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CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

A Safe, High-Performance, Rechargeable, Recyclable Zinc-Based Battery for Stationary Energy Storage Applications

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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.

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

The increasing demand for energy storage solutions, coupled with the limitations of lead-acid batteries and the safety concerns of lithium-based batteries, requires the exploration of alternative battery chemistries. Enzinc's development of a patented zinc sponge electrode offers such an alternative. The three-dimensional zinc sponge structure eliminates dendrite growth and has a high surface area, resulting in a battery with a high energy density comparable to lithium-based batteries, the robustness and low cost of lead-acid batteries, and a higher safety factor than either.

The project aimed to develop a stationary energy storage nickel-zinc battery and demonstrate a fabrication line for the patented zinc metal electrode, enabling zinc to be used as an anode for a family of safe, affordable, high-performance batteries. The project successfully achieved its objectives, including the development of a large format commercial-size zinc sponge anode, a nickel-zinc cell, a nickel-zinc stationary energy storage battery, and a zinc anode fabrication line. During the project, the technology progressed to higher technology and manufacturing readiness levels.

By supplying zinc anodes to legacy manufacturers for use in producing advanced nickel-zinc batteries, Enzinc will contribute to the realization of California's climate and clean energy goals.

Keywords: zinc, energy storage, battery, stationary, safety, thermal runaway, recyclability

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Executive Summary

Background

The demand for electricity must be balanced with an equal supply to avoid electricity interruptions and blackouts. By storing and releasing energy in the form of electricity when it is needed, energy storage systems help balance grid supply and demand and improve the quality and reliability of electricity delivery. According to the International Energy Agency's report, *Net Zero by 2050, A Roadmap for the Global Energy Sector*, electricity is expected to provide half of the world's energy consumption by 2050 (IEA, 2021). In anticipation of an electricity economy expansion and the need for zero-carbon emissions, California passed Senate Bill 100, "The 100 Percent Clean Energy Act of 2018," which requires renewable energy and zero-carbon resources to supply 100 percent of electric retail sales to end-use customers by 2045 (De León, Chapter 312, Statutes of 2018). The transition from a fossil-fuel-based energy system to electricity is paramount in the effort to reduce greenhouse gas emissions. That transition cannot occur without an enhanced ability to store energy.

Stationary energy systems enable the transition to electricity by virtue of their ability to store energy and release it as electricity on demand. A stationary energy storage system can store energy for a home, business, or community and release it in the form of electricity when it is needed. Most stationary energy systems include an array of batteries. Today, lead-acid and lithium-based batteries are two of the most widely deployed, commercially relevant solutions for stationary energy storage. However, their discharge times range from only 2 hours to 12 hours. Lead-acid batteries have been used in stationary energy storage applications for more than 150 years. Though dependable, they have low energy density and cycle life, causing installations to be heavy and costly. Lithium-based batteries have been employed in stationary applications for about 10 years. Though they have high energy density, they have reduced discharge times, safety concerns (thermal runaway, toxic outgassing), and environmental temperature constraints. Additionally, there is currently no cost-effective way to recycle lithium-based batteries, and the materials and manufacturing equipment are concentrated in foreign sources, which can hobble energy independence. Other technologies for stationary energy storage with longer discharge times have not yet reached maturity.

Project Purpose

Enzinc plans to expedite the advancement of California's clean energy objectives by leading the development of an alternative battery chemistry that combines the energy of lithium-based batteries with the low cost and operating temperature range of lead-acid batteries while maintaining superior safety standards. In addition to the growing need for energy storage, developing an alternative battery is urgent based on factors such as environmental issues linked to conventional energy sources, safety concerns related to lithium-based batteries, the impact of fossil fuels on public health and safety, greenhouse gas emissions contributing to global warming, and challenges regarding the sustainability and accessibility of energy resources.

In this project, Enzinc capitalized on its investigations into alternative battery materials that were conducted with the United States Naval Research Laboratory between 2011 and 2019. The United States Navy was seeking a higher performing alternative chemistry to the lead-acid batteries used for the last 100 years. The Navy had evaluated lithium-based batteries, but a fire aboard a prototype submarine caused them to re-assess their use. The Office of Naval Research tasked the Naval Research Laboratory to find a battery material that has the energy of lithium-based batteries and the robustness of lead-acid batteries, is safer than either and is not dependent on a foreign supply chain. This research led to the development of the zinc micro-sponge anode. An Advanced Research Projects Agency-Energy award to Enzinc validated three attributes of the zinc anode: (1) no dendrite growth (higher cycle life without needing mechanical subsystems or additives used by other zinc batteries); (2) higher surface area (resulting in twice the energy of other zinc anodes, three times the energy of a lead-acid battery, and equivalent energy of lithium ferrous phosphate or sodium); and (3) cathode agnostic (can be coupled with nickel, manganese, silver, or carbon for a zinc-air battery) for different applications at different price points. This project focused on nickel-zinc because nickel is well characterized, offers competitive energy density, and can be brought to market quickly.

Project Approach

The project built upon past development achieved in previous awards from the United States Department of Energy and the California Energy Commission. Whereas previous development efforts focused on validating the zinc technology, the current project assessed the suitability of the nickel-zinc battery for stationary energy storage applications. Additionally, the project explored the path to production, in anticipation of meeting the projected demand from legacy battery manufacturers.

The project employed relevant gating design reviews to monitor and manage the project execution. Enzinc initiated work from the smallest unit, the anode, and systematically scaled up development until the goal of producing a nickel-zinc battery was attained. The identified project's metrics encompassed specific energy, energy density, cycle life, capacity fade, rate capability, and cost.

The project centered on the development and scalability of Enzinc's zinc technology for long duration stationary energy storage. This involved:

- Scaling up the dimensions of the zinc electrodes from Enzinc's research and development size to practical sizes that match the size and shape of batteries currently on the market.
- Engineering the nickel-zinc battery to realize the full potential of the zinc sponge anode.
- Exploring the manufacturing processes of the commercial-size zinc anodes.

The project's focus and Enzinc's success developing the nickel-zinc stationary energy storage battery facilitates the integration of Enzinc's zinc technology into the production of advanced stationary energy storage batteries. As Enzinc transitions from the anode preproduction fabrication line to a full-scale production line, there is a need to refine the manual manufacturing processes to either semi-automated or fully automated. The anode preproduction fabrication line faced budgetary constraints due to the high cost of equipment, leading Enzinc to opt for used equipment during this project.

Enzinc's go-to-market business model is to partner with legacy battery manufacturers (for example, lead-acid battery manufactures) to upgrade their product offerings by adapting their factories to build nickel-zinc batteries using existing lead-acid manufacturing equipment and Enzinc produced zinc anodes. This "drop-in" approach is called Enzinc Inside™. The deployment of Enzinc Inside™ batteries has the potential to enhance grid resiliency, improve electricity reliability, and lower energy costs through the increased deployment of solar-plus-storage solutions at the residential and commercial levels. Furthermore, these batteries can act as building blocks for microgrid systems.

