higher C-rate (e.g., 2C) means faster charging or discharging, while a lower C-rate (e.g., C/2) indicates slower operation.

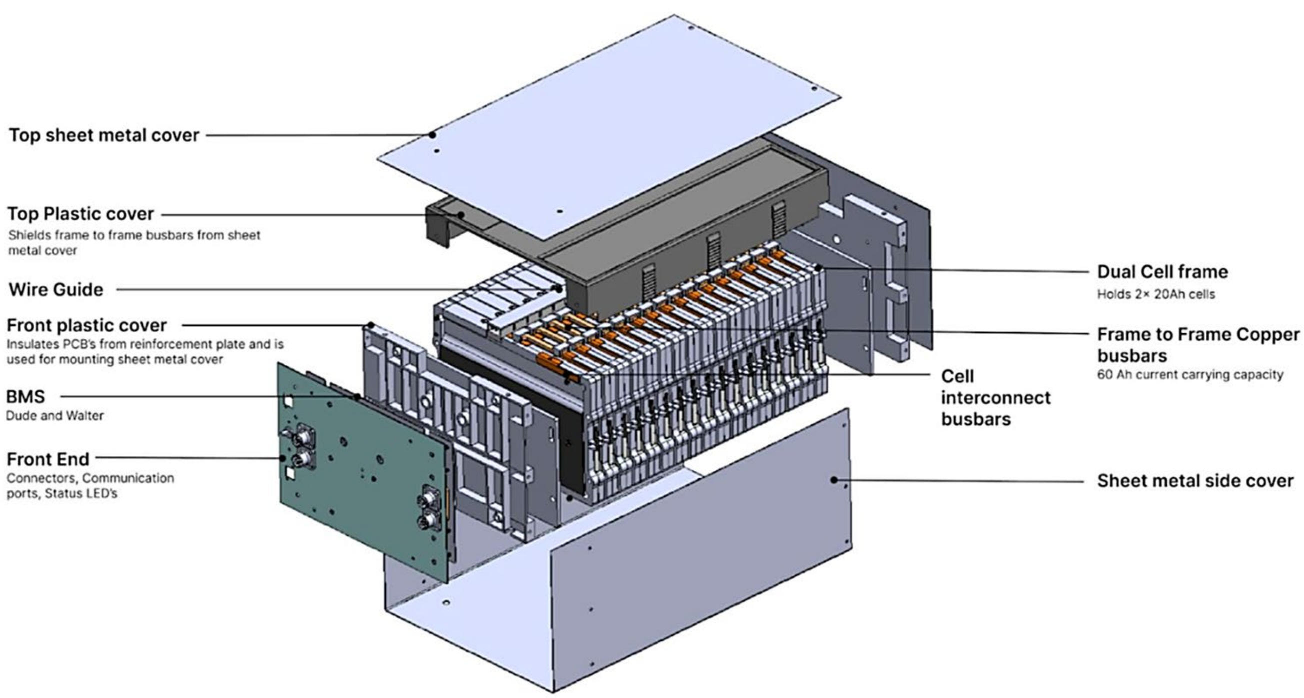
Figure 24: Components for the General System Construction of the Zn-Ion Demonstration System



Source: Salient Energy, Inc.

Figure 25 shows an exploded view of a 48-V Zn-ion module; an example of an assembled module is shown in Figure 26.

Figure 25: Exploded View of 48-V Zn-ion Module, Showing the General Construction, the 34-Cell Zn-Ion Battery Pack, Compression Plates, BMS, and Load Connections



Source: Salient Energy, Inc.

Figure 26: 48-V Zn-ion Module Prior to Demonstration System Assembly

Source: Salient Energy, Inc.

A custom 34-cell BMS was developed for the 48-V Zn-ion cell module to enable passive cell balancing, thermal shutoff capabilities, and cell monitoring.

Prior to full system assembly, all Zn-ion cells used in the demonstration system completed end-of-line testing. During this testing, the 272 Zn-ion LFCs had an average capacity of 7.4 Ah at C/3. This is less than the target capacity of 20 Ah, which reduced the expected capacity of the system. Resistance measurements of each cell were taken, and cells were batched to minimize resistance variations between modules, minimizing the impact of cell variability on system performance capabilities at the module level.

The 48-V Zn-ion modules with capacity of 7.4 Ah (at C/3) yielded expected total energy capacity of ~355 watt-hours (Wh) per module, compared with the 960 Wh (at C/3) target module capacity. This resulted in a total possible system capacity of 2.84 kWh or approximately 35 percent of the target of 7.68 kWh (at C/3).

