CALIFORNIA ENERGY COMMISSION

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Demonstrating an Aqueous Air-Breathing Energy Storage System for Multi-Day Resiliency

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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 & Electric Company, San Diego Gas & 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 increased safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emissions 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.

Demonstrating an Aqueous Air-Breathing Energy Storage System for Multi-Day Resiliency is the final report for the project (EPC-19-041) conducted by Form 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

The 2021 Senate Bill 100 Joint Agency Report concluded that clean firm resources such as multi-day storage could enable the state to meet its clean energy mandates and reduce electric system costs by $2 billion annually by 2045. However, the report also noted that no clean firm technologies were currently commercially available to fulfill these needs, spurring the California Energy Commission to increase its focus and incentives to bring longer-duration energy storage technologies to market. Multi-day storage resources are needed to provide low-cost, reliable service during multi-day periods of low renewable resource generation, extreme weather, wildfires, and other grid events. Multi-day energy storage technologies, including iron-air batteries, could help pave the way for California to build a resilient, clean, and reliable grid.

Form Energy was founded by energy storage veterans who collaborated in 2017 on a unified mission to reshape the global electric system by creating a new class of low-cost, multi-day energy storage systems. Form Energy's first commercial product was a grid-scale, iron-air battery capable of delivering power continuously for 100 hours (about four days). Made with iron, one of the most abundant minerals on Earth, this battery system could enable a reliable year-round electric grid.

Electric Program Investment Charge funding supported validation of the performance and functionality of a kilowatt-scale prototype module, a critical building block of Form Energy's iron-air energy storage system. As part of the project, third-party validation of the prototype module performance was provided, and modeling information was shared about how Form Energy's energy storage system could operate in the California Independent System Operator market. The modeling highlighted certain areas where multi-day storage resources could provide value to the Independent System Operator system, and where additional policy or market structures could best realize that value to the electric grid.

Keywords: Long-duration energy storage, iron-air battery, battery testing, Form Energy, battery safety

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Executive Summary

Background

California is a world leader in clean energy and energy storage, with the largest fleet of batteries operating on the electricity grid. Energy storage is an important tool to support grid reliability and complement the state's abundant renewable energy resources. These technologies capture energy generated during nonpeak times to be dispatched at the end of the day and into the evening as the sun sets and solar resources go offline, reducing dependence on fossil fuel generation to meet peak loads.

The Public Utilities Code defines an energy storage system as a commercially available technology that absorbs energy, storing it for a specified period, and then dispatches the energy. From 2018 through the first quarter of 2025, battery storage capacity in California increased from 500 megawatts (MW) to more than 15,700 MW with an additional 8,600 MW planned to come online by the end of 2027. The state projects 52,000 MW of battery storage will be needed by 2045.

The vast majority of storage deployed today stores energy for relatively short durations of four to eight hours. Multi-day storage could play a critical role in the California grid and beyond by offering low-cost firm dispatchable capacity to both bolster grid reliability and optimize integration of intermittent renewable renewables in this era of rapid load growth. Form Energy's (Form's) iron-air battery delivers power continuously for 100 hours, providing reliable service during multi-day periods of energy scarcity, extreme weather, wildfire, renewable energy lulls, regional fuel shortages, and other grid infrastructure outages. Additionally, Form's storage technology has no risk of thermal runaway, which is a risk associated with commercial lithium-ion batteries.

The building block of Form's iron-air battery system is a direct current (DC) battery module. The module contains a stack of approximately 30 1-meter-tall cells and is about the size of a side-by-side washer and dryer. Approximately 10 battery modules are grouped together in an environmentally protected enclosure about the size of a shipping container. Hundreds of these enclosures can be grouped in modular, megawatt-scale power blocks, with an inverter to discharge alternating current (AC) electricity. Depending on customer needs and applications, tens to hundreds of these power blocks could be combined and connected to the electric grid.

Project Purpose and Approach

This project supported the performance validation and continued improvement of Form's iron-air battery energy storage system and culminated in the first independent measurement and verification of a battery module prototype (test module). The test module was one of the first modules manufactured at Form Factory 1 and represents a current snapshot of Form's battery system since both the design and manufacturing process continue to be modified and improved.

This project encompassed several core activities including (1) codes and standards analysis and safety testing, (2) battery module design and commissioning, (3) independent measurement and verification, and (4) market participation modeling.

Key Results and Conclusions

Codes and Standards Analysis and Safety Testing

Form Energy's iron-air battery differs from today's commercially available storage technologies, so it required a holistic analysis of relevant codes, standards, and safety testing strategies. The Electric Power Research Institute (EPRI) reviewed the landscape of codes and standards and recommended practices relevant to the future commercialization of iron-air battery energy storage systems. The assessment identified relevant standards guiding design, performance tests, safety tests, installation, system management, and transportation.

One of the key distinguishing factors of Form's iron-air battery design is its safety relative to lithium-ion and other storage technologies, since Form's iron-air batteries cannot undergo thermal runaway. Form developed a safety test plan specific to identifying risks in Form's iron-air battery cells. During this safety testing for the project, zero safety events occurred. In short-circuit testing, which is an industry standard benchmark test for battery safety, there was minimal rise in temperature on the order of between 32° and 41° Fahrenheit (0° and 5° Celsius). The current and temperature generated from Form's battery cells during short-circuit testing were several orders of magnitude lower than other commercially available battery chemistries such as lithium-ion and lead-acid, demonstrating the unique safety profile of the Form iron-air battery.

Battery Module Design and Commissioning

Form successfully shipped, installed, commissioned, and operated the test module in a custom test stand at Form's engineering facility located in Berkeley, California. The test stand was built to test Form's technology and was assembled by staff at the Berkeley facility. The test stand was designed with auxiliary systems such as thermal management and supply air management, which are representative of those found in enclosures during commercial operation. Commissioning ensured that safety-critical systems, battery cyclers, and measurement and verification systems all functioned properly.