Key Goals and Objectives

The project goals were to:

- Design and test a nickel-zinc battery with a voltage of 12 volts and with 141 ampere hours to be used as a module for long duration stationary energy storage.
- Validate manufacturability of the proprietary nickel-zinc battery having high specific energy (120 watt-hours per kilogram), potential for lower cost (less than $150 per kilowatt-hour) compared to existing batteries, resistance to thermal runaway hazards, and temperature range of -40 to 140 degrees Fahrenheit (-40 to 60 degrees Celsius).
- Conduct environmental testing of the nickel-zinc battery (for example, temperature, shock, safety, and other factors).
- Test these nickel-zinc batteries for discharge times from 2 hours to 12 hours.
- Design and build a preproduction fabrication line for the zinc sponge anodes capable of producing at a rate of 1,000 anodes per day for one 8-hour shift with less than a 5 percent reject rate.

To realize the project goals, the objectives were to:

- Design, build, and test a large format zinc micro-sponge anode to showcase the ability to scale the size of the zinc anode to fit existing market battery enclosures.
- Design, build, and test a large format nickel-zinc cell to respond to batteries made up of a connection of cells in series or parallel.
- Design, build, and test a 12-volt nickel-zinc battery to be used as the battery element of a long duration stationary energy storage system. This battery demonstrated a discharge capability from 10 hours to 20 hours and short-duration energy storage from 30 minutes to 10 hours. The 12-volt battery is intended to be a demonstration "building block" for a 1 megawatt stationary energy storage system.
- Demonstrate a preproduction fabrication process for manufacturing large-scale zinc sponge anodes.

Key Results

The project achieved its objectives, and the results demonstrate the viability of the technology and highlight the potential benefits of widespread adoption. The project's successful results offer multiple benefits, including:

- Bringing the battery storage industry closer to realizing an alternative battery chemistry that, as an added benefit, uses easily sourced raw materials.
- Deploying zinc technology in the production of advanced batteries, which can enhance current lead battery offerings or result in the establishment of a new product line.
- Advancing California's climate and clean energy goals, as outlined in Senate Bill 100.

Over the lifecycle of the project, the technology readiness level developed from level 4, "basic technological components are integrated to establish that the pieces will work together," to level 7, "prototype full scale system," in a stationary use case (OSD ManTech Program, 2011). The successful upscaling of the anode size and the battery use case validates the current technology readiness level. The current limitations of lead-acid batteries, such as limited energy density, limited depth of discharge, excessive weight, and harmful environmental effects, are not evident in Enzinc Inside™ batteries. Enzinc's inherently safer battery chemistry will not experience thermal runaway, a safety concern in lithium-based applications.

Knowledge Transfer and Next Steps

At the outset of this project, Enzinc outlined the following eight-step go-to-market strategy built on the Enzinc Inside™ approach to sales and revenue generation:

1. Upscale the zinc anodes in sizes.
2. Develop the cell design.
3. Development at the battery level.
4. Explore anode fabrication using production-like equipment.
5. Qualify the anode fabrication process.
6. Demonstrate a sample battery with a legacy battery manufacturer.
7. Build a prototype battery with multiple battery manufacturers and mass production partnerships with existing industry partners.
8. Revenue generation from anode sales and battery licenses.

A previous grant award facilitated the completion of the first five tasks, and there is ongoing collaboration with members of the industry advisory group that Enzinc created to build multiple demonstration and prototype batteries.

The industry advisory group consists of 12 international companies, four of which are multi-billion-dollar operations, who have paid to be part of Enzinc's development program. The industry advisory group is composed of two groups of companies. The first are potential customers—legacy battery companies that would use Enzinc's drop-in zinc anode to build high performance batteries in their existing lead-acid factories. The second group consists of potential users of the battery—Enzinc's customer's customer.

To date, Enzinc has held regular consultations and discussions with members of the industry advisory group to provide updates on developments, which will ultimately result in the deployment of the zinc anodes in product offerings by members of the industry advisory group and other interested parties.

CHAPTER 1: Introduction

In response to the increasing need to transition to an electricity economy, Enzinc supports the advancement of California's climate and clean energy objectives by leading the development of an alternative battery chemistry.

Today, lead-acid and lithium-based batteries are two of the most widely deployed, commercially relevant solutions for stationary energy storage, which helps balance grid supply and demand and improve the quality and reliability of electricity delivery. However, current battery discharge times range from only 2 hours to 12 hours. Lead-acid batteries have been used in stationary energy storage applications for more than 150 years. Though dependable, they have low energy density and cycle life, causing installations to be heavy and costly. Lithium-based batteries have been employed in stationary applications for about 10 years. Though they have high energy density, they have reduced discharge times, safety concerns (thermal runaway, toxic outgassing), and environmental temperature constraints. Additionally, there is currently no cost-effective way to recycle lithium-based batteries, and the materials and manufacturing equipment are concentrated in foreign sources, which can hobble energy independence. Other technologies for stationary energy storage with longer discharge times have not yet reached maturity.

Urgency for an alternative battery chemistry arises from several factors, including the growing need for energy storage, environmental issues linked to conventional energy sources, safety concerns related to lithium-based batteries, the impact of fossil fuels on public health and safety, greenhouse gas emissions contributing to global warming, and challenges regarding the sustainability and accessibility of energy resources. These pressing issues underscore the need for innovative solutions in energy storage.

The project centered on the development of high-performance, safe, recyclable zinc anodes, domestically manufactured for integration into nickel-zinc batteries. Zinc-based batteries offer an alternative to the two most popular batteries in use today. Zinc batteries, first patented by Thomas Edison in 1901, suffer from excessive, rapidly forming dendrites. These needle-like formations grow upon charge and discharge with all batteries but grow quickly in zinc. These dendrites can pierce the protective separator between the anode and the cathode, shorting out the battery. For decades, zinc batteries were relegated to primary or disposable batteries. With the growth of renewable energy demands and because zinc is the fourth most commonly mined metal on the planet, efforts have increased to make zinc batteries a secondary or rechargeable battery. Efforts over the last two decades used electrolyte additives or mechanical systems to slow down dendrite growth. The result was a battery with energy density roughly twice that of lead-acid and/or very large-scale batteries.

Enzinc, working with the United States Naval Research Laboratory, developed a zinc micro-sponge anode that eliminates—not just slows—dendrite growth. This patented architecture allows zinc, for the first time, to be used in a high-performance rechargeable battery with the energy of a lithium ferrous phosphate or sodium-ion battery and that is safer than either lithium ferrous phosphate or lead-acid.

This strategic focus aims to meet the soaring demand for advanced battery technologies capable of addressing the multifaceted challenges facing traditional energy sources, thus facilitating the accelerated transition to clean energy in California and beyond. While previous development initiatives validated Enzinc's zinc technology in an e-mobility application, this project was tailored to development of a stationary energy storage battery. Advancements achieved through this project are also applicable to e-mobility applications, as Enzinc's nickel-zinc chemistry can be scaled to fit existing battery form factors. Moreover, the project prioritized market adoption of the zinc technology by constructing multiple demonstration batteries in collaboration with an established battery manufacturer.