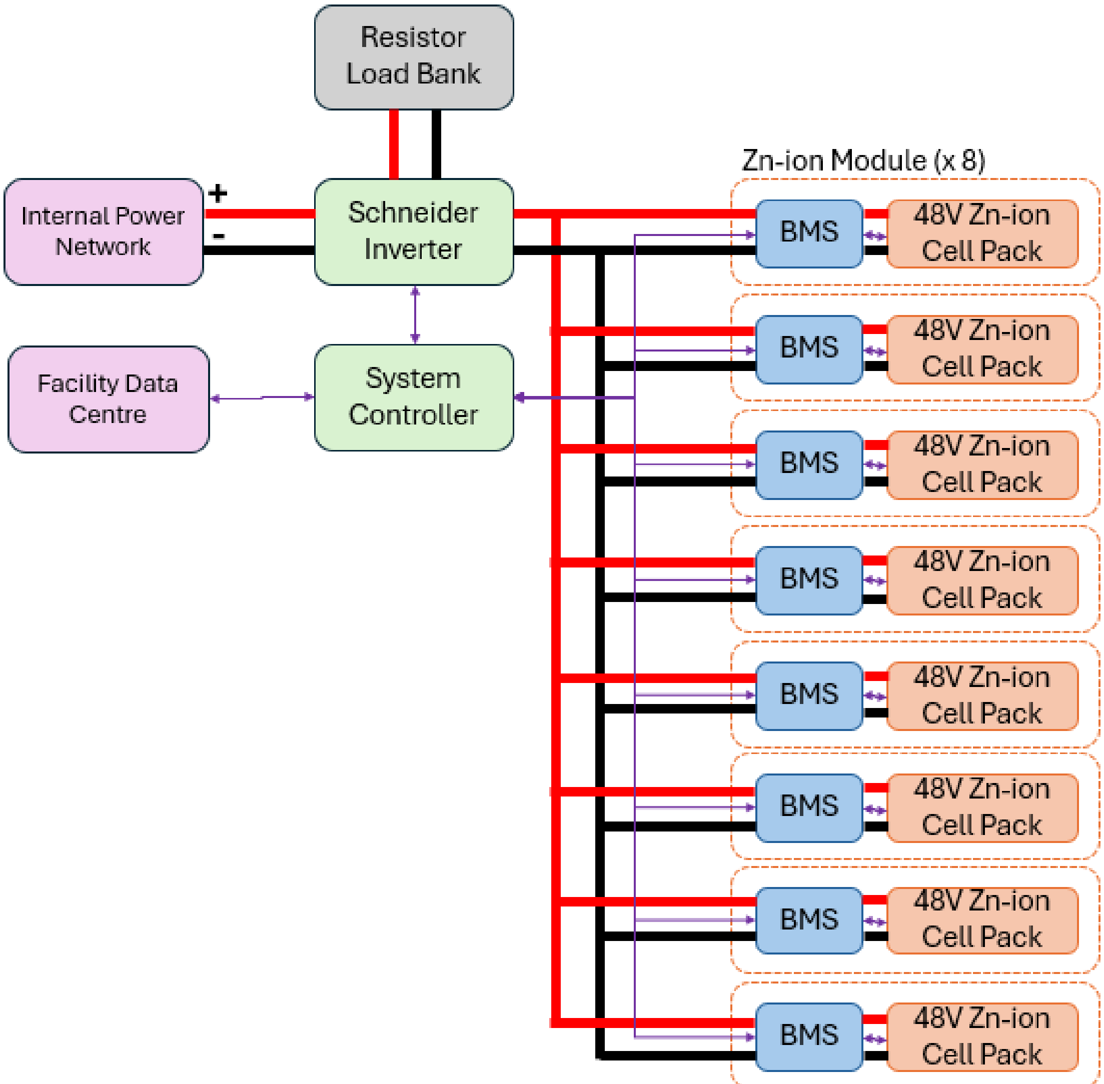
A single 48-V module was tested separately and achieved 0.3 kWh at ~C/6 for over 100 cycles without significant degradation.

System Testing

Demonstration system testing was performed at three rates (C/3, C/6, and C/10) to simulate varying residential loads of intra-day residential battery energy-storage systems. These rates were calculated from previous individual module cycling to meet the discharge time targets.

The demonstration system was assembled at Salient's third-party systems engineering partner and connected to the internal power distribution network through a Schneider Electric Conext XW Pro 48 VDC/120-V AC inverter to simulate residential loads. The system interface block diagram is illustrated in Figure 27.

Figure 27: 48 V Zn-ion Residential Demonstration System Integration Block Diagram



Source: Salient Energy, Inc.

Power delivery was handled through the inverter; cell data, module performance, and BMS states were handled through the BMS, system controller, and output to the facility's internal data center.

In addition to cell and module performance data, thermal data was recorded during all system testing. Cell temperatures were monitored on the positive terminal of each cell frame and module temperatures were measured at the front and rear of the modules and battery packs. Ambient temperatures were also recorded using the same system. No significant increases in temperature were identified during system testing.

Considering the capacity of the Zn-ion cells used in the system, the highest attainable capacity was 2.84 kWh at C/3.

