Roadmap to Develop Zinc Batteries for Safe and Cost-effective Energy Storage Solutions

Josef Daniel-Ivad[1], Martin van Leeuwen[1], Tanya Correa[1], Vincent Sprenkle[2], Xingbo Liu[3]

[1] International Zinc Association; [2]Pacific Northwest National Lab; [3]West Virginia University

INTRODUCTION

The International Zinc Association and West Virginia University jointly held a Zinc Battery Workshop on April 8-9, 2026, in Morgantown, West Virginia, to develop a roadmap to scale commercialization of zinc batteries. The two-day event brought together the U.S. Department of Energy, zinc battery researchers, manufacturers, and suppliers, and energy storage leadership from Argonne, Oakridge, Pacific Northwest, and Sandia National Laboratories. One of the goals of the gathering is to create a white paper outlining next steps in the private-public collaboration to support the development of a resilient zinc battery industry in the United States.

ZINC BATTERY HISTORY

Zinc has been successfully used in energy storage for over a century in various primary battery types, of which the zinc-carbon, silver-zinc, and alkaline batteries are the best known; however, rechargeable zinc batteries only developed as a viable industry over the past two decades when researchers overcame previous shortcomings regarding dendrites, shape change, gassing, and cycle life. Given these advances, rechargeable zinc-based batteries are gaining traction in the energy storage space in the chemistries of Zinc-Nickel, Zinc-Manganese, Zinc-Ion, Zinc-Bromine, Zinc-Iodine, and Zinc-Air.

ZINC ADVANTAGES: PERFORMANCE, SAFETY, SUSTAINABILITY AND SECURE SUPPLY CHAIN

What makes zinc so effective in energy storage is its versatility. Myriad chemistries enable zinc batteries to support a wide range of demanding commercial and industrial applications, from storing and supplying energy to the power grid and providing backup power to data centers to meeting the safety challenges and constraints demanded by submarines and fighter jets.

Another zinc battery advantage is a long service life of almost 20 years, 25 percent longer than lithium batteries under the same conditions. Zinc batteries also operate spanning an impressive temperature range (-30°C to 75°C). Most importantly, zinc batteries are not flammable and do not require thermal management or fire suppression systems which, along with their longer service lives, render zinc batteries a more affordable option requiring lower maintenance and fewer replacements. Finally, zinc can be recycled through well-established channels and reused in new batteries.

Zinc batteries also benefit from zinc's resilient and globally sourced supply chain. The United States has zinc mining capacity to supply more than 80% of the domestic zinc market demand. Next to metal, North America has a large industry for zinc oxide production from both primary and secondary sources. Canada also produces sufficient high-purity nickel products for batteries, while the U.S. has a large production facility for Electrolytic Manganese Dioxide (EMD). The U.S. also produces separators and electrolyte in ample supply.

In 2023, domestic demand for refined zinc totaled 921,000 tonnes (ref. USGS). The U.S. produced 766,000 tonnes of zinc in concentrate, with the largest mine located in Alaska (Red Dog). Although the U.S. has a large mining capacity, it lacks smelting capacity. Therefore, of the 766,000 tonnes of mined zinc, a total of 641,000 tonnes of zinc in concentrate was exported, mostly to neighboring Canada and Mexico. Slightly more than that amount of zinc in concentrate, 705,000 tonnes, was refined in Canada and Mexico and then reimported to the U.S., accounting for 77% of U.S. zinc demand. The other 23% of refined zinc demand was refined domestically. The U.S. produced 220,000 tonnes of refined zinc in 2023, using 110,000 tonnes from concentrate and 110,000 tonnes from secondary feed.

With the recent effort to reshore mining and refining capabilities, the U.S. government has fast-tracked the licensing of South32's Hermosa zinc mine in Arizona to increase domestically mined zinc. Along those same lines, the U.S. Departments of Commerce and War have heavily invested in the rebuilding of the largest zinc smelter in the U.S. When completed, the Clarksville, Tennessee, smelter will nearly triple its refining capacity for zinc and its high-demand co-products gallium and germanium. Total domestic zinc refining capacity is expected to grow to 410,000 tonnes per year.