The goals of the project were to:

- Design and test a nickel-zinc battery with a voltage of 12 volts (V) and with 141 ampere hours (Ah) to be used as a module for long duration stationary energy storage.
- Validate manufacturability of the proprietary nickel-zinc battery having high specific energy (120 watt-hours/kilogram [Wh/kg]), potential for lower cost (less than $150 per kilowatt-hour [$/kWh]) compared to existing batteries, resistance to thermal runaway hazards, and temperature range of -40 degrees Fahrenheit (°F) to 140°F (-40 degrees Celsius [°C] to 60°C).
- Conduct environmental testing of the nickel-zinc battery (for example, temperature, shock, safety, and other factors).
- Test the nickel-zinc batteries for discharge times from 2 hours to 12 hours.
- Design and build a preproduction fabrication line for the zinc sponge anodes capable of producing at a rate of 1,000 anodes per day for one 8-hour shift with less than a 5 percent reject rate.

To realize the project goals, the objectives were to:

- Design, build, and test a large format zinc micro-sponge anode to showcase the ability to scale the size of the zinc anode to fit existing market battery enclosures.
- Design, build, and test a large format nickel-zinc cell to respond to batteries made up of a connection of cells in series or parallel.
- Design, build, and test a 12 V nickel-zinc battery to be used as the battery element of a long duration stationary energy storage system. This battery demonstrated a discharge capability from 10 hours to 20 hours and short-duration energy storage from 30 minutes to 10 hours. The 12 V battery is intended to be a demonstration "building block" for a 1 megawatt (MW) stationary energy storage system.
- Demonstrate a preproduction fabrication process for manufacturing large-scale zinc sponge anodes.

The key milestones during the project were as follows:

- Questionnaire: Members of the industry advisory group were surveyed to collect system level requirements, enabling Enzinc to tailor a battery solution to address real-world challenges. This marked the initiation of the nickel-zinc battery development.
- Anode scaled in size: This milestone demonstrated the capability of scaling zinc sponge anodes to fit existing cell form factors, aligning with the Enzinc Inside™ strategy of integrating zinc anodes into manufacturers' existing products, thereby minimizing the need for significant modifications.
- Anode integrated into acrylic enclosures: This was a critical milestone for validating scaled anodes. Testing anodes in representative cell enclosures ensured they met required specifications.
- Enzinc Inside™ cell testing: This milestone showcased the practical integration of Enzinc zinc anodes into existing cell enclosures. Enzinc anodes were supplied and used in the assembly of a production-representative cell at the battery manufacturing plant of an industry advisory group member to further demonstrate the practicality of the Enzinc Inside™ strategy.
- Enzinc Inside™ battery testing: This milestone was achieved by assembling cells in series to meet specified target battery requirements.
- Line equipment installation: Using knowledge gained from laboratory-based anode development, the project sourced production-representative equipment, enabling the demonstration of anode manufacturability. Acquisition and installation of this prototype line were pivotal in advancing the manufacturing readiness level of the technology.
- Line calibration and qualification: The introduction of novel processes and equipment posed challenges to the manufacturing team. Individual pieces of equipment underwent qualification to ensure the quality of the system and zinc anodes were manufactured using conveyor furnaces.

The six performance metrics summarized in Table 1 were used during the project to assess the technology's potential success.

Table 1: Project Performance Assessment Metrics

Performance Metric	Benchmark Performance	Metric Category	Significance of Metric
Specific Energy	100 Wh/kg	Energy - Energy efficiency and generation related	Energy per weight; the higher the metric, the lighter the battery
Energy Density	300 Wh/liter	Energy - Energy efficiency and generation related	Energy per volume; the higher the metric, the smaller the battery

Performance Metric	Benchmark Performance	Metric Category	Significance of Metric
Cycle Life	500 cycles	Technology - Industry standards and solutions to barriers being advanced	Higher cycle life reduces the life cost to operate the battery
Capacity Fade	20% at 500 cycles	Technology - Industry standards and solutions to barriers being advanced	Defines the effective operational use of the battery
C-Rate	1C to C/12	Technology - Industry standards and solutions to barriers being advanced	Defines the type of applications; the smaller the ratio, the longer the discharge time
Cost (techno-economic)	<$100/kWh	Technology - Industry standards and solutions to barriers being advanced	The lower the cost, the more attractive to customers

Enzinc demonstrated the ability of its anodes to fit into existing cell enclosures currently used by battery manufacturers. The results from this project will be advantageous for battery manufacturers focusing on stationary energy storage solutions, as well as for e-mobility applications, given the dual use case of the nickel-zinc chemistry. The adaptability of the anodes to conform to these existing enclosures means battery manufacturers intending to incorporate Enzinc's anodes into their existing use cases will require minimal modifications. Additionally, a new product line using zinc technology can be developed to cater to various niche markets. The cost-effectiveness and ease of substituting zinc anodes into existing legacy offerings will contribute significantly to the technology's projected adoption. Enzinc's unique business model will provide zinc anodes to existing lead-acid and Nickel Cadmium manufacturing factories, facilitating a transition from producing legacy batteries to manufacturing advanced nickel-zinc batteries. These advanced batteries offer two to three times the energy density of lead-acid batteries, which is comparable to lithium ferrous phosphate batteries.

CHAPTER 2: Project Approach

The purpose of the project was multifaceted, aiming to fund the scaling of the zinc anode sponge, the development of nickel-zinc batteries, and the design and demonstration of an anode preproduction fabrication line. The anode preproduction fabrication line was intended to explore the manufacturability of the zinc anodes for use in advanced nickel-zinc stationary energy storage batteries. With such ambitious goals, the project was strategically divided into two main sections: administrative and technical tasks. Insights gleaned from the prior California Sustainable Energy Entrepreneur Development Initiative (Phase I and II) projects were instrumental in shaping the goals, scope, and approach of this project.

The technical section of the project was broken down into five sequential tasks. Details for each task are provided in the sections below.

Create Systems Level Requirements Document

This initial task involved the creation of a stationary storage systems level requirements document, which laid the foundation for subsequent development activities. This task was accomplished by distributing system requirements surveys to industry advisory group members—including battery manufacturers, utility companies, and battery recyclers—and documenting the received requirements data. Requirements focused on several key areas, such as:

- Operational parameters, including peak current, total life cycles, depth of discharge, state of charge, duration of discharge, shelf-life, and self-discharge rate of cell.
- Safety parameters, encompassing safety standards and features.
- Design parameters, including battery weight, size, voltage, specific energy, efficiency of cell, internal resistance of pack, cell operating voltage, and current cutoff.
- Environmental parameters covering the operating temperature of the cell and battery, peak temperature of pack, temperature cutoff, seismic rating, and recycling requirements.
- Financial parameters, including pack cost, warranty period, recycling costs, and recycling benefits.

