Form Energy Iron-Air Multi-Day Storage System Technology & Compliance Overview

Background

Form Energy, Inc. ("Form") was founded by energy storage veterans who came together in 2017 with a unified mission to reshape the global electric system by creating a new class of low-cost, multi-day energy storage. Form has grown to over 800 employees across four locations in Massachusetts, California, Pennsylvania, and West Virginia. The company has also raised over $820 million in venture capital from prominent investors such as Breakthrough Energy Ventures, TPG, Coatue, Energy Impact Partners, MIT's the Engine, and ArcelorMittal.

Form's multi-day storage solution (MDS) is a rechargeable iron-air battery capable of continuously dispatching for 100 hours with one-tenth the installed energy cost of lithium ion (<$20/kWh). Form's iron-air system uses the lowest cost active materials available: iron, water, and air. There are no heavy or rare earth metals in Form's MDS solution, and no pathway for thermal runaway or dendrite formation. The principle of operation is reversible rusting.

When paired with wind and solar resources, Form's iron-air system provides a zero-carbon, firm capacity resource to the electric grid, enabling an affordable, reliable electric grid capable of running on renewable energy year-round. Form MDS can also support the broader resiliency of the electric grid to combat the adverse impacts of catastrophic weather events exacerbated by climate change.

Form has received significant commercial traction from a wide range of customers with aggressive decarbonization targets. Form's first commercial project will be deployed in Minnesota with utility partner Great River Energy, and this pilot demonstration will be followed by a series of additional commercial projects in 2025 and 2026, including two deployments with Xcel Energy, one with Dominion Energy, and one with Georgia Power. Form has also been awarded funding from the state of California and New York for demonstration projects, with operations anticipated in 2025 and 2026 respectively. Form was also selected by the US Department of Energy to deploy an 85 MW / 8500 MWh multi-day storage system in Maine, the largest energy storage project by energy capacity announced to date in the world.

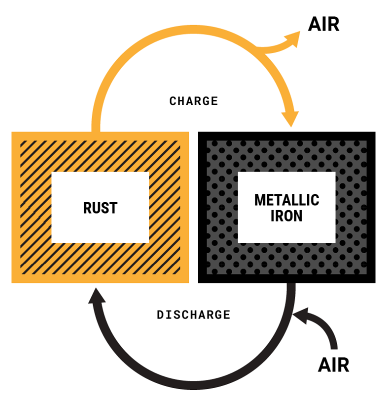
Table 1. Form Energy Commercial Projects

Project	Location	System Size	Commercial Operation Date
Great River Energy	Minnesota	1.5 MW / 150 MWh	2025
Xcel Energy	Minnesota	10 MW / 1000 MWh	2025
Dominion Energy	Virginia	5 MW / 500 MWh	2025
California Energy Commission	California	5 MW / 500 MWh	2026
Xcel Energy	Colorado	10 MW / 1000 MWh	2026
NYSERDA	New York	10 MW / 1000 MWh	2026
Georgia Power	Georgia	15 MW / 1500 MWh	2026
Power Up New England	Maine	85 MW / 8500 MWh	2027 - 2028

Technology Description

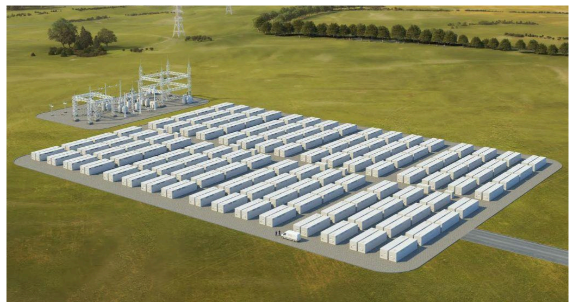
Form's multi-day storage solution (MDS) is a rechargeable iron-air battery capable of continuously dispatching for 100 hours with one-tenth the installed energy cost of lithium ion (<$20/kWh). Made from iron, one of the most abundant materials, this front-of-the-meter turnkey battery system enables a cost-effective renewable grid year-round. Form's iron-air system uses the lowest cost active materials available: iron, water, and air. There are no heavy metals in MDS, and no pathway for thermal runaway or dendrite formation. The principle of operation is reversible rusting.

Each cell consists of iron anodes and commercially proven air cathodes submerged in water-based, non-flammable alkaline electrolyte (similar to the electrolyte used in primary alkaline batteries). While discharging, the battery "breathes in" oxygen from the air and converts iron metal to rust. While charging, the application of an electrical current converts the rust back to iron and the battery "breathes out" oxygen.