Independent Measurement and Verification

To evaluate the performance of the system, Form developed a model of predicted AC load profiles to capture anticipated hourly operation of the iron-air battery system when connected to the electric grid. Form translated these into an equivalent DC battery duty cycle—a pattern of charging and discharging over time—for implementation with the test module.

With EPRI's guidance, Form adapted existing test protocol guidelines to develop a test protocol that considered key battery metrics common to testing in the industry. The key metrics of interest were rated continuous discharge power, available discharge energy capacity, discharge duration, charge duration, and round-trip efficiency. The test protocol also included a duty cycle tailored to future commercial adoption.

Form transferred test performance and event data to the EPRI team throughout the test period for analysis. At the end of the data collection period, the test module met all key performance metrics. In addition, the module successfully completed a representative duty cycle similar to anticipated commercial operation.

Market Participation Performance Modeling

The project team assessed how Form's multi-day storage system would operate in the wholesale energy market operated by the California Independent System Operator (ISO). This analysis, conducted by EPRI, indicated that multi-day storage deployments could both respond to short term (daily) price signals in California's market and help balance seasonal variability in demand and renewable generation, especially in scenarios where combustion resources are limited. The key takeaways highlight an iron-air energy storage system's responsiveness to market dynamics and its potential to suppress price volatility, though current market signals may not fully incentivize its beneficial deployment.

Knowledge Transfer and Next Steps

This project supported Form's achievement of a critical milestone on the path to commercialization: third-party validation of the functionality and performance of the battery module. Project results were shared over the course of this grant with the California Energy Commission and the project's technical advisory committee. The technical advisory committee advised the project team on how to best frame the commercial value of multi-day storage in the California ISO market, including the value of intraday and seasonal cycling. In addition to publishing this final project report, Form worked with EPRI to provide summary performance data to EPRI members through EPRI's Emerging Energy Storage report.

Ongoing Commercialization

Since the start of this project, Form has achieved significant commercial interest in its iron-air battery product, with nearly 140 MW/14 gigawatt-hour of signed agreements with leading utilities and funding agencies across the United States. These agreements illustrate broad commercial interest in iron-air battery energy storage for the role it can play in enabling a cost-effective, reliable electric grid with high renewables and load growth. These commercial deployments will also provide critical learnings for the industry about the value of long-duration energy storage in enhancing grid reliability, as well as opportunities for Form to continue optimization and improvements to its iron-air battery product.

Because the test module was an early prototype of Form's eventual commercial-scale product, Form applied learnings from this project to inform design, cost, performance, and manufacturing improvements. For example, the 1.5 MW/150 megawatt-hour iron-air battery system described here will be located at a Pacific Gas & Electric Company substation in the Redwood Valley area of Mendocino County, California and will be owned and operated by Form Energy. Learnings from this project will inform the Mendocino County deployment, including improvements to the module and overall product design, as well as the dispatch of the battery to provide maximum grid reliability benefits.

Recommendations for Utility Planners, Regulators, and Policymakers

This project can also inform policy and planning actions that would be beneficial to the deployment of multi-day storage. To further the beneficial commercial adoption of novel technologies like Form's iron-air multi-day storage, Form recommends that policymakers and utility planners engage with technology providers and market regulators to fully understand the potential ratepayer benefits of these technologies. With respect to multi-day storage, Form specifically recommends that policymakers consider the following actions:

- Resource planning processes should model various storage options and durations, including multi-day energy storage. Planning processes should also undertake appropriate methodologies to accurately model the operation of these resources.
    - Modeling should account for the ability of multi-day storage to support reliability, especially over extended grid stress events.
    - Modeling should ensure that the portfolio of energy storage devices on the grid represent both a variety of durations and the various functions in each duration.
    - Modeling should consider the operation of resources over the full 8,760 hours in a year.
- Explore market products and price signals that can unlock a suite of benefits from multi-day storage, such as its ability to optimize the overall portfolio and its ability to meet loads during multi-day grid stress events (values not currently recognized by market signals in the existing market).
- Engage directly with providers of new technologies to ensure that the policy assists development of a market that provides maximum value for ratepayers.

Benefits to California Ratepayers

This project accelerated the commercialization of Form's iron-air battery, offering several benefits to California ratepayers. Commercialization and adoption of long-duration storage technologies such as Form's iron-air battery can help reduce electricity costs during high-demand periods by discharging electricity stored from times of abundant renewable production, which in turn can support lowest-cost attainment of the state's clean energy goals. Multi-day storage deployments can also enhance grid resiliency and reliability during events like wildfire-related power shutoffs. Additionally, Form's iron-air technology contributes to supply chain security through its abundant, domestically sourced materials.