With increased U.S. investment in mining and refining, investment in end-use products such as rechargeable zinc batteries makes sense as well as ensures America's energy independence and resilience. U.S.-based zinc battery companies AEsir Technologies, Eos Energy Enterprises, Urban Electric Power, and ZincFive already produce batteries commercially. AEsir, Eos, and Urban Electric Power have secured multiple federal contracts, while ZincFive is partnering with private companies to make a battery that powers data centers, electric vehicle charging systems, and traffic signals. These companies continue to press for federal support and convincing more utilities, traditionally resistant to innovative technology, to work with zinc batteries. Eos and ZincFive are selling their batteries both in the U.S. and abroad.

Other battery developers, such as Abound, Coulomb Technologies, Enzinc, e-Zinc, Salient, and Zelos, still are developing their battery technologies for large-scale manufacture and seek to reduce both the risk and investment cost of manufacturing as well as accelerate both testing and manufacturing.

CHALLENGES FACED BY THE ZINC BATTERY INDUSTRY

The recent Zinc Battery Workshop provided an opportunity for the zinc battery industry to present ongoing challenges to scaling to mass manufacture and create a roadmap to overcome these challenges through private-public collaboration.

1. COSTLY PILOT LINES

One challenge presented by zinc battery developers is the **prohibitive cost of accessing a pilot line** for routine testing of battery chemistry performance and production issues prior to mass manufacture. World class pilot lines are available at U.S. national laboratories, but using these facilities is often too expensive for young companies and can cost as much as $50,000 per week. Providing affordable access to testing, validation, and improvement would speed commercialization as well as build a resilient and diverse domestic energy storage industry. Independent safety, performance, and grid integration data from national labs also reassures utilities, resulting in technology investment and adoption. Affordable pilot line access lowers risks for battery developers while increasing investor and utility confidence.

2. Commercialization and Manufacturing Lines

Another challenge is the **costly endeavor of scaling manufacture**. Over $1.3 billion has been invested in zinc battery technology so far, and regulators can help the industry grow by encouraging cautious utilities to adopt this promising technology, which offers clear long-term advantages. Production tax credits, investment tax credits, or performance-based incentives specifically designed for non-lithium, long-duration storage would motivate utilities to try a new technology.

If zinc battery commercialized manufacturing lines can grow to use 10% of domestic refined zinc demand, or about 100,000 tonnes annually, they will be able to produce 40,000MWh (40GWh) storage capacity with only 10% market demand (average zinc intensity is 2.5 tonnes/MWh). An additional 10% demand for zinc will not be disruptive, and the market will simply be able to provide this tonnage with slightly more refined metal imports to the U.S. This shows the potential for abundant zinc resources, available as alternative chemistry for energy storage.

3. Safety Standards

One of the greatest challenges for emerging energy storage technologies is **existing safety standards**. As discussed in the Zinc Battery Workshop, these regulations were written for flammable lithium-ion batteries, which require expensive monitoring systems due to their propensity for thermal runaway. Zinc batteries, which are nonflammable and excel in long-duration and stationary applications, are forced into regulatory frameworks that don't reflect their strengths or their risk profile. Updating national and industry standards to explicitly include zinc-based chemistries would enable utilities, regulators, and developers to evaluate zinc systems on their merits rather than by the risks associated with lithium. Safety standards tailored to zinc would accelerate permitting and motivate risk-averse utilities to look beyond lithium to safer, higher performing battery chemistries.