These documented requirements served as the voice of the customer, providing a comprehensive framework guiding the development of a product that prioritizes customer needs and preferences.

Scale Zinc Sponge Anode

The objective of this task was to increase the production size of the zinc sponge anode to support a stationary energy storage battery. In this task, the molds used for anode production underwent evaluation, resulting in the scaling of the zinc anodes. This marked a significant advancement in the project, transitioning from the battery requirements gathering phase. Three-stage design reviews, serving as gating reviews, facilitated the selection of designs, progress documentation, and change control. Members of the technical advisory committee were present during these reviews, and their feedback was incorporated into the product development. The successful completion of this task contributed to cell development, the design of the production line, and the procurement of equipment for the preproduction fabrication line.

Enzinc's proprietary zinc sponge electrode increases the rechargeability, cycle life, and energy of zinc-based batteries by eliminating the formation of dendrites. This allows the batteries to compete with lithium-ion in certain use cases, while eliminating the risk of thermal runaway and outperforming the best-in-class lead batteries. This was achieved by creating an interconnected lattice that was maintained throughout cycling. Control of key metrics allowed the anode to be tailored to different cathode chemistries as well as different use cases, from more energy intensive to power intensive applications. Electrochemical properties were coupled with mechanical properties to produce a free-standing electrode that can survive handling during cell assembly.

Anode Characterization and Testing

Anode thickness and composition targets were developed from cell builds at different size scales. From performance testing, key metrics were adjusted to balance the capacities as well as achieve the proper long-term cycling performance. Testing of the anode fell into three main categories: physical dimension validation, chemical validation, and cell performance.

Measurement of Physical Dimensions

In developing the quality measures needed to design and control the manufacturing process, the physical output of the process was measured, in addition to using multiple techniques to measure thickness in determining the origin of process variation.

Inter- and intra-sample variation were compared with the help of a measuring instrument to standardize thickness measurement to ensure a consistent approach in the test protocol during measurements. Pictures of the anode through each step of the process were collected, providing the means to track surface defects that might arise due to handling. Lastly, external dimensions of the anode, alongside other relevant dimensions of the anode were measured.

Chemical Validation and Characterization

In addition to the physical characteristics of the anode, a certain composition of the chemical composition was required to achieve proper performance in the cell. Given that the proportion of active ingredients in an anode affects cell performance, it was necessary to have a quick and reliable way of measurement. Several approaches were considered in selecting an appropriate measure for characterization. The development team employed selection criteria based on accuracy, repeatability, consistency, and time savings.

Anode Qualification in Cell Testing

Ultimately, anode performance could only be confirmed through cell testing. Single paired electrode cells were produced using the baseline design, with the cell materials and batch identification tracked for traceability. By testing anodes with variations in the measured properties and analyzing the process data, the development team could control variation in the cell build. Drawing conclusions from the cell cycling behavior, the development team set process limits on anode characteristics required for optimal cell performance.

Manufacturing Design

The anode manufacturing process was divided into four distinct steps: mixing, deposition, drying, and firing. The slurry components were mixed, deposited on a substrate at net shape of the final anode, dried of solvent, and then put through the proprietary firing process to sinter the zinc particles together and form the oxide shell. The key development for scalability of the anode dimensions was implementation of the stenciling step during deposition. Through this method, the development team could specify the dimensions of the anode by fabricating a stencil with the desired anode shape and thickness. The process development around this manufacturing technology allowed Enzinc to easily design electrodes for any battery form factor. Scalability of the mixing, drying, and firing processes is discussed in detail in the anode fabrication section.

Design and Test Cells

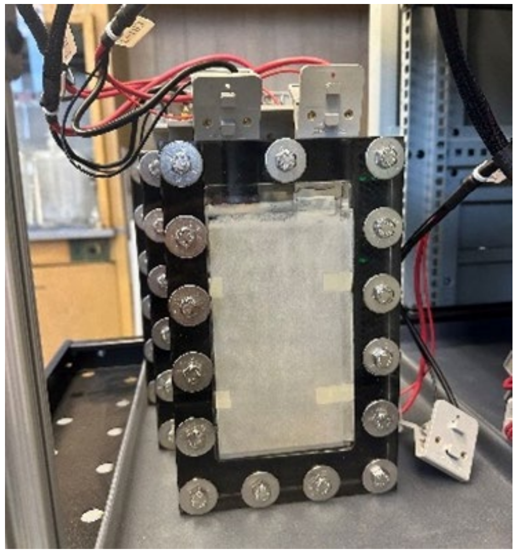
The objective of this task was to integrate and test the developed zinc anode with other cell components, including the nickel cathode, current collectors, separators, electrolyte, vent, and enclosure. Operational testing protocols for cell-level requirements were established during this phase. Acrylic enclosures were employed for rapid testing and iterative development of the cells. The use of acrylic enclosures for testing and development served to minimize the generation of cell enclosure waste. Safety tests were also conducted on nickel-zinc cells. Additionally, a member company of the industry advisory group supplied their production cell enclosures to demonstrate a nickel-zinc cell configuration. In addition to the above, Enzinc's nickel-zinc cells were assembled at the battery facility of this industry advisory group company. Design reviews were also conducted akin to the scale zinc anode use cases to ensure alignment with project goals and requirements.

Cell Design for Performance Optimization

With the aim of testing the form factor of Enzinc's customer's product, the development team designed an enclosure out of acrylic plastic to mimic the customer's product. The stationary prototype assemblies were constructed inside acrylic enclosures designed to mimic the prismatic enclosures, designed by the battery partner, that will be used to assemble Enzinc's stationary batteries.

The acrylic enclosure allowed for precise control over critical metrics such as stack compression and stack wetting. A picture of the acrylic enclosure is presented in Figure 1.

Figure 1: Enzinc's Acrylic Test Enclosure Used to Test Zinc Sponge Electrodes



This strategy allowed for a quick and efficient transition from a prototype cell in an acrylic enclosure to a finished product, as illustrated in Figure 2, within the battery partner's enclosure.

Figure 2: Enzinc Inside^{TM} Battery Cells

Cell Testing for Performance Optimization

To accelerate the adoption of the technology by future customers, Enzinc designed and built demonstration batteries and performed a variety of testing. Tests were completed on nickel-zinc battery cells featuring the Enzinc zinc sponge anode.

Optimization Testing

The following sections describe a suite of tests that were used to optimize the cell design.

Electrolyte Optimization

Enzinc tested a series of electrolyte formulations and observed an optimal electrolyte formulation, based on the total hydroxide concentration. At low concentrations, the available capacity in the cell was low as the electrode kinetics were limited by hydroxide transport across the cell. At high concentrations, the capacity faded rapidly with cycling due to the increased zincate solubility. As a result of this test, the team determined the optimal electrolyte formulation to use in the stationary energy storage product.

Compression Optimization

Enzinc performed testing on the cells under a variety of compression forces. The test demonstrated that the cell performance was not a strong function of the compression force. However, it was clear that the uniformity of the compression was more important.