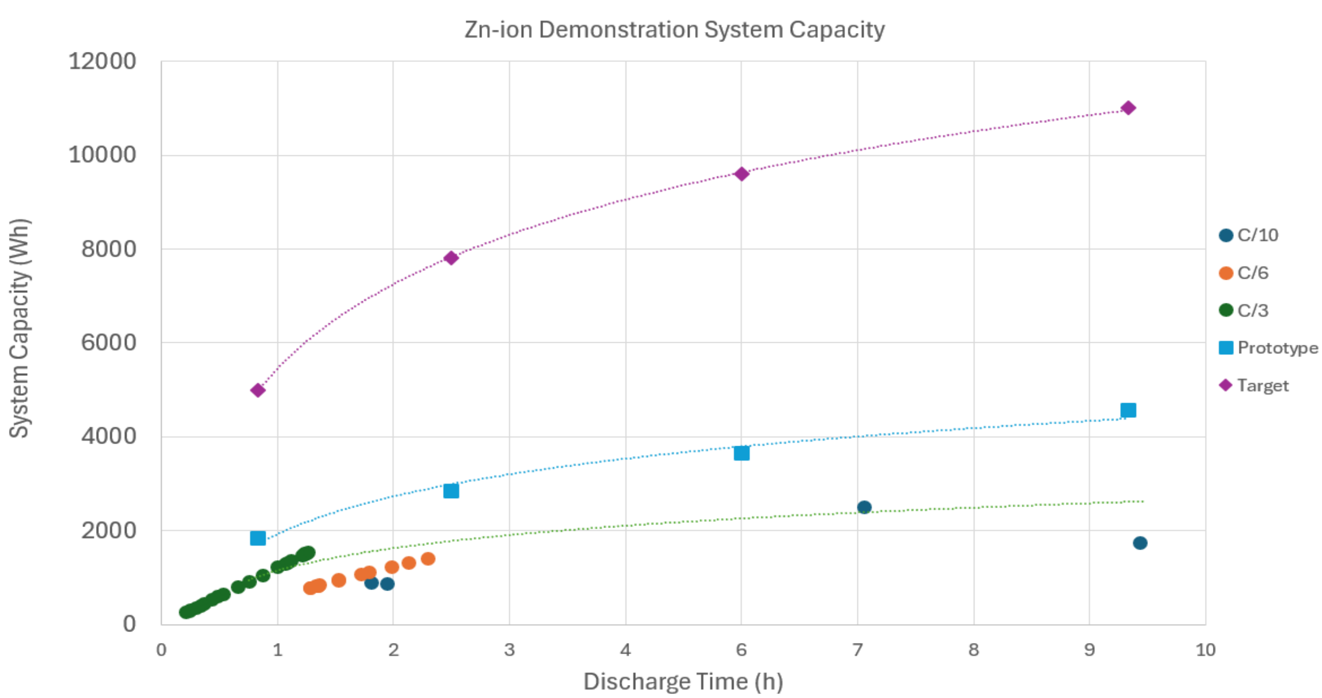
The testing protocol included an initial equalizing discharge of the system, followed by a cycle at C/10 to measure initial module and system capacities. After completing a week of C/6 cycling, the system underwent another C/10 cycle to assess the mid-testing module and system capacities. Finally, after completing a week of C/3 cycling, the system was tested with a C/10 charge/discharge to determine the end of testing system capacity.

The highest capacity of 2.5 kWh was achieved during C/10 cycling, followed by a decrease in capacity at C/6 and C/3 cycling rates.

A summary of the system capacity data during C/10, C/6, and C/3 cycling tests versus discharge time is shown in Figure 28. As previously noted, the highest projected system capacity was observed during the second set of C/10 cycles, where the system reached a total capacity of 2.5 kWh with a discharge time of approximately 7 hours. In the C/6 cycling, the system's maximum capacity was 1.4 kWh, with a discharge time of around 3 hours. During the C/3 cycling tests, the system achieved a peak capacity of 1.5 kWh, with a discharge time of roughly 1.5 hours.

The diamond-marked trendline shown in Figure 28 is the design capacity of the system. The square-marked trendline is the approximate possible system capacity given the prototype of Zn-ion cells used in the assembly of the system. The circle-marked trendline is based on the peak capacity achieved at each rate during system testing.

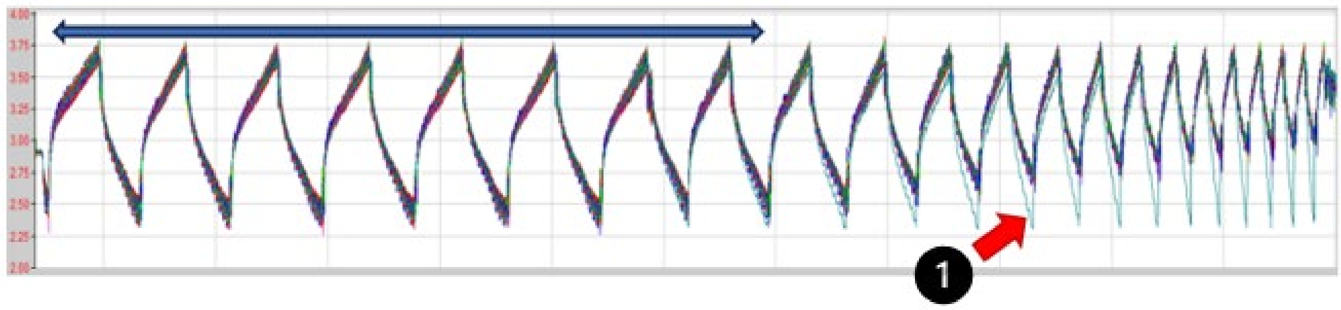
Figure 28: System Rate Capability: System Capacity Versus Discharge Times: Additional Trendlines Highlight both Prototype and System Capacity Targets



Source: Salient Energy, Inc.

The lower-than-targeted capacity and discharge times can be attributed to the ~7.4-Ah Zn-ion cells used and their respective ages upon assembly. The unexpected degradation of the cells over the course of the cycling tests reduced the system capacity significantly by limiting the voltage cutoffs during both charge and discharge (Figure 29).

Figure 29: Cell Voltages During C/3 Cycling of the Demonstration System



Source: Salient Energy, Inc.

Routine assessments of key performance characteristics and cell cycling were periodically carried out to ensure expected functionality prior to module assembly. Despite these precautions, some cells still experienced performance decreases during testing, leading to further replacements. In total, 3 cells were replaced during cycling, in addition to potentially an additional 3 cells within modules excluded from testing due to degradation. Given that the system contained 272 cells, these replacements and exclusions may seem relatively inconsequential; but they had a significant impact on overall system performance due to the system-wide voltage limitations during both charge and discharge.