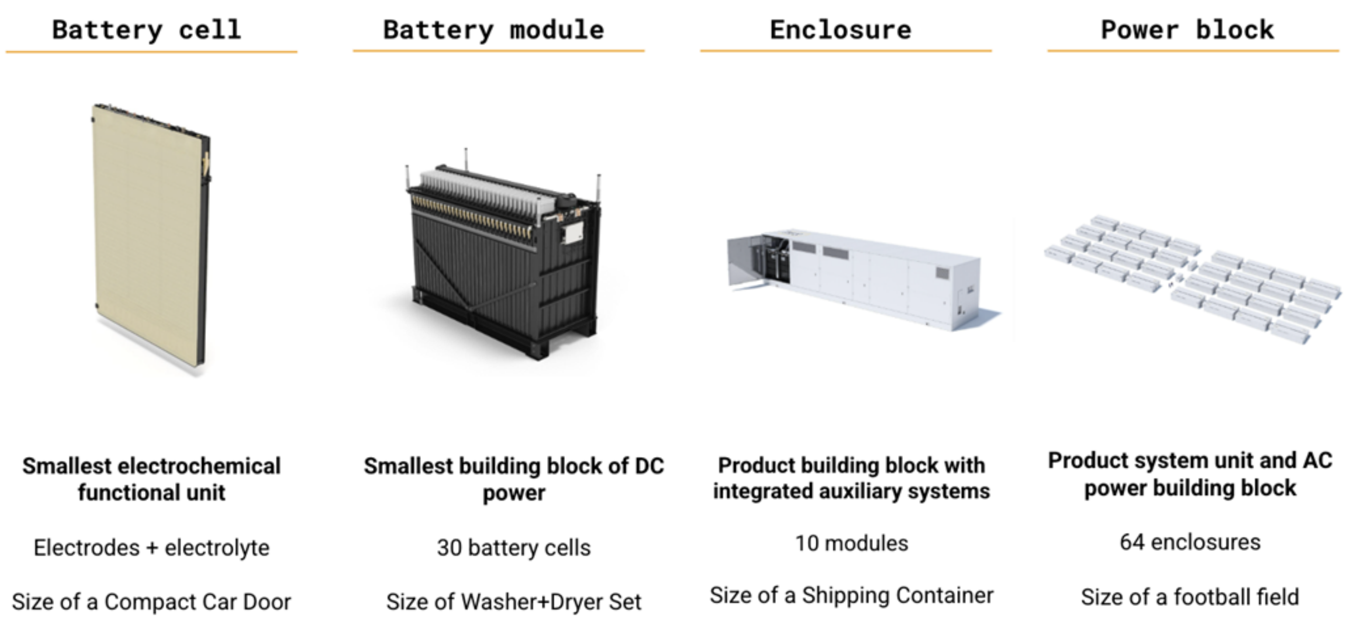
CHAPTER 1: Introduction

Project Purpose

There are currently no low-cost, commercially available clean technologies that provide multiple days of electricity storage. These technologies are potentially useful for maintaining electricity service in the event of multi-day grid outages such as wildfire-related public safety power shutoffs, multi-day renewable energy lulls, extreme weather, or other grid stress events. This project evaluated the performance of iron-air batteries for long-duration storage, supporting their commercialization to help mitigate the impacts of these events.

Form Energy's (Form) iron-air multi-day battery energy storage system provides multi-day storage, which can provide value beyond existing short-duration storage technologies by enabling intraday, intraweek, and seasonal shifting of surplus renewable energy. This flexibility can provide significant value during extreme weather and peak net load events. Form's system is modular and flexible and can be sited anywhere with available land and grid capacity. The different delineations of Form's battery are shown in Figure 1.

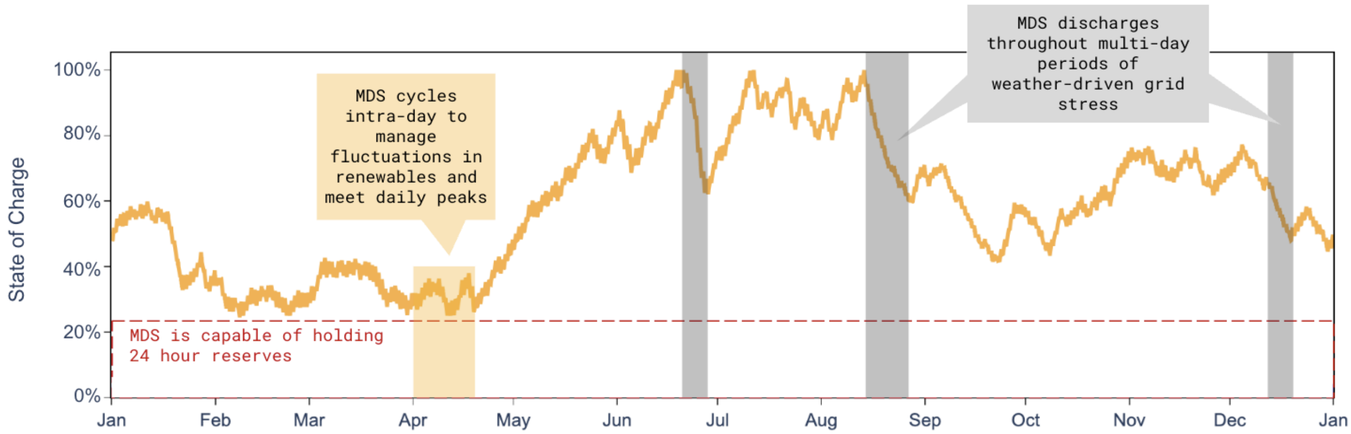
Figure 1: Form Energy's Iron-Air Battery System: From Cell to Power Block



Source: Form Energy

As shown in Figure 2, dispatch of this system in utility-scale operations would be significantly different from systems with short-duration batteries. Its seasonal and annual shape helps balance loads and meet system needs during periods of grid stress (for example, late summer), with energy that is stored from times of abundant, low-cost production (for example, late spring).

Figure 2: Form Energy's Simulated Multi-Day-Storage Duty Cycle in the Independent System Operator



Source: Form Energy

This project helps support ratepayer benefits of lower cost, increased safety, increased reliability and resiliency, and lower greenhouse gas emissions and air pollutants, primarily by furthering the development and accelerating the commercialization of a safe, domestically sourced long-duration energy storage technology. Previous studies have found that long-duration storage, including multi-day storage, could provide energy during key grid stress events to support grid reliability.[1] In addition, multi-day storage could provide local capacity and criteria air pollutant reductions in urban areas like the Los Angeles Basin, while enabling reliable implementation of the state's ambitious decarbonization mandates.

Market Analysis

California's electric transmission grid would benefit from new forms of low-cost, long-duration energy storage to meet its future loads reliably and cost effectively. Academic studies show that low-cost, long-duration energy storage could be critical to enable affordable, clean electric grids that are reliable even during multi-day weather events or other grid disruptions.[2]

However, existing energy storage technologies may be too expensive for extended-duration uses (for example, lithium-ion [Li-ion]), geographically constrained (for example, pumped-storage hydro), or limited in scalability (for example, various mechanical systems) to cost effectively meet grid and customer demands. Long-duration storage operates throughout the year providing intraday, multi-day, and seasonal energy balancing, reducing renewable curtailments, costly in-state gas generation, and criteria air pollutant emissions across a wide range of policy scenarios.