Performance Characterization Testing

The testing described in this section was aimed at characterizing the performance of the cell under various operating conditions.

Capacity Testing

Capacity testing for Enzinc batteries was measured at a C/3[1] discharge rate. The team defined the available capacity as the average discharge capacity obtained in the first five cycles after formation.

Cycle Life Testing

Prior to the design of the acrylic enclosure for testing the stationary zinc sponge electrodes, the team discovered issues with the pouch cell that led to a significant loss in capacity. By using the acrylic cell, the team achieved a threefold increase in the number of cycles with greater than 80 percent capacity retention.

Rate Testing

The team tested the discharge capacity of the single layer stationary prototypes as a function of discharge rate. The cell was rated for a C/3 discharge rate, specifically, the nominal capacity. The development team found that by discharging at 1C (three times faster than the rated value), the team was able to obtain about 80 percent of the rated capacity. Additionally, the team found that when discharging at C/20 (about seven times slower than the rated value), the team obtained 115 percent of the rated discharge capacity.

Temperature Testing

Low temperature operation is important for many applications where the battery system is exposed to the elements. It is important to understand how the battery behaves when it is exposed to low temperature charge and discharge. The team tested the stationary single layer prototype at 32°F and -4°F (0°C and -20˚C). At 32°F (0°C), the team obtained about

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[1] The C Rating indicates the maximum current (in amperes) that a battery can safely handle during discharge or charge. It is a measure of the battery's ability to deliver power.

80 percent of the rated capacity at room temperature on both charge and discharge. At -4°F (-20˚C), the team obtained about 50 percent of the rated capacity.

Safety Testing

The team performed preliminary safety testing on the fully charged battery through the nail penetration test and short circuit test. The nail penetration test involved driving a nail through the center of the cell and measuring the increase in temperature of the cell. The short circuit test involved placing a copper busbar across the two terminals of the cell to create a short circuit. In both tests, the team observed no thermal runaway and no buildup of pressure in the cells. The development team is in the process of obtaining third-party certification (DEKRA North America) for the safety of Enzinc's batteries; however, the preliminary results give strong indication that the chemistry is much safer than lithium-ion battery alternatives.[2]

Design and Test Battery

This critical phase focused on integrating the cells and carefully evaluating the battery's performance against the specified parameters included in the systems requirements document. Serving as the culmination of the nickel-zinc battery development, this phase was pivotal in ensuring the realization of the project's goals and objectives. Routine design reviews were diligently conducted with the participation of the technical advisory committee members and the participating industry advisory group members. Their presence provided oversight and helped gather valuable feedback, fostering an iterative approach aimed at refining and optimizing the design to meet specified standards of performance and reliability.

Battery Design

Producing a 12 V Enzinc battery required careful design of cell interconnects and housing to ensure safe high-performance output. Pulse discharge of cells at rates up to 2C can produce currents of 200 Ah and require robust cell interconnects to support the current without generating unnecessary heat. A case was built to hold the individual cells while maintaining the intercell connection. For demonstration of this battery, a lead-acid battery box was adopted to house the Enzinc prismatic cells, maintaining the position and protecting the cell interconnects from accidental contact.

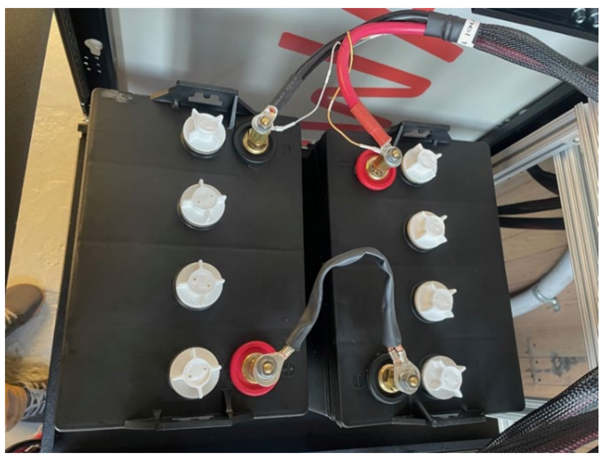
Figure 3 shows seven nickel-zinc cells in series made for one 12 V battery. For demonstration purposes, Enzinc used two four-chamber lead-acid battery boxes to house the prismatic cells, as illustrated in Figure 4.

Enzinc's nickel-zinc battery was designed to operate without the use of a sophisticated battery management system. To deliver long-term performance, the cells were first passed through a quality check process to ensure the internal resistance and capacity of the cell was within specification. Any cells that fell outside the specification were removed. Next, the quality cells were connected in series, as described in the Battery Design Report. Cells were seated in place and a secondary containment lid was attached to protect the inner cell connections. From this point, the battery went through another quality check for short/open circuits.

[2] Testing is complete as of the date of this report and Enzinc is awaiting the formal test report.

Figure 3: Composition of Enzinc Inside™ Battery Box

Figure 4: Enzinc's 12 V Nickel-Zinc Stationary Energy Storage Battery



Battery Test

While series connections of cells yield higher voltage, battery performance can be constrained by the weakest cells. Moreover, cell interconnects may disproportionately impact overall battery performance. Centralizing cells in a single unit intensifies heat generation during charge and discharge. These factors collectively contribute to potential deviations in battery performance from individual cell performance. To assess the impact of design choices on battery performance, the development team subjected the 12 V battery to three cycles at full depth of discharge, ranging from 9.1 V to 13.5 V, with a midpoint voltage of 11.55 V during discharge. Throughout the charge and discharge tests, the development team monitored individual cell voltages closely.

Once initial cycling was complete, the battery was subjected to discharge at rates from C/20 to C/5 to gain an understanding of the rate capability of the battery pack. With individual cells, any impedance at the connection point can be removed from the calculation through proper test setup. Using a full battery, the intercell connections cannot be ignored and begin to play a larger role in determining the rate capability of the battery. Upon completion of the rate testing, the battery was also subjected to pulse discharges to further characterize the battery performance. A range of pulse currents was applied while monitoring the battery and cell voltages, allowing the development team to compare voltage drops from cells and interconnects.

Demonstration of Anode Production

The objective of this task was to identify and address any issues within the three primary production sub-processes involved in the zinc sponge anode manufacturing. Throughout this endeavor, the focus was on assessing both product quality and the feasibility of anode production (specifically, rate, and performance). While the earlier task of scaling zinc sponge anodes employed batch furnaces and a variety of manual processes, the anode preproduction fabrication line drew upon insights gained from this prior task to structure the production workflow. It used large-scale conveyor furnaces and other production-like equipment for anode fabrication. Given the significant investment required for production-representative equipment, efforts were made to explore the used market for sourcing identical items.