This baseline data will be valuable for the development of next-generation Zn-ion systems. The improvements in cell design, performance, and cycle life will help optimize the systems' overall efficiency and rated capacity in the next phase of development.

Plans are underway to investigate failures of the cells that limited the system's full capacity. It is expected that failure modes have since been identified and solved, but these failures were learning opportunities to confirm failure types and test remaining cells.

Ongoing Development

Alongside system development and testing, cell development met the target cell capacity of 20 Ah. However, these cells were not used throughout the project, including long-term life cycle testing and demonstration-system testing.

Outside of the project, substantial improvements have been made in Salient's Zn-ion active material to reduce the impact of the active material dissolution. The stability of Salient's new active material supports hundreds of cycles before significant capacity fades.

Through continuous cell technology and cell design improvement, integration of this active material could result in substantial cycle-life improvement in large-format Zn-ion cells.

Industry Impact on Project

Along with the rest of the world, Salient experienced setbacks caused by the COVID-19 pandemic. The pandemic led to significant increases in lead times for nearly everything:

materials, time availability with contract manufacturers, and, especially, equipment lead times required to bring production processes in-house.

The most substantial impact on Salient was the uncertainty brought about by the COVID-19 pandemic, alongside the impact of the active-material dissolution failure mode, leading to difficult decisions in scaling the company. This led to the closure of Salient's California office and re-location to Salient's facility in Dartmouth, Nova Scotia, to finish the remaining tasks.

These events had important impacts on the outcome of the project, including the following.

- Testing protocols for both cell- and system-level testing were impacted due to time limitations, delays, and availability of testing with the new third-party systems contractor.
- Delays associated with the closure of the California office and assembly of the 10-kWh residential demonstration system resulted in the use of Zn-ion cells that were ~18 months old and shipped across North America twice before time-system testing.
- Increase in responsibility for Salient's Canadian team to understand and continue the work that completed by the California team
- Delays associated with BMS development and required modifications for system testing

Public Awareness of Project

Throughout this research project, Salient gained valuable insights that have contributed to the growth and evolution of both current and future technologies. Ensuring that this knowledge is shared not only within the organization but also externally is essential for future growth and development.

Salient has shared developments in Zn-ion technology and product development with external stakeholders through venues including conferences, publications in the scientific community, discussions with national-standard authorities, and engagement with potential customers.

Salient presented at and attended the following events.

- **Presented:**
    - Canada's Rising Stars in Electrochemical Systems Symposium (2022, 2024)
    - NAATBatt Sodium-Zinc Battery Workshop (2023)
    - Zinc Battery Workshop (2024)
- **Attended:**
    - Smart Energy Event (2022, 2024)
    - RE+ (2023, 2024)
    - International Battery Seminar (IBS, 2023)
    - International Battery Materials Association Meeting (2024)

Salient Energy published the following publications and journal articles.

- T. N. T. Tran, S. Jin, M. Cuisinier, B. D. Adams, D. G. Ivey, "Reaction Mechanisms for Electrolytic Manganese Dioxide in Rechargeable Aqueous Zn-ion Batteries," Scientific Reports, 11 (2021) 20777
- O. Rubel, T. N. T. Tran, S. Gourley, S. Anand, A. V. Bommel, B. D. Adams, D. G. Ivey, D. Higgins, "Electrochemical Stability of ZnMn2O4: Understanding Zn-Ion Rechargeable Battery Capacity and Retention," The Journal of Physical Chemistry C, 126 (27), (2022) 10957-10967
- S. Anand, S. Gourley, C. Miliante, B. D. Adams, D. Higgins, O. Rubel "Computational Screening of Cathode Materials for Zn-ion Rechargeable Batteries," arXiv preprint, (2022) 2212.05319
- S. W. D. Gourley, R. Brown, B. D. Adams, D. Higgins, "Zn-ion Batteries for Stationary Energy Storage," Joule, 7(7), (2023) 1415-1436
- C.M. Miliante, S. Gourley, B. D. Adams, D. Higgins, O. Rubel, "Roadmap for the Development of Transition Metal Oxide Cathodes for Rechargeable Zn-ion Batteries," The Journal of Physical Chemistry C, 128 (41), (2024) 17261- 17273

Beyond events and publications, Salient has shared its technology and expertise with the industry and beyond through the following activities.

- Zn-Ion Cell Development Through Development Work with Contract Manufacturers for Zn-Ion Electrode Manufacturing
- Presentations with the CEC and Stakeholders
- LinkedIn Posts Highlighting Company Milestones

Salient will continue to share its findings and developments across the Zn-ion technology development pathway — from core technology to future large-scale energy storage system development and installation.

CHAPTER 4: Conclusion

Zn-ion Tech, Product Development, and Key Outcomes

Key outcomes for the development of Zn-ion cell technology, large format Zn-ion cells, and the 10-kWh residential Zn-ion demonstration system follow. For a comprehensive summary of project metrics and results, please refer to the table in Appendix A: Project Metrics**.**

Zn-ion Cell Development + Testing

Cell development during the project increased the capacity of Zn-ion cells from 1-Ah prototype cells to Zn-ion large-format cells (LFC), reaching 5-Ah capacity and up to 20-Ah pouch cells. Limitations were identified in the original plan to scale from 1-Ah prismatic cells to 20-Ah prismatic cells; a pivot was made to design 5-Ah pouch cells. Following the successful testing of 5-Ah Zn-ion pouch cells, 20-Ah Zn-ion pouch cells were designed, but performance limitations resulted in ~7-Ah Zn-ion LFCs.