This project explores and advances the commercialization of a product that could serve a key unmet need on the electric system (and for which very little market activity exists today). Once commercialized and scaled, the 100-hour battery system could find a significant market

1 Go et al., 2024, "Assessing the Value of Long-Duration Storage in California"

2 Long 2021; Sepulveda et al., 2018; and Sepulveda et al., 2021

in California, as well as in other states and countries dealing with system dynamics that would benefit from multi-day energy storage systems.

Project Goals

Project researchers performed both a demonstration and independent measurement and verification of a prototype: a kilowatt-scale component of a 100-hour battery energy storage system, operating under customer use conditions. The goals of this project were to:

- Deliver independent, third-party validation of technology progress by demonstrating module-level performance.
- Build capabilities to engage third parties to review the technology, including building infrastructure to test battery components and collaborating with third parties for data analysis.
- Understand how a commercial version of this project could operate in the California energy market, and what can be realized from that analysis.
- Demonstrate module-level functionality by demonstrating how a module could operate in a commercial setting.

This information should help utilities, regulators, and system operators identify least-cost energy resource solutions to address the state's energy requirements.

CHAPTER 2: Project Approach

Safety Codes and Standards Evaluation and Testing

Form Energy's iron-air battery energy storage system has a unique safety profile when compared with other commercially available storage technologies. To address potential gaps in codes and standards, Form worked with the Electric Power Research Institute (EPRI) to review the code, standard, and recommended practice landscape. This evaluation included:

- A code review of how applicable battery safety tests could be adapted to test aqueous iron-air technology (in comparison to Li-ion, lead-acid [Pb-acid], or zinc-air [Zn-air]). The applicable standards defining the key certifications required to commercialize Form's iron-air technology are summarized in Table 1.

Table 1: Key Certifications Required for Form Energy's Technology

Standard	Title	Notes
Underwriters Laboratories (UL) 1973	Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail Applications	This certification standard covers battery systems that would be employed in energy storage systems.
UL 9540	Energy Storage Systems and Equipment	This certification standard evaluates the compatibility and safety of these various components integrated into an energy storage system.
UL 9540A	Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems	Test method to evaluate the fire characteristics of a battery energy storage system that undergoes thermal runaway.

Source: Form Energy

- Recommendations from industry experts on product safety testing, certification, and the project permitting process. Form's participation included:
    - Participating in the development of new standards and the review of existing standards.
    - Conducting an upfront, detailed review of hazards with project stakeholders to accelerate permitting and avoid misaligned expectations.
    - Applying practices and lessons learned from the commercialization of flow batteries, fuel cells, and Zn-air batteries to identify potential hazards.

Prior to module testing, Form completed a failure mode and effects analysis to identify pertinent operational safety hazards and conduct safety tests to validate the module's safety.

During safety testing, which encompassed common battery hazards (short circuits) and Form-specific hazards (draining electrolyte from the cell), zero safety events occurred in the cells tested. In short-circuit testing, there were minimal increases in both temperature and generation of incident current. These results were several orders of magnitude better than other chemistries such as Pb-acid and Li-ion, demonstrating iron-air's unique safety profile.

Design, Manufacturing, and Commissioning of the Kilowatt-Scale Battery Module

The battery module is the smallest field serviceable direct current (DC) building block within the iron-air battery energy storage system. The test vehicle was a full-scale, early prototype battery module consisting of 30 cells in series (Figure 3). The test module demonstrates the basic functionality of the core DC building block. The test module can also provide insights that inform future versions of the product in commercial projects.

Figure 3: A Prototype Module in Form Energy's Berkeley Engineering Facility

Source: Form Energy

The test module was manufactured at Form Factory 1, where Form manufactures electrodes, assembles the electrodes into cells, and assembles them into modules, as shown in Figure 4. The modules were then placed into enclosures and shipped to deployment sites for connection to the grid.

Figure 4: Prototype Module at Form Factory 1

Source: Form Energy

Form installed the test module in its engineering facility in Berkeley, California. The test stand serves many purposes and was custom designed and assembled at the company’s Berkeley facility for testing. In a commercial product, modules will be installed in weatherized enclosures with auxiliary systems in each enclosure including electrolyte management, air handling, cooling and heating, and gas management. The test stand provides similar auxiliary systems to those housed in the enclosure, with additional instrumentation (beyond what would be in a field enclosure) to support data collection to inform product design and optimal operation. The test stand includes components required to apply a current to operate the module and sensors to monitor and track performance, as well as several mechanisms to ensure safe operation, as shown in Figure 5.

Figure 5: Test Module in its Test Stand in Form Energy's Berkeley Facility

Source: Form Energy

EPRI provided independent verification of performance testing. Form collaborated with EPRI to develop a test plan that captured relevant battery metrics, as shown in Table 2. EPRI and Form outlined a measurement and data transfer process before beginning the test to ensure that appropriate data were collected. Form periodically transferred the data with an attached event log to the EPRI team throughout the test period for observation and analysis; EPRI also provided an independent analysis of relevant battery metrics. Finally, EPRI conducted a lab tour of the test stand for verification of both setup and data collection.

Table 2: Data Metrics that Form Energy Shared with EPRI

Signal Name	Units	Description
Cell Voltage(s)	V	Individual cell voltages measured at the terminals of the electrode busbars
Cell Power	W	Individual cell power measured at the terminals of the electrode busbars
Module Current	A	Module current measured using a hall effect sensor
Cell Temperature(s)	degC	Individual cell temperatures measured from the outside of the cell vessel

Signal Name	Units	Description
Charge Capacity	Ah	Module current integrated over time during charge
Discharge Capacity	Ah	Module current integrated over time during discharge
Module Charge Energy	Wh	Module power integrated over time during charge
Module Discharge Energy	Wh	Module power integrated over time during discharge
Module Voltage	V	Module voltage measured at the contactors
BDPS Voltage	V	Output voltage of the Bi-Directional Power Supply (BDPS)
BDPS Current	A	BDPS reported current
BDPS Power	W	BDPS reported power