Battery safety standards cover the full product lifecycle, including manufacturing, storage, transportation, installation, use, and end-of-life for industrial and commercial batteries. Fire safety standards during manufacturing, installation and use are specified by Underwriters Laboratories in North America, for example UL1973, UL9540 and UL9540A. For installation, National Fire Protection Association regulations also are relevant, such as NFPA70, NFPA800 and NFPA855. The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR 2023) sets special provisions for battery transportation, where batteries are classified with their own UN classification (e.g., UN3480 and UN3481 for Li-ion batteries). Zinc batteries are classified under UN2794, UN2795, UN2800, and UN3028 categories for primary batteries. Some manufacturers of rechargeable zinc batteries have already successfully applied for a unique UN classification for their product/chemistry.

Opportunities for the Zinc Battery Industry

Discussions during the recent Zinc Battery Workshop also provided opportunities for the zinc battery industry to scaling to mass manufacture.

1. Battery Design Optimization

An ongoing challenge as well as a large opportunity is **enhancing zinc battery performance**, as zinc batteries have not yet reached their theoretical energy density. Pre-competitive research is required to improve the efficacy of the zinc anode; this research is done on material level rather than on cell level because cell levels are not cathode material agnostic.

Standardized performance testing protocols will be critical to achieve maximum energy density. Large datasets can be used by AI to improve anode performance and optimize energy density performance. Benchmark targets can be set for performance parameters, such as determining what is considered world-class in various technologies and chemistries.

2. Manufacturing Optimization

Modelling full-scale production lines with AI, and with digital twins[1], will be a prerequisite for continuous improvement, both on a cell level as well as on a battery level. Finding **best practices in zinc battery manufacturing** can benefit the whole industry.

Establishing performance testing protocols is critical for scaling zinc battery production, as markets for energy storage typically demand low costs and performance predictability. The economy of scale of lithium-ion batteries has resulted in significant price drops of these batteries, while the scale of application has anchored performance expectations. Both reduce investment risk significantly, regardless of battery chemistry.

3. Matching battery technology to application needs

There is no "One-size-fits-all" in zinc battery technologies, and a positive exception to the trend towards cheap energy storage is the **market for data centers**. Energy storage in data centers is provided on a rack level, on an Uninterruptible Power Supply (UPS) level, and on a Battery Energy Storage System (BESS) level, to supply energy and storage capacity on different time scales – from milliseconds to several hours. Energy storage systems in data centers need to be performant and reliable; costs are less important and often considered a very small part of the total investment. Investors are less concerned about a "First-of-a-Kind" (FOAK) technology as long as performance can be shown, which is best validated with standardized performance tests done by third parties.

Action Plan

The International Zinc Association and West Virginia University have developed an action plan to address the above-mentioned challenges and opportunities. They will use the mechanism of Public-Private Partnerships (PPPs) to improve products and bring the next generation of anodes, cathodes, and electrolytes to the market. A three-way partnership among academic institutions, national labs, and industries, including zinc battery developers, and suppliers can result in better utilization, more stable anodes and cathodes, and scaling manufacturing.

1. Reducing the Cost of PPLs

To accelerate the transition from laboratory research to commercial viability, there is a critical opportunity for the U.S. Department of Energy (DOE) and other federal agencies to **invest in a pilot production line (PPL) specifically dedicated to zinc battery technologies**. Zinc batteries possess distinct chemical properties and physical characteristics - such as being non-flammable and having a different risk profile than lithium-ion systems, which make existing lithium-centric infrastructure difficult and costly to reconfigure.

Currently, many zinc battery developers are in the early stages of scaling their technology and face prohibitive costs when attempting to access world-class testing facilities. Routine testing and validation at national laboratories can cost as much as $50,000 per week, a price point that is often

---

[1] Digital twins are real-time, virtual replicas of physical assets, processes, or entire systems, leveraging IoT, AI, and data analytics to simulate, predict, and optimize performance.

unattainable for young, innovative companies. By investing in a shared "community" PPL through Public-Private Partnerships, the federal government can provide affordable access to the specialized equipment needed for zinc-based chemistries. This collective resource would significantly lower development risks, reduce individual capital expenditure, and shorten the timeline for bringing resilient, domestic energy storage solutions to the power grid and industrial sectors.