Limitations associated with the cathode active material were identified following substantial improvements in the performances of the cathode slurry, electrolyte, and separator. Poor cyclability created additional limitations in cell design and development. A new active material has since been developed to solve this issue and is currently being incorporated into Zn-ion LFCs.

Zn-ion Cell Production

Expanded manufacturing of Zn-ion cells was completed by developing roll-to-roll manufacturing for both positive and negative electrodes. Producing the positive electrode consisted of roll-to-roll slot-die coating onto a metallic current collector, comparable with that found in Li-ion cell production. Producing the negative electrode was a simple lamination process of zinc foil onto a metallic current collector. This is found in many industries, ensuring both simple processing and high throughput.

The throughput attained from quality positive electrode at a contract manufacturer is up to 110 m per day on a 300-mm width substrate.

The throughput attained in negative electrode production at a contract manufacturer is more than 3 m/min line speed, resulting in over 1,000 m of 300 mm width negative electrode produced per day.

Densification of the cathode was performed at Salient up to 5 m/min, resulting in the capability to process up to 2,000 m of 300 mm wide positive electrode per day.

Laser-cutting was employed to cut the positive electrode to shape and is capable of processing over 300 m of 300 mm width cathode per day.

Production of a safe, competitive energy storage system in North America will provide jobs in safe environments, enabling a high level of learning and a capable workforce while targeting carbon-neutral energy production through renewable-resource policies such as those mandated in SB 100 and SB 350 in California.

UL 9540A Testing

The safety of Zn-ion cells was successfully tested against standard UL9540A, "Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage System," which was unable to either force Zn-ion cells into thermal runaway or generate hazardous gases. Thermal runaway was force-tested through short-circuit, overcharging/over discharging, and externally applied heat. No indication of thermal runaway or hazardous gas was detected.

Due to the inherent safety of Zn-ion cells displayed during cell-level testing of UL9540A, further testing at either the module or system level was not required.

Zn-ion System Development + Testing

A 10 kWh Zn-ion residential demonstration system was designed, manufactured, assembled, and tested. The total capacity of the system was limited due to older generation Zn-ion cells installed during the testing of the system; however, all design work was carried out with the anticipated 20-Ah cell capacity, ensuring that all connections, spacing, and limitations were sized appropriately.

The system was tested at a third-party engineering firm, reaching a peak capacity of 2.5 kWh during ~C/10 cycling. The variation in the prototype Zn-ion LFCs used in the system caused limitations in the total-capacity capability of the system, limiting charge and discharge by the voltage of the weakest individual cell (out of all 272 cells in the system).

Recent developments in core technology and cell design will directly translate to both improved system performance and capacity.

This is a successful step toward commercialization of Zn-ion technology; however, it is not without challenges.

The next step in commercializing a residential Zn-ion system is refining the design of the residential system to enable the first 10-to-100 installations of Zn-ion residential systems in the field for further testing. This will include improved testing metrics and provide greater understanding of Zn-ion cell use in the field for daily energy-storage use. This will require further increases in Zn-ion cell and system production capacity, which are both planned in the near future.

Market Opportunities

The inherent safety of Zn-ion offers significant opportunities in residential, commercial, and industrial markets, and in grid-scale energy storage. Resistance is increasing against other battery technologies due to large-scale battery-storage fires throughout both North America and the world. Even when the batteries aren't the source of the fire through thermal runaway, there is the potential for significant release of toxic gases, which require residential evacuations and continuous monitoring.

Beyond the residential market, additional markets could include high-value, eco-conscious communities that focus on minimizing harmful impacts to the environment. These communities typically value sustainability, ecological harmony, and self-sufficiency by integrating renewable energy, organic farming, natural building practices, and collaborative living to reduce environmental impacts and foster closer connections with nature. As the number of these communities grows, the comparatively low environmental impact of Zn-ion energy storage solutions could become more attractive.

As production capabilities of Zn-ion cells and systems grow, larger-scale opportunities will be targeted (including commercial and industrial and grid-/utility scale installations), providing value in substantially increased safety, affordability, and sustainability over both current and emerging energy-storage system solutions.

Future-Looking Projects

To further the development and commercialization of Zn-ion technology, the following projects are under development.

Active Material Development

Salient has been working on developing a new active material, which could greatly reduce Mn dissolution in current Zn-ion cells. Early results show that over 300 cycles this new active material can significantly reduce both discharge capacity loss and cell polarization over the baseline. While still in development, this advancement has the potential to greatly improve cycle life, capacity, and rate capability, while maintaining commercially viable capacity.

Large Format Zn-ion Cell Design

Integration of the new active material will be the first step toward improvements in the design of large format Zn-ion cells. Building on the knowledge gained from this research project, development will be carried out to increase cell capacity, improve rate capability, and improve the cycle life of Zn-ion cells.

Module and System Field Demonstrations

Design replication of the current residential energy storage system will be completed to build on knowledge generated by the assembly and production of the world's first Zn-ion energy-storage system. The initial target will be toward a design to enable the production and installation of systems for field demonstration testing. These residential demonstration systems will include improved testing protocols and various integration types, such as pairing with renewable-energy resources, both grid-connected and completely isolated.

Further improvements will be made through learnings gained from the numerous residential installations for field demonstration, ultimately preparing for the commercial availability of Zn-ion residential energy-storage systems.

Increased Zn-ion Production

Initial production targets were to increase the production capability of the current manufacturing facility to over 10 MWh annually. This will support in-the-field demonstration systems and the first commercial residential units, and support development of larger Zn-ion building blocks for commercial, industrial, and grid-scale modules and systems.