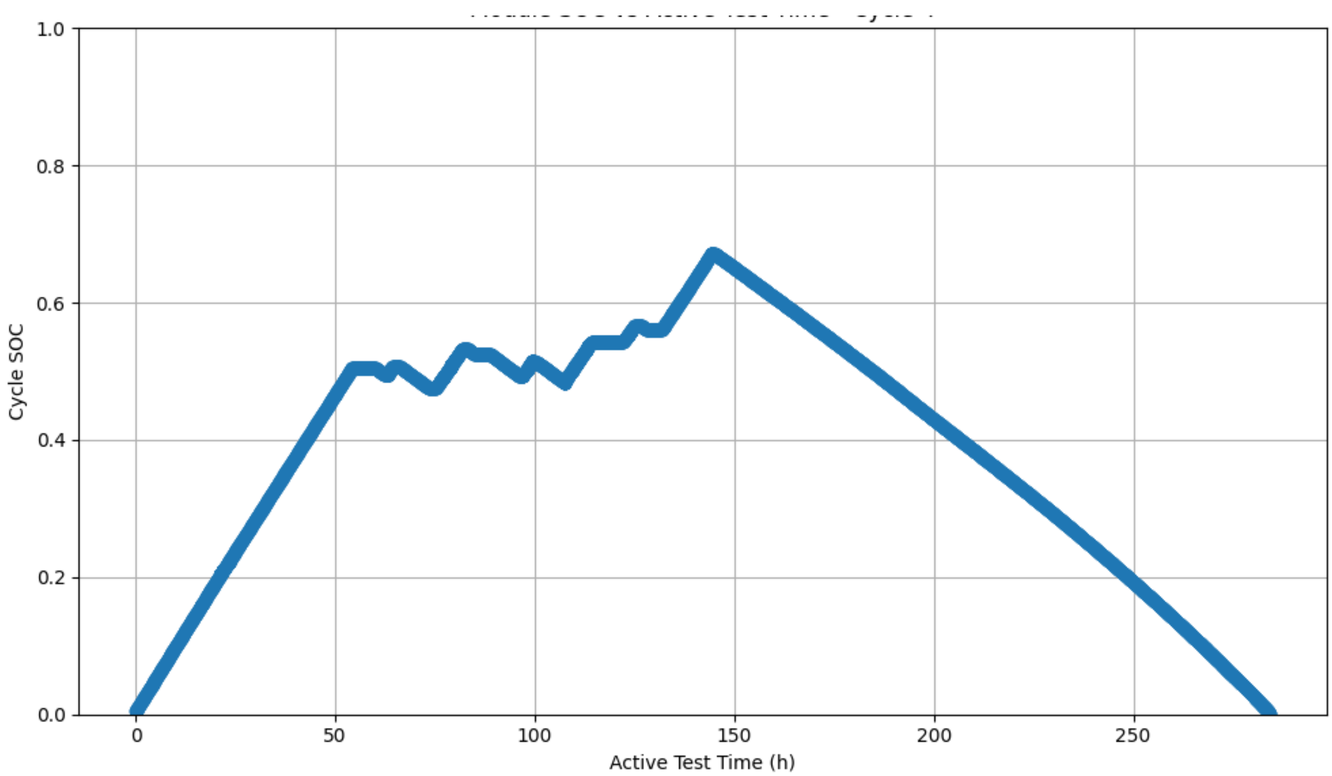
Source: Form Energy

DC Battery Performance, AC Interface Modeling, and Verification

Form Energy modeled relevant potential customer load profiles and translated expected alternating current (AC) customer use profiles into a DC duty cycle utilizing Formware™, which is a capacity expansion, unit commitment, and economic dispatch model developed by Form. Formware differs from other industry models because it performs its optimization over 8,760 hours both per year and across multiple weather years. It is therefore better able to simulate the operation of long-duration energy storage technologies to capture the impacts of weather variability on renewable-intensive electric grids. Formware was benchmarked against the Energy and Environmental Economics RESOLVE model and produced similar results using the same input assumptions and time-sampling chronologies.

To determine the intended product dispatch profiles for duty-cycle testing, Form used the model to analyze year-long hourly dispatch profiles across three commercial projects representing various weather, renewable-resource energy generation, and grid conditions. Form separated these duty cycles into different power, depth-of-discharge, and state-of-charge (SOC) ranges and distilled these annual metrics into a testable, accelerated duty cycle of about 300 to 500 hours that could be used on a single module. This single representative duty cycle captured the dynamics identified in all three customer-use-case profiles, as shown in Figure 6.

Figure 6: Representative Accelerated Product-Intent Module Test Duty Cycle



Source: Form Energy

Form and EPRI collaborated to adapt EPRI's Energy Storage Integration Council (ESIC) test protocol guidelines to ensure that the test considered key battery metrics common in industry testing. Several required changes were implemented to account for notable differences in the iron-air electrochemistry, 100-hour duration, and DC (rather than AC) testing protocol. Key metrics included:

- Discharge Energy Capacity: available energy to discharge in a battery.
- Charge Duration: speed at which the battery can recharge to full SOC.
- Rated Discharge Power: continuous discharge power at which the battery releases its energy.
- Round-Trip Efficiency (RTE): total charge energy divided by discharge energy.

The test protocol additionally expanded on ESIC's guidelines to include the accelerated product intent duty cycle that captured how the battery would be used in actual operation.

The test protocol is summarized in Table 3. Cycles 3 through 5 were three constant power cycles, which demonstrated basic functionality in a standard battery testing protocol for an early verification prototype module and consistency of performance across cycles. The energy throughput from six full cycles on the module was equivalent to six to twelve months of product operation, depending upon project applications and seasonal conditions. Completing six cycles therefore demonstrated up to one year of operation for one module.