Iron-air has the lowest active materials cost entitlement (<$1/kWh) of any known rechargeable battery chemistry. Iron-air chemistry performance, durability, and cyclability had been demonstrated for decades. In the 1970s, Siemens, Westinghouse (with financial support from the US Department of Energy), and the Swedish National Development Company conducted industrial R&D for 1-7 hour iron-air batteries for automotive traction applications. In the 2010s, the University of Southern California led an ARPA-E supported program conducting R&D on 1-2 hour duration iron-air systems for grid storage applications. Form is reinventing this known chemistry for a new, reliable, resilient, and secure electric grid and Form is the first company to commercialize iron-air for long-duration, grid-scale storage.

Fully Integrated Modular System



The system is a turnkey 100-hour energy storage system that can scale from 10 MW (1 GWh) to 500 MW (50 GWh), deployable anywhere on the grid, depending on each project's unique site, space, and power requirements. The smallest DC building block is the battery module, which is the size of a side-by-side washer/dryer set and contains a stack of approximately 30 one meter-tall cells. The cells include iron and air electrodes, the parts of the battery that enable the electrochemical reactions to store and discharge electricity. Each of these cells are filled with water-based, non-flammable electrolyte, like the electrolyte used in primary alkaline batteries.

Battery modules are housed in factory-assembled, weatherized enclosures. In addition to pre-installing modules, battery enclosures come pre-integrated with commercially available auxiliary systems including air handling, thermal management, and water management to support charge and discharge operations.

Approximately 64 battery enclosures are connected via a DC voltage network and aggregated up to a single utility-grade, bi-directional inverter to form an AC power block. Depending on the system size, tens or hundreds of these AC power blocks can then be connected to the electric grid. For reference, the Ballynahone Project will consist of four AC power blocks, with a total capacity of 10 MW, similar to what is shown in the image above.

Iron-Air Safety Features

Iron-air is a fundamentally stable and safe battery chemistry that eliminates the risk of thermal runaway. Thermal runaway is typically caused by an internal short, external short, overcharging, overdischarging, and overtemperature conditions of the battery cell. While these factors can lead to thermal runaway in other battery chemistries, they do not cause uncontrolled destructive reactions in iron-air batteries.

The primary safety risks to mitigate for during operation of the Form Battery System is (1) hydrogen evolution on charge (as a side reaction) and (2) the spill of caustic electrolyte.

Hydrogen Management

When the battery is charged during normal operation , a minimal amount of hydrogen gas may be produced. This is similar to other aqueous batteries such as lead-acid. Hydrogen is not toxic. The primary safety issue is to ensure that hydrogen does not build up in a confined space to a concentration where it could become flammable or an explosion risk.

The Form battery enclosures include a functional safety subsystem for monitoring and limiting the production of hydrogen gas as well as venting it to the atmosphere to reliably maintain the concentration in the system below 25% of the Lower Flammability Limit. The vented gas poses no health or safety risk to the local community. It is odorless, non-toxic, and non-flammable at these concentrations.

Prior to deployment in Ireland, Form will conduct rigorous safety testing as part of its product certification with Underwriters Laboratories, a leading global independent science safety company. This testing will validate the product safety across a number of worst-case conditions, including proving that cell fault conditions do not lead to thermal runaway, and that worst case hydrogen saturated conditions (comparable to those found in a typical lead-acid or nickel-cadmium battery cell) do not pose any safety concerns.

Electrolyte Containment

During system commissioning, each battery cell is filled with a water-based, non-flammable electrolyte, similar to that found in primary alkaline batteries. There is inherent redundancy in electrolyte containment. The cell serves as the primary containment of the electrolyte. The battery enclosure acts as the secondary containment, with the base of the enclosure serving as a basin to retain electrolyte in event of a battery electrolyte leak and thus preventing such a leak from resulting in a release to the environment. In addition, Form's enclosures will include leak detection and monitoring, with associated faults and alarms from the Battery Management System that will send alerts to the Energy Management System and Future Energy Ireland’s Supervisory Control and Data Acquisition (SCADA) system. Upon detecting a leak, the system will automatically cut off power and move the affected enclosure to a safe state. As needed, designated personnel will address any issues according to the site-specific emergency response plan.

Fire Safety Considerations & Mitigation Strategies

As part of the project detailed design, a licensed fire protection engineer will review local code requirements to ensure compliance. The Form Battery Equipment will be designed to meet the required installation codes. Prior to permitting, Form Energy and Future Energy Ireland will have a pre-alignment meeting with the local fire department to discuss the project and any potential impacts on their jurisdiction. This early engagement will help align expectations and inform the project's design. As the design is finalized, site-specific emergency response plans will be developed, incorporating Form equipment product recommendations. Near project completion, the on-site team will host the local fire department for a walkthrough and review of the response protocol.