Beyond the 10-MWh annual cell production, scaling to 100 MWh annual production is planned and will continuously grow by adding more production lines to meet 1-GWh annual production capacity.

System assembly will be completed and scaled alongside Zn-ion cell production to meet the requirements of residential demonstration systems, commercial residential units, and ultimately commercial, industrial, and grid-scale modules and systems.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Ah (mAh)	A unit for a measure of a battery cell's capacity (to store and deliver energy)
BESS	Battery Energy Storage System
BMS	Battery Management System, controls the charging/discharging of cells in a battery through cell balancing and thermal monitoring/ protection
CapEx	Capital Expenditure, initial cost for facility and equipment
CEC	California Energy Commission
C-Rate	C-rate is a measure of the rate at which a battery charges or discharges relative to its maximum capacity, where 1C corresponds to a full charge or discharge in one hour. A higher C-rate (for example, 2C) means faster charging or discharging, while a lower C-rate (for example, C/2) indicates slower operation.
Cycle Efficiency	Measure of energy output relative to input during energy storage system and cell cycling
Depth of Discharge (DoD)	As a property of a battery cycling regime, it quantifies the cycling depth, defined as the discharged Ah during a single cycle, divided by the nominal (rated) capacity of the battery (from Karden, In *Encyclopedia of Electrochemical Power Sources*, 2009).
Energy Efficiency	Measure of energy output relative to input during energy storage system and cell cycling.
EOL	End-of-line, associated with cell testing for quality control
ESS	Energy storage systems
GHG	Greenhouse gases such as CO_2, CH_4, N_2O, O_3
GW	Gigawatt, 1 X 10^6 watts of power
Intercalate/intercalation	Intercalation is the process where ions or molecules are reversibly inserted into the structure of a host material without significantly altering its framework.
IOU Ratepayer	Utility customer paying regulated rates to investor-owned utilities (IOU)
Kg	Kilogram, standard international unit of mass
$kgCO2_e$	KG of CO_2 equivalent
L	Liter, standard international unit of volume
LCOS	Levelized cost of storage, total cost of energy stored per kWh over the life of an energy storage system

Term	Definition
LFC	Large-format cell
LFP	Lithium-iron-phosphate
Li-ion	Lithium-ion cell technology that utilizes lithium-ions on both the positive and negative sides of the cell
m	meter
mm	millimeter
pH	Measure of acidity or alkalinity on a scale from 0-14, where 7 is neutral
PSPS	Public safety power shutoffs
RTE (RTE %)	Round-trip efficiency, equivalent to energy efficiency
Specific Capacity	Capacity stored per unit mass of cathode material
TRL	Technology readiness level
V	Voltage, unit of cell potential
Wh (kWh, MWh, GWh)	Watt-hour (kilowatt-hour, megawatt-hour, gigawatt-hour), unit of energy storage capacity
Zn-ion	Zinc-ion cell technology that uses zinc-ions on both the positive and negative sides of cells

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Project Deliverables

The project deliverables as identified in the technical section of the Agreement and Scope of Work are listed below.

- Electrode and Cell Test Plan Report
- CPR Report #1
- Quality Control Procedure Report
- Manufacturing Control System
- Production Report
- Accelerated Life Cycle Testing Protocol Report
- Interim Life-Cycle Test Results Summary Memorandum
- Collective Results Summary on Life-Cycle Testing Report
- Module Development Report
- Module Testing Protocol and Results Report
- System Development Report
- CPR Report #2
- UL9540A Testing Report
- System Validation Test Protocol
- Demonstration System Performance Report
- CPR Report #3

Project deliverables are available upon request by submitting an email to pubs@energy.ca.gov.

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APPENDIX A: Project Metrics

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APPENDIX A: Project Metrics

Table A-1: Project Metrics

Metric	Baseline	Target	Evaluation Method	Metric Significance	Project Outcome
Large Format Cell Design					
Large Format Zn-ion Prototype Cell Design	100 mAh test cells	20Ah multi-layer Zn-ion Cells	Electrochemical testing and evaluation of prototype Zn-ion cells	Increasing the size of Zn-ion cells enables the ability to develop a Zn-ion energy storage system	Large format, multi-layer Zn-ion cells were designed to exceed 20Ah capacity but were limited to ~7Ah for demonstration system testing. Ongoing cell development outside of this project resulted in prototype Zn-ion cells with 22Ah capacity.
Testing of 20Ah Zn-ion Cells	N/A	Successful testing of large format Zn-ion cells	Electrochemical and environmental testing for prototype large format Zn-ion cells	Evaluating the performance of the Zn-ion cell for system design and continued cell development	Design and characterization of prototype Zn-ion cells was completed, but limited due to failure modes identified
Projected Volumetric energy density (Cell)	170 Wh/L	330 Wh/L	Energy capacity of prototype Zn-ion cells divided by the design volume.	A significant metric for stationary energy storage, noting the amount of energy capable of stored per volume; higher volumetric energy density, smaller system footprint.	Assuming custom Zn-ion separator, over 300 Wh/L is achievable in Zn-ion cells.
Projected Specific Energy Density (Cell)	60 Wh/kg	120 Wh/kg	Energy capacity of prototype Zn-ion cells divided by the design mass.	A less significant metric for stationary energy storage, used as a basis for cost evaluation to compare to other battery technologies; increased energy per mass of material leads to cheaper storage costs (less material required)	Assuming custom Zn-ion separator and minimal zinc, over 100 Wh/kg is achievable.