Table 3: Test Protocol Part I

Cycle Number	Cycle Type	Test Purpose	Metrics of Interest
1	Formation cycle	Prepares cells for discharge	N/A
2	Constant current reference performance test	Provides a reference for battery performance to compare following or previous tests	N/A
3,4,5	Constant power exhaustive cycle	Demonstrates basic functionality in standard battery testing protocol. This uses the EPRI ESIC Test Manual Reference Performance Test Metrics (module-level)	Rated continuous discharge power Discharge duration Charge duration Round-trip efficiency
6	Constant current reference performance test	Provides a reference for battery performance to compare following or previous tests	N/A

Source: Form Energy

The first test module experienced test downtime due to test stand specific faults including sensor issues, airflow losses, and product-related faults that led Form to switch to a new test module. At the conclusion of cycle 6, Form switched to a test module with vessel seal-design upgrades. Using the new test module, Form conducted a modified test protocol that consisted of two formation cycles, one constant power exhaustive cycle, and one accelerated product-intent duty cycle (Table 4).

Table 4: Test Protocol Part II

Cycle Number	Cycle Type	Test Purpose	Metrics of interest
1	Formation cycle	Prepares cells for discharge	N/A
2	Formation cycle*	Prepares cells for discharge	N/A
3	Constant power exhaustive cycle	Demonstrates basic functionality in standard battery testing protocol using ESIC	Rated continuous discharge power Discharge duration Charge duration Round-trip efficiency
4	Accelerated product intent duty cycle	Provides a reference for battery performance to compare following and/or previous tests	N/A

*Note that cycle 2 was originally intended to be the constant power exhaustive cycle; due to unforeseen test stand down times, this could not be completed. The constant power cycle was repeated in cycle 3 to validate consistent performance between the first and second test modules.
Source: Form Energy

Grid-Scale Modeling Efforts

This project also evaluated the potential operations of grid-scale deployment of Form's battery system. This was performed by evaluating a portion of the economic value of Form Energy's multi-day storage system in the California energy markets in the year 2035, assuming responsiveness of the battery to market-price arbitrage signals. This analysis was conducted by EPRI, which analyzed the modeled performance of a 1-megawatt (MW) AC-connected system operating under realistic grid conditions. The primary objectives of this EPRI work were to:

- Assess the economic dispatch of Form's multi-day storage technology in 2035.
- Provide a high-level assessment of the value the system could provide to the state's electric grid.
- Identify any obvious barriers to the market's ability to fully realize these benefits.
- Allow comparison of the expected operational behavior of the battery with previously expected SOC plots from Form.

EPRI used its modeling tools—U.S. Regional Greenhouse Gas and Energy (US-REGEN) and Distributed Energy Resource Value Estimation Tool (DER-VET)—with battery system specifications provided by both Form and prior analyses for comparison. These specifications reflected a commercial-scale iron-air battery and assumed that systems would incorporate further design improvements to enhance performance and manufacturability while reducing costs. As a result, Form expects commercial-scale batteries to demonstrate improved performance metrics when compared with the test module featured in this project.

CHAPTER 3: Results

Battery Module DC Battery Performance Outcomes

The test modules met all performance expectations for a prototype module, demonstrating the basic functionality of Form's 100-hour iron-air technology. The first test module completed Test Protocol I, cycles 1 through 6, demonstrating both cycling and basic performance for one year. Table 5 summarizes performance metrics from test cycles 3 through 5. Note that RTE is marked as proprietary in Table 5 to protect Form's intellectual property relating to battery testing. While RTE is lower than Li-ion batteries, it is higher than other long-duration storage technologies such as hydrogen-based power-to-power systems. Lower RTE is expected for long-duration storage technologies and ultimately is less impactful to their economic performance given their relatively lower number and less frequent cycling compared to Li-ion batteries.

Table 5: Performance Results for Test Protocol I Cycles 3 Through 5*

Metric	Units	Relevant Cycle(s)	Expected Performance	Results	Actual
Rated continuous discharge power	kW	Constant power, duty cycle	2.13 kW*	Met expectation: ~0.5% above	~2.14 kW for 23S
Available discharge energy	kWh	Constant power, duty cycle	> 213 kWh*	Met expectation	~257 kWh for 23S
Discharge duration	hours	Constant power, duty cycle	> 100 hrs	Met expectation	117 to 126 hrs
Charge duration	hours	Constant power, duty cycle	< 65 hrs	Met expectation: 3.0% faster	64 hrs
RTE	%	Constant power	Proprietary	Met expectation within 0.5%	Proprietary

*Note that the expected performance for power and available discharge energy was scaled to the number of active cells in the module.
Source: Form Energy

The first test module experienced downtimes after the sixth cycle and was retired. Testing proceeded and was completed with a second module that included manufacturing improvements but was otherwise electrochemically similar to the first test module. The second test module completed its test protocol but also met all performance expectations for the prototype module, as shown in Table 6. In addition, the second test module completed the product intent accelerated test duty cycle, demonstrating that the module could charge and discharge as would be expected under real-world operational conditions in energy markets like the Independent System Operator.

Table 6: Performance Results for Test Protocol I Cycles 3 Through 5*

Metric	Units	Relevant Cycle(s)	Expected Performance	Results	Actual
Rated continuous discharge power	kW	Constant power, duty cycle	2.78 kW for 30S	Met expectation: ~1% above	~2.81 kW for 30S
Available discharge energy	kWh	Constant power, duty cycle	> 278 kWh for 30S	Met expectation	~306 kWh for 30S
Discharge duration	hours	Constant power, duty cycle	> 100 hrs	Met expectation	108 to 110 hrs
Charge duration	hours	Constant power, duty cycle	<65 hrs	Met expectation: 1.5% faster	63 hrs
RTE	%	Constant power, duty cycle	Proprietary	Met expectation within 0.5%	Proprietary

*Note that the expected performance for power and available discharge energy was scaled to the number of active cells in the module.
Source: Form Energy