2. INCENTIVIZING SCALING OF MANUFACTURING LINES

To achieve the commercial scale necessary for a resilient power grid, the zinc battery community looks to the federal agencies like Office of Critical Minerals and Energy Innovation (CMEI) and the Office of Energy Dominance Financing (EDF) in DOE to prioritize the scaling of domestic manufacturing facilities. While the federal energy landscape has been restructured to emphasize American energy dominance, the mandate to secure a stable and independent energy supply remains a primary industrial objective. Specifically, the community seeks to **leverage available federal manufacturing grants and financing programs** to bridge the "valley of death" for zinc technologies. By positioning zinc as a critical mineral that provides non-combustible, long-duration storage for baseload reliability, the DOE can de-risk private capital investment and unlock a secure, domestic supply chain capable of meeting the nation's rising industrial energy demands.

3. INCENTIVIZING POWER AND UTILITY INVESTMENT

As power systems shift from constant to more variable generation, utilities increasingly rely on energy storage to maintain stability and balance supply and demand. Zinc batteries contribute in two key ways. First, they enhance grid stability by providing very fast response to frequency deviations. Battery systems can absorb or release power within milliseconds, helping replace the stabilizing role of traditional rotating generators and maintaining reliable grid operation. Battery systems can also support Combined-Cycle Gas Turbines (CCGTs) to operate at their optimal working point, saving costs by maximizing turbine efficiency and minimizing energy losses. Second, they support load management through peak shaving and load shifting. Zinc batteries store excess energy during low-demand periods and discharge it during peaks, reducing curtailment and lowering reliance on peaking plants. The **decisive criteria for power producers and utilities to invest in energy storage and to select specific storage technologies are unclear**; by starting discussions with power producers, utilities, and transmission system operators (TSOs), they shall be better understood and the unique attributes and performance of zinc battery technologies can be presented.

4. ENHANCING BATTERY MATERIALS AND BATTERY PERFORMANCE

To ensure that foundational material research translates effectively into market-ready technology, federal agencies like the DOE Office of Electricity (OE) should continue its vital role in funding innovation through its network of national laboratories and academic institutions. However, to maximize the industrial impact of these investments, we recommend the **establishment of a Zinc Battery Industrial Advisory Board within the OE portfolio**. This board would serve as a mechanism for commercial developers and material suppliers to provide real-time feedback, ensuring that pre-competitive research is focused on solving high-priority manufacturing hurdles, such as anode shape change, electrolyte stability, and long-term cycle-life under varying grid conditions. By fostering a three-way partnership co-steered by national labs, manufacturers, and suppliers, the OE can ensure that its R&D programs are directly aligned with the performance and cost metrics required for utility-scale deployment. Such a collaborative framework would provide a clear pathway for commercializing lab-scale breakthroughs and securing domestic leadership in zinc-based energy storage.

5. Developing Battery Performance Testing Protocols

To provide the transparency and consistency required for utility adoption, the DOE Office of Electricity (OE) should spearhead the development of **standardized performance testing protocols specifically for the zinc battery ecosystem**. The OE would fund a consortium of experts from universities, national laboratories, and industry to convene for annual workshops and regular technical sessions. The goal is to move beyond proprietary metrics and establish a unified baseline for evaluating different zinc-based technical routes. These protocols would be hosted on an open-access DOE Data-Hub and published in peer-reviewed journals, providing a transparent, third-party validated benchmark. By fostering this spirit of cross-sector collaboration and data-sharing, the OE can help the industry avoid duplicative efforts, accelerate the R&D cycle, and provide utilities with the "apples-to-apples" performance data they need to de-risk their long-term investments.

6. Developing Standards specific to Zinc Batteries

The International Zinc Association's Zinc Battery Initiative (ZBI) will survey which battery companies are actively involved in **working groups for safety standards**. ZBI will get involved with committees and working groups of the National Fire Protection Association and other associations, and will either join a group, or solicit within the ZBI member base to join a group when relevant.