Metric	Baseline	Target	Evaluation Method	Metric Significance	Project Outcome
Energy Efficiency (Cell)	85%	85%	Energy efficiency measured during cycling of Zn-ion cells; percentage of energy retrieved during discharged divided by energy stored during charge.	Significant metric for stationary energy storage, resulting in direct operational costs in efficiency losses every cycle of the cell. 85% is considered the baseline target for energy storage systems.	Through EOL cycling of Zn-ion cells the energy efficiency is ~85%.
Cell voltage (nominal)	1.3 V	1.3 V	Mid-point discharge voltage; voltage potential when half of the energy of the cell has been discharged.	Important metric for system design and understanding energy densities.	This remained at 1.3V, as expected.
Internal resistance	30 mΩ	30 mΩ	Impedance measurement of Zn-ion cells	Direct impact on the energy efficiency of the cell, including electrical and electrochemical resistances.	The impedance measurements of cells used for the demonstration system testing were <20 mΩ. This is expected to decrease further.
Operational Temperature Range	0°C to 50°C	0°C to 50°C	Environmental testing of Zn-ion cells	A wide operational temperature range is important to maintain cell capabilities within the expected temperature range requirements of the target stationary energy storage market	This remained at 0°C to 50°C, as expected.
Projected Cost per kWh (cell)	$103/kWh	$86/kWh	Previously estimated using BatPac, newly projected by the prototype Zn-ion cell BOM, considering at-scale costs of materials and comparative manufacturing of Li-ion cells	Cost of a Zn-ion cells per kWh at scale to compare to currently available and emerging technologies	Through improved cell development, decreasing costs, this is projected to be $25/kWh at the GWh scale.
Projected Cost per kW (cell)	$206/kW	$192/kW	Equivalent power output at 2h discharge rates.	Cost per unit power, metric to compare power delivery of stationary energy storage systems, depending on timescale of energy-use	The equivalent at a 2h discharge rate would be projected at $50/kW.

Metric	Baseline	Target	Evaluation Method	Metric Significance	Project Outcome
Projected LCOS (cell)	0.03 $/kWh	0.02 $/kWh	Levelized Cost of Storage (LCOS) of the cell only, cell BOM and manufacturing costs, divided by the total energy stored through the warrantied life of the cell (3500 cycles)	The Levelized Cost of Storage for a cell measures the total cost of manufacturing and operating a storage cell over its lifetime, divided by the total energy it delivers. Excluding system, installation, maintenance costs.	Considering the above projected at-scale costs and required cycle life for the stationary energy storage market, this is <$0.01 / kWh.
Long Term Testing					
Accelerated Life Cycle testing	Test cell testing only	Cary out Accelerated Life Cycle Testing	Testing life of Zn-ion cells through different cycling protocols and environmental affects	This gives an accelerated way to determine cycle life of Zn-ion cells considering performance metrics that can be collected faster than just cycling the cell.	Accelerated life cycle testing of Zn-ion cells was limited due to the failure modes discussed in this project. Cells were cycled to >3000 cycles at limited protocols.
Cycle Life	1500 cycles	3500 cycles	Through the accelerated life cycle testing, using collected performance metrics to determine estimated cycle life during electrochemical cell testing.	Cycle life measures how many cycles a battery can complete before its capacity drops below a useful level. For stationary energy storage, a longer cycle life reduces replacement frequency and lowers the overall cost of energy storage over the system's lifetime.	Limited cycle life was identified as a hurdle during this project – outside of this project, development has enabled improved cycle life of Zn-ion cells to hundreds of cycles without capacity fade.
Cell Production					
Develop electrode roll-to-roll production	N/A	Positive and negative electrode process develop-ment for roll-to-roll production	Process development completed for roll-to-roll production of electrodes	Roll-to-roll production of electrodes enables high throughput manufacturing of the core components of the cell, borrowing from the Li-ion thin-film cell design and production methodology.	Roll-to-roll process develop-ment was completed to produce >200m of cathode and >2000m of anode per production day
Quality test plan for electrodes and cell quality	N/A	Test plan for roll-to-roll produced electrodes and EOL	Capability to evaluate the quality of incoming elec-trodes, and produced cells	Maintaining quality compo-nents are required to produce quality Zn-ion cells, improving	A quality plan was successfully implemented to evaluate and improve incoming electrodes and produced cells.

Metric	Baseline	Target	Evaluation Method	Metric Significance	Project Outcome
		(end of life) testing for Zn-ion cells		cell performance and reducing costs due to waste.	
Develop assembly processes for large format cells	N/A	In-house assembly for large format Zn-ion cells	Process development to process incoming electrodes, assemble large format cells	Large format cell production required to meet system development and testing.	Assembly processes were implemented, including manual, semi-automated and automated functions to produce large-format Zn-ion cells.
Produce 100 large format cells per month	N/A	Production capability to meet 100 large format Zn-ion cells per month	Measured by the production capability of each production process, ensuring the lowest output process is >100 large format cells per month.	Throughput of 100 large format cells per month enables Zn-ion system development and testing	All major production processes for Zn-ion cells have throughput greater than 100 cells per month.
Implement Quality Control procedures	N/A	Implementation of QC processes for critical production processes	Implementation of control processes to evaluate quality of incoming electrodes and cell assembly processes	Maintaining quality components are required to produce quality Zn-ion cells, improving cell performance and reducing costs due to waste.	Quality control has successfully improved both electrodes in Zn-ion cell production and controlled critical measurements during production of Zn-ion cells.
Safety Demonstration of Zn-ion Cell					
Complete Safety Testing of Zn-ion Cells, showcasing thermal stability	In-house thermal runaway testing	Successfully complete UL9540A testing with no indication of thermal runaway	Contract UL Solutions to carry out UL9540A testing methodology	Completing UL9540A safety testing demonstrates that battery technology meets stringent safety standards for thermal runaway, fire propagation.	Zn-ion cells were successfully tested and passed UL9540A testing at the cell level.
Toxicity	Non-toxic	Non-toxic	Consideration of the Zn-ion cell BOM, no toxic materials used	Non-toxic battery technology improves environmental safety, simplifies recycling and disposal, and reduces health risks during manufacturing and operation.	Zn-ion cells remain non-toxic, as expected.
Electrolyte pH	4-6	5-7	Electrolyte pH range of Zn-ion cells	A near-neutral pH electrolyte enhances safety during manufacturing, operation,	Maintained near-neutral electrolyte pH, as expected.