Technical Barriers and Resolutions

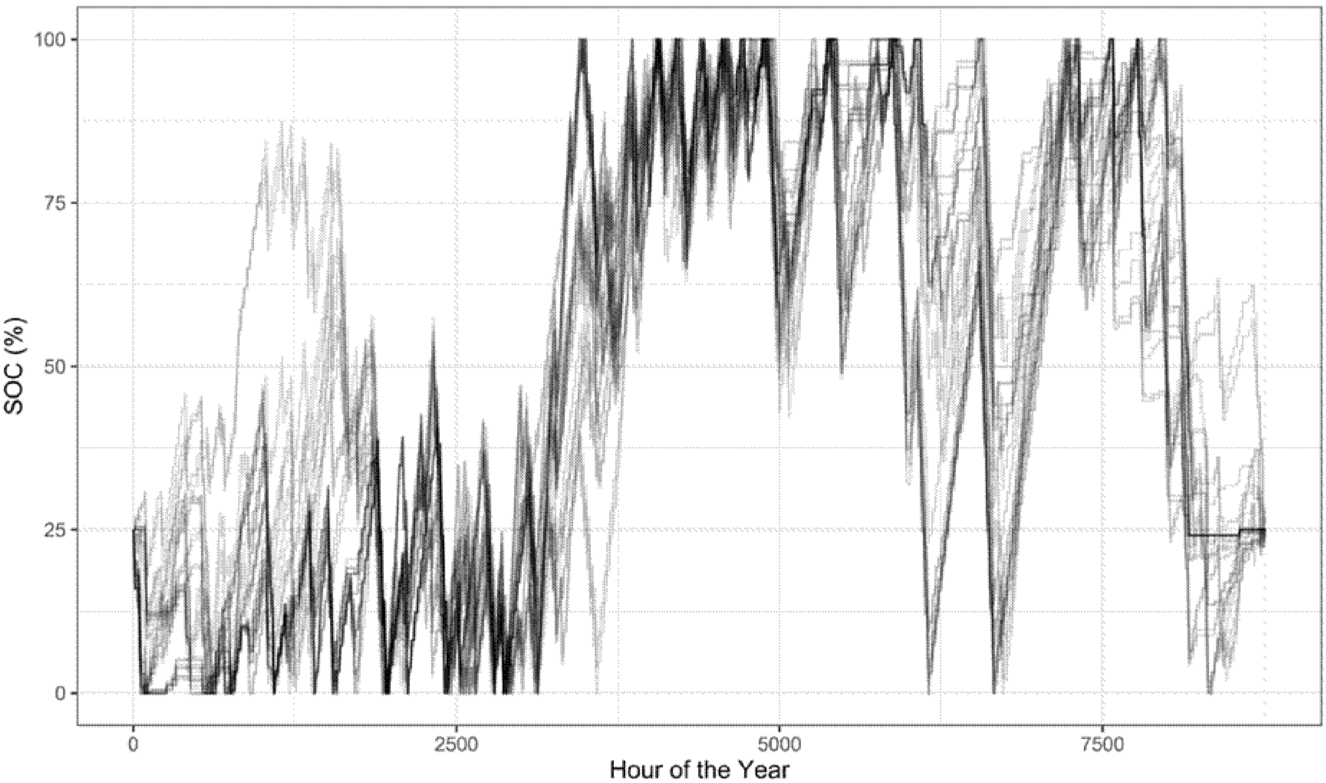
The University of California, Irvine (UCI) lab space originally scoped for the project required modifications and significant overhead to ensure safe operation and compliance for module testing. Form Energy’s Berkeley, California engineering facility was built for hazard mitigation and safety requirements for its iron-air electrochemistry. Form and the California Energy Commission (CEC) team therefore decided to move the testing location from the UCI lab to Form’s engineering facility in Berkeley to both reduce project costs and schedule.

The first test module experienced downtime after the sixth cycle and was retired. Form identified root causes for the downtime, some of which were due to test setups and some of which were due to module manufacturing processes at Form Factory 1. Form addressed these through manufacturing process improvements in a new module that improved overall functionality while maintaining electrochemical performance; testing of the second module was then completed.

Grid-Level Modeling Outcomes

The EPRI study produced expected dispatch plots for the 1-MW, 100-megawatt-hour system over the course of the year (Figure 7) and highlights the operational characteristics of the 100-hour iron-air battery. The results reflect both daily arbitrage and additional seasonal patterns as the battery responded to market and weather conditions.

Figure 7: Annual Dispatch of 1-Megawatt System Across Various Market Conditions and Assumptions



Source: EPRI

These dispatch plots generated by EPRI's modeling tools (US-REGEN and DER-VET) appear comparable to dispatch plots provided by Form, created using its Formware software, as shown in Figure 1. Both show general net charging during spring, with the ability to dispatch for long periods during grid stress events in subsequent weeks and months. Subtle differences between the two can be explained by the following facts:

- In the DER-VET study, EPRI did not impose a minimum SOC constraint, so the SOC used the full 0- to 100-percent range.
- EPRI's and Form's tools handled the beginning and end of the year differently: EPRI assumed a starting and ending SOC, where Formware let that constraint be flexible.

The EPRI study provides the following high-level takeaways:

- The modeling shows significant deployments of multi-day storage in the California market in scenarios where combustion resources are limited.
- The battery system is responsive to market dynamics, with its SOC affected somewhat by responses to intraday price arbitrage opportunities, but more significantly affected by the months of operation, reflecting the battery's responsiveness to seasonal dynamics.

- At larger scales of deployment, the multi-day storage system's discharging during high-price times and charging during low-price times should reduce market-price volatility.

It also identifies that other market signals may affect the operation of the battery (such as ancillary service markets or resource adequacy payments), but that those would not have significant impacts on operational characteristics so were not included in the modeling exercise.

The report also reveals that current market signals for energy storage systems may not fully incentivize the beneficial deployment and operation of a multi-day storage system. For example, current market-price signals may not incentivize the deployment of multi-day storage due to market-price arbitrage opportunities alone, even though a least-cost portfolio would include significant deployments. Additionally, the battery system may provide beneficial energy reserves both throughout the year or during certain seasons—but such activity may not be incentivized by current market structures. Market structures that compensate for extended reliability or stored energy reserves could help incentivize the beneficial deployment of these resources and add stability to the grid. Additionally, overall policy signals or market elements that incentivize the deployment of this type of resource by fully recognizing the overall portfolio benefits of such resources.