Project Approach Summary

The project involved the active participation of Enzinc's engineering and manufacturing personnel, who were responsible for carrying out the technical tasks. Additionally, key management staff played a crucial role in facilitating communication with members of the industry advisory group, which consisted of companies operating within the battery ecosystem, particularly during the battery development phase. Members of the technical advisory committee were invited to participate in various design reviews, including preliminary, detailed, and critical design reviews, across each project phase. Enzinc maintained a structured briefing cadence with advisory members to ensure the consistent gathering of feedback. Enzinc also collaborated with an industry advisory group company, resulting in the provision of their production cell enclosures used during the cell development phase and the assembly of nickel-zinc cells at the company's battery facility.

CHAPTER 3: Results

Enzinc's primary strategy was to produce zinc sponge anodes for integration by customers into nickel-zinc batteries. This project was centered on stationary storage applications, with the goal of constructing a stationary storage battery within an existing enclosure originally designed for nickel-cadmium batteries. The aim was to showcase Enzinc's ability to replace a cadmium anode with an Enzinc zinc sponge anode, resulting in improved performance at a reduced cost and with safer materials. To achieve this, the development team upscaled the form factor of the zinc sponge anode to match that of the customer's enclosure and successfully demonstrated the performance of these anodes within nickel-zinc batteries.

Building on the prismatic cell design, Enzinc found that acting as a backup power solution for the telecommunications industry was an attractive entry point for Enzinc's nickel-zinc technology. Lithium-ion chemistries are not well suited for such an application unless an expensive battery management system is implemented. Based on the application, these batteries may be held in a fully charged state—termed "float charge"—for months or even years without discharging.

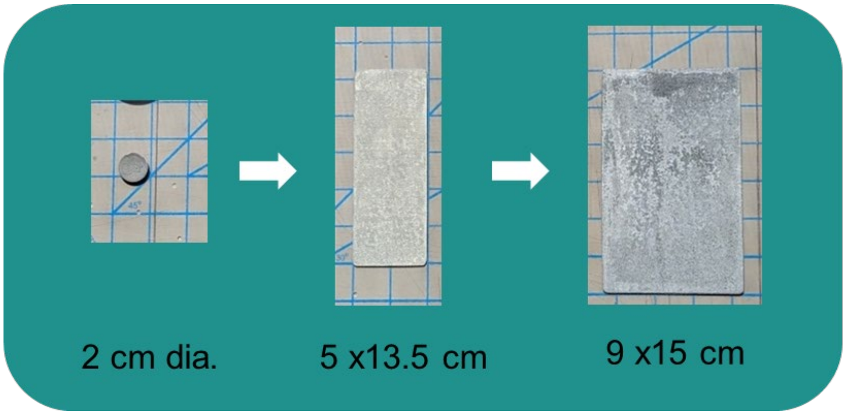
Telecommunication systems operate backup batteries in a float charge configuration, with multiple cells in series connection. The total energy and voltage required is highly dependent on individual applications, but based on industry standards, these batteries are designed around 12 V batteries as the primary building block. Batteries were attached to a busbar, which floats at a potential when energy is supplied to the station from the grid in normal operation. In the event of power outages, the batteries began to discharge to maintain power to the station. These systems operate with essentially no controls in place, and therefore the chemistry must be robust enough to handle the operating conditions.

Results for key development phases of the project are provided in the sections below.

Scale Zinc Sponge Anode

Enzinc made great progress in its ability to manipulate electrode dimensions and thicknesses. The x- and y-dimensions of the electrode (specifically, the footprint) were determined by the physical dimensions of the battery. The z-dimension was determined by the capacity of the positive electrode in the battery. For this chemistry, the desired thickness was typically in the range of 0.6 millimeters (mm) to 1.2 mm. The stationary energy storage product that Enzinc was targeting requires anodes with a footprint of 9 centimeters (cm) x 15 cm. A major milestone for Enzinc was to scale the footprint of the anode from a 2-cm-diameter puck to the full stationary dimensions. As an intermediate step, the team first scaled the electrode to 5 cm x 13.5 cm and performed a variety of cell testing and optimization. In doing so, the team developed a stenciling process that allowed easy scaling of the anode footprint by changing the dimensions of the stencil. The team was able to rapidly scale the dimensions to 9 cm x 15 cm and began testing in the stationary product form factor. The scaling up of the anode dimensions is shown in Figure 5. The team also demonstrated tunability of the thickness of the anode by changing the dimensions of the stencil. Enzinc achieved anodes with thickness as low as 0.6 mm using this method in the 9 cm x 15 cm form factor.

Figure 5: Scaling Up of Anode Dimensions from R&D Testing to Stationary Energy Storage Product



Demonstration of Anode Pilot Line Production

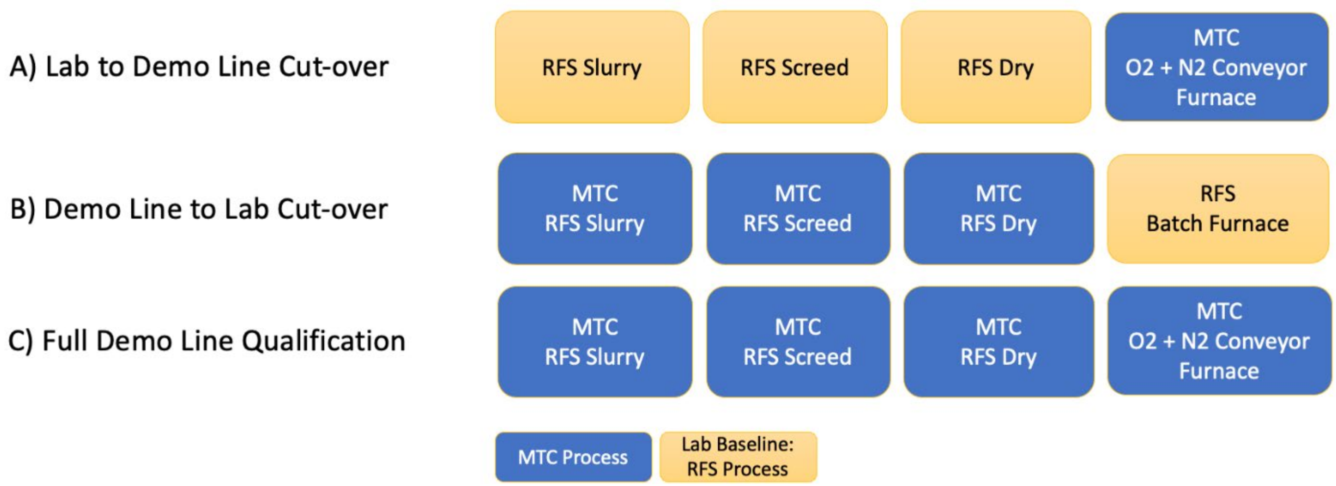
Enzinc successfully designed, built, installed, and commissioned the 10,000 square foot Manufacturing Technology Center (MTC) located in Oakland, California. The MTC, shown in Figure 6, houses the anode preproduction fabrication line for demonstrating anode manufacturability and process validation. This demonstration line is specifically engineered for scaling and demonstrating the manufacturing capabilities and processes in zinc anode production. The MTC is also equipped with quality control analytical testing capabilities. Commissioning of the MTC equipment was completed in the fourth quarter of 2023, and process qualification runs have been underway since the fourth quarter of 2023.