Metric	Baseline	Target	Evaluation Method	Metric Significance	Project Outcome
				and transport by reducing the risk of chemical burns, toxic gas release, and hazardous reactions.	
Demonstration System Design					
Develop Zn-ion module with integrated BMS	N/A	Design Zn-ion module appropriate for Residential Demonstration System testing with an integrated BMS.	Complete module design, manufacture and assemble modules	Proving the functionality of Zn-ion cells in modules	48V Zn-ion modules were designed, manufactured and assembled including an integrated BMS.
Complete Testing on Zn-ion Modules	N/A	Complete electrochemical/module testing	Evaluate electrochemical/ energy efficiency of Zn-ion modules, confirm overcharge and thermal cutoff protections.	Confirm the functionality of the designed Zn-ion modules.	48V Zn-ion modules were tested, including BMS protection testing. Capacity of the modules were lower than expected due to lower capacity Zn-ion cells used.
Design 10kWh Zn-ion Energy Storage System	N/A	Design 48V 10kWh Zn-ion residential demonstration system.	Complete Zn-ion energy storage system design, manufacture and assemble system.	Building capacity of the Zn-ion modules into a functional energy capacity (10kWh)	48V Zn-ion residential energy storage system was designed, manufactured and assembled.
Volumetric Energy Density (Module)	N/A	100 Wh/L	Energy capacity of the module, divided by the volume of the module.	A significant metric for stationary energy storage, noting the amount of energy capable of stored per volume; higher volumetric energy density, smaller system footprint.	Due to the low capacity of cells used, the Zn-ion modules cycled as part of the system were ~10 Wh/L. This will be substantially improved during system refinement and cell improvements.
Overcharge tolerance	N/A	BMS to prevent overcharge.	BMS testing to confirm no overcharge.	Limiting overcharge is an important requirement for a BMS to ensure the long life Zn-ion cells.	BMS confirmed to prevent overcharging.

Metric	Baseline	Target	Evaluation Method	Metric Significance	Project Outcome
System Demonstration Testing					
Complete System Validation Testing of 10kWh Zn-ion Demonstration System	N/A	Conduct Zn-ion system testing.	Carry out cycling at different rates to determine electrochemical performance, as well as evaluate system capability of the designed Zn-ion demonstration system.	The resulting testing of the system design of the world's first Zn-ion energy storage system. Creating a baseline for system design when working with the Zn-ion cell technology in module and system design.	The demonstration system was tested and carried out at 3 varying rates (C/3, C/6, C/10). Although performance was lower than anticipated, including the lower capacity due to the lower cell capacity, the system generally functioned, despite significant delays throughout the project.

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APPENDIX B: Comparison of Zn-ion Cells to Other Cell Technologies

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APPENDIX B:
Comparison of Zn-ion Cells to Other Cell Technologies

Table B-1: Comparison of Zn-ion Cells to Other Cell Technologies

	Zn-ion	Zinc-Nickel	Zinc-Bromide	Zinc-Air	Li-ion (NMC)	Li-ion (LFP)
Commercial Application	Stationary Storage (3-12h)	UPS (<1h)	Stationary Storage (3-12h)	Stationary Storage (24h+)	Electric Vehicles; Stationary Storage (1-4h)	Electric Vehicles; Stationary Storage (1-4h)
Gravimetric Energy Density (Wh/kg)	150	140	60-75	100-400	250-300	90-205
Gravimetric Energy Density (Wh/L)	100-400	300	60-70	135-1000	650-800	250-400
Voltage (V)	1-1.5	1.2-1.9	1-1.8	0.9-1.4	2.5-4.2	3.6
Cycle Life	5,000-10,000	500	10,000	500	1500	3000
Round Trip Efficiency (RTE)	85-95%	80%	75%	<60-70%	85-90%	95%
Depth of Discharge (DoD)	100%	100%	100%	100%	80-95%	90%
Calendar Life	15-20 years	15 years	20 years	15-20 years	10 years	5-10 years
Safety	Non-flammable, not reactive to air or water	Non-flammable, not reactive to air or water	Non-flammable, not reactive to air or water	Non-flammable, not reactive to air or water	Poor	Poor

Zinc and Li-ion Battery Information[38,39]
NMC = nickel-manganese-cobalt

[38] Volta Foundation. 2024. 2024 Annual Battery Report. Volta Foundation. Available online: https://volta.foundation/battery-report-2024

[39] U.S. Department of Energy, Office of Electricity. (2022). Storage Innovations 2030. Online: https://www.energy.gov/sites/default/files/2022-10/Storage%20Innovations%202030.pdf