CHAPTER 4: Knowledge Transfer

Form and the project team are pursuing several avenues to broadly share knowledge about the project, including the following:

- Form Energy's Public Website: Form Energy's website[3] offers the most up-to-date overview of its technology, its manufacturing progress at Form Factory 1, its media and press announcements, and insights about the value of multi-day storage in different markets.
- Public Conferences Attended: Form has presented (and continues to present) the benefits of multi-day storage (and how to include this technology in future grid planning) at a number of conferences. These included associations of regulators and policymakers around the country at regional meetings, associations of energy project developers, and a variety of broad public forums around energy policy and technology developments. Notably, Form attended the Redwood Valley Municipal Advisory Council in February 2025 to discuss the Mendocino County project and the value of Form's 100-hour iron-air battery on the electricity grid.
- EPRI Member Presentations: Form conducted a number of presentations to EPRI members over the course of the project:
    - September 2021: Form Energy was invited to speak at EPRI's biannual Power Delivery & Utilization Emerging Technology Advisory session to discuss EPRI's research direction with utility members in 2021. The presentation included interactive Q&A with utility members.
    - November 2023: Form presented to EPRI's members about the technology and scope of the project.
    - January 2025: Form presented the technology, its approach to conducting accelerated duty cycling, and module cycling progress to EPRI members.
    - EPRI Energy Storage Technology Database: EPRI will publish a high-level overview of Form's iron-air technology in its Energy Storage Technology Database for public access at the end of 2025.
    - EPRI Performance Analysis of CEC Module Testing: This will be in two parts: the "Emerging Energy Storage Technology Supplemental: 2024 Report," which will be published soon[4] and encompasses the analysis of the first six cycles of module performance data; and the last four cycles of module cycling will be included in a future report.

[3] https://formenergy.com/

[4] https://www.epri.com/research/products/000000003002033521

CHAPTER 5: Conclusion

This research project enabled important milestones in the development and commercialization of Form's iron-air battery technology, including:

- Delivering Independent Third-Party Validation of Technology Progress: This project demonstrated that a prototype module met performance expectations and validated the 100-hour performance of Form's iron-air battery. This project was the first time that an external party, EPRI, validated these battery-performance metrics.
- Building Form Energy's Capabilities in Engaging Third Parties to Review this Technology: Form successfully built testing infrastructure and installed and operated modules at its engineering facility in Berkeley, California. Form additionally shared data with EPRI throughout the project period and worked closely with EPRI to provide context for data analyses. Form will continue to expand these capabilities to engage third parties to validate commercial viability as it continues to develop this technology.
- Understanding How a Commercial Version of the Product Could Operate in the Energy Market: EPRI and Form analyzed how a battery could charge and discharge throughout the year (including daily arbitrage and additional seasonal patterns). The modeling showed significant deployments of multi-day storage in California's market in scenarios where combustion resources are limited in response to the state's clean energy goals.
- Module-Level Functionality and Potential Operations in the Market: This project projected commercial duty cycles and translated them into a module-level duty cycle. The prototype module successfully completed this representative annual duty cycle, demonstrating that the iron-air battery could effectively drive annual electric grid reliability.
- This research project enabled significant technical and commercial progress of Form's iron-air battery technology, which is critical to the success of future commercial projects including its CEC-sponsored project in Mendocino County, California.

Benefits to California Ratepayers

This project accelerated Form's path to commercialization of its iron-air battery product, which offers the following benefits to California:

- Lowering electricity costs while achieving Senate Bill 100 clean energy mandates by storing energy that would otherwise be wasted and deploying it in the most high-value and constrained time periods reduces the total amount of future renewable energy capacity requirements.
- Enabling compliance with state policy and deep emissions reductions. There is the need for 5 to over 30 gigawatts of long-duration storage in California, which would deliver

grid resiliency across a wide range of weather conditions.[5] These deployments could help the state achieve emissions reductions, at both cost parity and cost benefit, that go beyond the state's current energy policy trajectory.

- Enhancing resilience and reliability, including reducing the costs and impacts of wildfire public safety power shutoffs and other extended grid outage events by providing customers and communities with multiple days of zero-carbon back-up power, depending upon grid configurations.
- Providing local capacity since the technology's long-duration and ability to be sited anywhere would support local reliability in transmission-constrained areas. Multi-day storage can cost effectively maintain local capacity requirements and reduce air pollution, which would benefit disadvantaged communities across the state.
- Bolstering supply chain security by using the most abundant materials in the world—iron, air, and water. Form's technology does not rely on critical or rare earth minerals, and the supply chain is over 80 percent domestically sourced, dramatically reducing supply-chain risks when compared with externally sourced energy storage technologies like Li-ion.
- Increasing safety with a battery design that prevents thermal runaway and has a unique and beneficial safety risk profile compared with other storage technologies like Li-ion.

[5] Go et al., 2024, "Assessing the Value of Long-Duration Storage in California"

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AC	alternating current
BDPS	Bi-Directional Power Supply
CEC	California Energy Commission
DC	direct current
DER-VET	Distributed Energy Resource Value Estimation Tool
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
ESIC	Energy Storage Integration Council
Form	Form Energy
ISO	Independent System Operator
Li-ion	lithium-ion
MW	megawatt
Pb-acid	lead-acid
PCE	Peninsula Clean Energy
PG&E	Pacific Gas & Electric
RTE	round-trip efficiency
SOC	state-of-charge
UCI	University of California, Irvine
UCI APEP	Advanced Power and Energy Program at the University of California, Irvine
UL	Underwriters Laboratories
US-REGEN	U.S. Regional Greenhouse Gas and Energy
Zn-air	zinc-air

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Project Deliverables

- Codes and Standards Report
- Safety Test Report
- kw-Scale Module Design Report
- Assembly Documentation Report
- Commissioning Report
- Modeling Summary Report
- Expected Use Case Scenario Report
- Performance Verification Summary
- Grid-Level Performance Model Summary
- Project Fact Sheet
- Technology/Knowledge Transfer Report
- Production Readiness Plan
- CPR Report #1
- CPR Report #2