Figure 6: Enzinc Manufacturing Technology Center with Stationary Energy Storage Anode

Bringing the MTC online allowed Enzinc to develop and demonstrate formalized work processes, tools, and strategies for bringing new manufacturing assets online. This includes creating work processes for prestart-up review, standard operating procedures, process qualification methodology, quality management systems, and process control monitoring. Additionally, scaling up the MTC led to establishing production specifications for the anodes—effectively providing metrics of success to the MTC scale-up team.

The scaled manufacturing process is qualified with a series of "cut-over" batches, where the manufacturing team focuses on specific unit operations of the anode manufacturing process to validate MTC operations. Figure 7 illustrates the manufacturing team's approach to qualification.

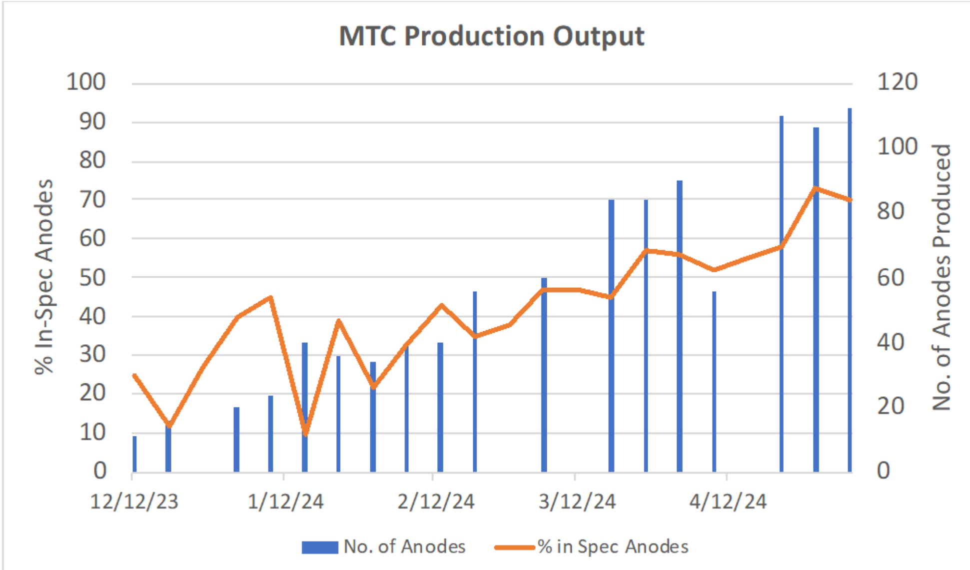
Figure 7: Process Flow Schematic for Cut-over Qualification Runs



In option A, anodes prepared in the laboratory baseline process are fired in the MTC furnace. In option B, anodes prepared and dried on the MTC equipment are sent to be fired in the lab baseline furnace. In option C, full qualification of the MTC demo line is conducted. All three lines of process qualification investigation are being run in parallel. Full line qualification material is being run alongside cut-over batches acting as a "control." Quality analytical data are reviewed after each run, and the resultant data inform adjustments to recipes and equipment tuning to drive desired results (in-spec quality analytics).

Figure 8 provides a summary of the anodes produced from the anode fabrication demonstration line to date. As the manufacturing team incorporated its learnings into subsequent runs, the graph shows a steady increase in the output and the percentage of quality anodes.

Figure 8: Comparison Between Produced Anodes and the Percentage of Quality Anodes



The MTC qualification process provided the Enzinc team with several important lessons in scaling manufacturing processes. High cost and limited availability of furnace equipment at the desired size led the team to reduce production rate expectations to match available and affordable equipment size capability. The team also confronted technical challenges as the process was scaled. For example, analytical method capabilities were refined to provide reliable feedback on process changes.

The team is confident in its ability to close out unknowns in the process qualification process and converge on a fixed process recipe that meets defined quality specifications. The manufacturing team will continue with the process qualification until three runs with the same process conditions can be demonstrated to reproducibly make anodes that meet all intermediate quality metrics. Once this recipe has been "locked," the team will conduct a 24-hour demonstration run to establish baseline throughput rates and quality yield metrics.

Results Summary

Table 2, Table 3, and Table 4 present the results of the project's goals, objectives, and metrics.

Table 2: Results of Project Goals

Goals	Result Statement
Design and test a nickel-zinc 12 V 141 Ah battery to be used as a module for long duration stationary energy storage.	Achieved 12 V battery with 85 Ah capacity. The capacity of the cell scales proportionally to the number of layers. The demonstration battery consisted of 10 layers (8.5 Ah per layer). To achieve 141 Ah, 17 layers would be required. Scaling up the number of layers simply requires a

Goals	Result Statement
	wider container and more electrode pairs. In the future, the team can easily scale the number of layers by increasing the size of the container. For this project, the team used off-the-shelf containers. For future prototype development with battery manufacturing partners, the team will specifically design the enclosure case with appropriate dimensions to fit the number of layers required to obtain the desired capacity.
Validate manufacturability of the proprietary nickel-zinc battery having high specific energy (120 Wh/kg), potential for lower cost (<$150/kWh) compared to existing batteries, resistance to thermal runaway hazards, and temperature range of -40°F to 140°F (-40°C to 60°C).	Achieved 120 Wh/kg and $150/kWh targets. The rated capacity of the cell was established at temperatures of -4°F, 32°F, and 77°F (-20°C, 0°C, and 25°C) using R&D scale cells. Establishing the minimum and maximum operating temperature of the 12 V, 80+ Ah product will require a larger temperature chamber. This testing is planned as part of the product roadmap to be undertaken in collaboration with Enzinc customers.
Conduct environmental testing of the nickel-zinc battery (for example, temperature, shock, safety, etc.).	Achieved. Cell penetration, short circuit, and thermal abuse safety tests were conducted. Safety tests (UL9540a) were successfully conducted by a third-party laboratory.
Test these nickel-zinc batteries for discharge times from 2 hours to 12 hours.	The rated capacity was determined to be about 10% greater at a 12-hour discharge compared to a 2-hour discharge. This is consistent with lead-acid products.
Design and build a preproduction fabrication line for the zinc sponge anodes capable of producing at a rate of 1,000 anodes per day for one 8-hour shift with <5% reject rate.	Achieved. Two 60-inch-wide furnaces with a total cost of $1.33 million are required to produce 1,000 anodes in 8 hours. To work around this financial constraint, a used 12-inch-wide furnace and 50-inch-wide furnace were procured at a total cost of $133,000. The physical dimension of the smaller furnace places a production constraint on the total anode output. Therefore, the production target was de-rated by a factor of 1/16 (0.0625%) based on plate width and stack height. This resulted in a de-rated target output of 7.8 anodes/hour from an initial 125 anodes/hour. The team demonstrated an output rate of 8 anodes/hour. Challenges arose due to the novel nature of the manufacturing process and the high cost of production-representative equipment.