Code Compliance

Iron-air is widely recognized as a fundamentally stable and safe battery chemistry that eliminates the risk of thermal runaway, which is typically caused by internal or external shorts, or battery overcharging. While these issues can trigger thermal runaway in other chemistries, iron-air batteries are designed to prevent uncontrolled reactions. The system is being developed to meet all leading safety standards, with the goal of obtaining necessary certifications. However, these certifications are seen as minimum safety benchmarks. Form aims to exceed these standards, ensuring the highest possible safety. In addition to addressing single-fault scenarios, the approach involves rigorous testing for multiple faults, including rare, low-probability events. This thorough testing strategy is designed to mitigate all types of risk, ensuring unparalleled safety for the systems.

The Form battery system will be designed and manufactured in strict compliance with applicable codes and standards governing energy storage system safety and performance. To ensure the highest level of safety and reliability, Form has collaborated closely with industry-leading entities such as DNV, EPRI, and UL throughout the development process.

Form completed the New & Innovative Program with Underwriters' Laboratories in 2023. The intent of this program was to develop a system design, test, and compliance strategy targeted to the unique safety profile of the Form iron-air battery. Through this program, Underwriters' Laboratories identified product certification standards that would be required for iron-air systems. These product certification standards included UL 1973 and UL 9540. Additionally, the system would also be required to complete UL 9540A testing.

Form is in the process of completing these certifications in preparation for the deployment of our first demonstration project with Great River Energy in 2025, and we anticipate having them finalized well before the project at Ballynahone. More information on each certification is provided in the following sections.

Table 2. System Certification Standards

Certification Standard	Applicable System	Description	Completion Timeline
UL 1973	Cell, Module	Cell and module level standard designed to ensure the safety and reliability of the electrical, thermal, mechanical, and fire safety systems.	2024
UL 9540A	Cell, Module, Enclosure	Test method for evaluating thermal runaway fire propagation in battery systems.	2024
UL 9540	System	System level standard designed to ensure the safety and reliability of the electrical, thermal, mechanical, and fire safety systems.	2025

UL 1973

UL 1973 is one of the main battery safety standards designed to ensure batteries are safe and reliable for real-world applications. It defines specific requirements that manufacturers must meet to achieve safety certification.

To comply with UL 1973, the Form Battery System must meet stringent construction standards. These include the durability of the metal enclosure, its ability to withstand mechanical loads, protection against water and debris ingress, corrosion resistance, and proper electrical bonding to ground. Additionally, non-enclosure requirements involve evaluating insulating materials that support live parts, ensuring they meet UL 746C standards for fire resistance, tracking resistance, temperature ratings, and compatibility with the system's aqueous electrolyte. The Form Battery System must also comply with standard electrical insulation ratings and internal spacing requirements.

Other tests that are required by UL1973 include the Overcharge Test, the High Rate Charge Test, the Short Circuit Test, the Overload Under Discharge test, and the Overdischarge Protection Test. The unique characteristics of the Form Battery System allow it a certain level of inherent safety in these tests relative to a lithium-ion, since the iron-air charge and discharge reactions occur at a much slower rate than the charging and discharging reactions internal to lithium-ion.

UL 9540

UL9540 is a system level standard for evaluating the safety of energy storage systems, including battery systems but also other technologies like flywheel or thermal energy storage. It requires the completion of a holistic hazard analysis and a corresponding Functional Safety System, which is designed to prevent or control specific safety concerns. It also applies many prescriptive construction requirements and test methods which are similar to those in UL1973, as well as some additional system level considerations, like a minimum level and corresponding unit level test of electrical isolation for isolated circuits.

UL9540 applies additional safety requirements for systems installed inside habitable structures or buildings and for systems designed to be walk-in for service personnel. It is important to note that the Form Battery Enclosure is not designed to be entered by persons. It is to be installed in an access controlled location and maintained only by specially trained personnel.

UL 9540A

UL9540A is a test method standard. As part of the test, Form will demonstrate that “thermal runaway” is impossible for iron-air systems. Thermal runaway is the most concerning failure mode in other battery energy storage systems (especially lithium-ion), and is defined in UL9540A as “when an electrochemical cell increases its temperature through self-heating in an uncontrollable fashion. The thermal runaway progresses when the cell's generation of heat is at a higher rate than the heat it can dissipate. This may lead to fire, explosion and gas evolution.”

Form’s iron-air battery technology is novel and has an inherent safety advantage with respect to the hazard of thermal runaway. Form’s UL9540A testing will prove this through a series of severe battery abuse tests which normally induce thermal runaway in lithium-ion cells.