Table 3: Results of Project Objectives

Objectives	Result Statement
Design, build, and test a large format (120 mm x 135 mm) zinc micro-sponge anode.	The team demonstrated the ability to tune the dimension of the anode through a stenciling method. The 94 mm x 152 mm format was most practical for this demonstration. Future projects are aimed at 160 mm x 160 mm electrodes.
Design, build, and test a large format nickel-zinc cell (1.65 V) to be used in a 12 V nickel-zinc battery.	Achieved. The 1.65 V nickel-zinc cell can be easily scaled to tune the capacity in Ah of the cell, and cells can be wired in series to reach the required voltage.
Design, build, and test a 12 V, 141 Ah nickel-zinc battery to be used as the battery element of a long duration stationary energy storage.	The project demonstrated the scalability of the product, uncovering no fundamental limitations in the scale that can be achieved; using the battery as a "building block" for a 1 MW stationary energy storage system is plausible. The chemistry is suitable for discharges in the range of 2 hours to 20 hours.
Demonstrate a preproduction fabrication process for manufacturing large-scale zinc sponge anodes.	Achieved. The novel nature of the manufacturing process coupled with the high cost of manufacturing equipment posed challenges. Success was ensured by leveraging the used market for lower-cost equipment and adopting an experimental approach to the anode fabrication line.

Table 4: Project Performance Measured Metrics

Performance Metric	Minimum Target Performance	Final Measured Performance	Notes
Specific Energy	100 Wh/kg	120 Wh/kg	The team demonstrated a specific energy density that meets the project goal and exceeds the minimum performance target.
Energy Density	300 Wh/liter	260 Wh/liter	Further improvements to energy density will be achieved through elimination of unnecessary headspace above the stack
Cycle Life	500 cycles	150 cycles	Engineering of the cell design and anode tolerances is ongoing to replicate the performance of the R&D cell (1,000+ cycles) in the full-size stationary battery.

Performance Metric	Minimum Target Performance	Final Measured Performance	Notes
Capacity Fade	20% at 500 cycles	15% at 100 cycles	Capacity fade will improve with further design iterations to approach the minimum performance target.
C-Rate	1C to C/12	1C to C/20	The team demonstrated a wide rate capability for the chemistry, which appeals to short and long duration energy storage.
Cost (techno-economic)	<$100/kWh	<$150/kWh	Economies of scale will drive this metric further down as the team scales.

CHAPTER 4: Conclusion

Enzinc's core technology is the three-dimensional zinc sponge electrode, which is the foundation of high energy density nickel-zinc batteries. Enzinc successfully developed the technology from a research and development interest to a product closing in on commercial viability.

Enzinc's technology will assist the goals of Senate Bill 100 and benefit the ratepayers of California by providing safer, cost-effective alternative energy storage for short to medium duration (2 hours to 12 hours) requirements with a high-performance nickel-zinc battery. The advantages are that the Enzinc Inside™ nickel-zinc battery has the energy density of a lithium-based battery and the robustness of a lead-acid battery, exhibits no thermal runaway, uses the fourth most mined metal on the planet (zinc), and can be cost effectively recycled. The manufacture and deployment of the Enzinc Inside™ batteries will benefit low income and disadvantaged communities in California in four ways: (1) the materials used are nontoxic, unlike lead-acid or lithium batteries, and can be built in economic development zones with cost-effective factories; (2) the batteries do not catch fire so they can be used in high density housing to make neighborhood microgrids more resilient; (3) the batteries can be cost effectively and safely recycled; and (4) the Enzinc Inside™ batteries are competitively priced to lower the cost of both stationary and mobility applications.

Using Boundless Energy's manufacturing Greenhouse Gas Emission Cost modeling software, the manufacturing of the zinc anode and the resulting battery produces one-half the greenhouse gas (GHG) emissions of lead-acid battery manufacturing and one-twentieth the GHG emissions of lithium-based battery manufacturing. Deployments of the nickel-zinc battery using Enzinc Inside™ technology were considered for three categories: (1) residential for solar plus storage and energy load shifting; (2) utility scale for microgrids; and (3) nonresidential (industrial) for applications such as data centers. According to Enzinc projections, the resulting GHG emissions savings for California in 2030 are approximately 350 metric tons per year for residential applications, 24 metric tons per year for microgrid storage, and 6 metric tons per year for nonresidential (industrial) at a 10 percent adoption rate.

Enzinc's successful project demonstrated the following:

- A nickel-zinc battery based on Enzinc's patented zinc micro-sponge-anode can provide the energy of a lithium-based battery (for example, lithium ferrous phosphate), more than any other zinc-based technology, without the need for safety or thermal management subsystems.
- Enzinc's nickel-zinc battery is safer than lithium-based batteries; does not exhibit thermal runaway when heated or punctured; is validated in third-party testing; and does not release toxic gasses.

- The zinc anode can be manufactured at high rate, high production yield, and high quality using a continuous conveyor furnace design rather than a batch furnace.
- The Enzinc "drop-in" technology results in a nickel-zinc battery that doubles (compared to Nickel Cadmium) or triples (compared to lead-acid) the battery's performance.
- The resulting nickel-zinc battery can be manufactured in a legacy battery production facility, using a legacy battery manufacturer's existing manufacturing equipment. This answers the question, "What is the most cost-effective advanced battery factory?" with "The one that is already built."

Enzinc will commercialize its technology by capitalizing on the formation of its industry advisory group, four of which are multi-billion-dollar operations. This group of Enzinc's customers will play key roles in accelerating the manufacturing of Enzinc nickel-zinc batteries by using legacy battery manufacturing companies and supplying them with Enzinc "drop-in" zinc anodes (the Enzinc Inside™ approach).

In conclusion, the project successfully demonstrated that a high performance, safe, and recyclable stationary energy storage battery using a unique micro-sponge, made from the common material zinc, has been designed, manufactured at scale, and tested. Enzinc nickel-zinc batteries provides a competitive alternative to lithium-based chemistries, thereby expanding the options available to the State of California (and the world) in its mission to deploy 100 percent renewable energy by 2045.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Ah	ampere-hour
°C	degree Celsius
cm	centimeter
°F	degree Fahrenheit
GHG	greenhouse gas
kg	kilogram
$/kWh	dollars per kilowatt-hour
kWh	kilowatt-hour
mm	millimeter
MTC	Manufacturing Technology Center
MW	megawatt
R&D	research and development
V	volt
Wh	watt-hour
Wh/kg	watt-hours per kilogram
Wh/liter	watt-hours per liter

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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.

- System Requirements Survey
- Systems Level Requirements Document
- Systems Level Test Requirements Document
- Anode Design Report
- Anode Manufacturing Report
- Anode Test Report
- Cell Design Report
- Cell Manufacturing Report
- Cell Test Report
- Battery Pack Design Report
- Battery Pack Manufacturing Report
- Battery Pack Test Report
- Verification Plan
- Verification Report (draft and final)

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