Long-Duration Energy Storage: *Emerging Pilot Project Summaries*

SI: EPRI Insight

TECHNOLOGY INNOVATION

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Introduction

Purpose:

This report summarizes recent pilot projects of Long-Duration Energy Storage (**LDES**) technologies, specifically technologies developed by **CMBlu, Energy Dome**, **Storworks Power (Storworks)**, and **RedoxBlox.**[1] It aims to provide highlights on the technological processes, performance and cost metrics, and potential viability as demonstrated through field work of these emerging energy storage solutions. By examining these pilot projects, the report provides insights into understanding how these technologies function and how they may fit into perspective portfolios to enhance grid stability and variable renewable energy utilization. Please note that the projections and evaluations within this report are primarily based on forward-looking statements from the manufacturers of the LDES technologies and have not been independently verified by EPRI, except where explicitly stated.

Relevance:

Insights from these energy storage pilot projects offer high-level qualitative and quantitative information for utilities. These insights include summaries of performance and cost data, which are important for evaluating LDES systems.[2,3] Additionally, the report highlights activities and findings from the pilot testing, providing a better understanding of the status and maturity of these technologies and their use cases. By understanding the performance, costs, and maturity of these pilot projects, utilities can make more informed decisions about the potential benefits of LDES technologies for their energy portfolio.[4] More details on these and other energy storage technologies can be obtained through participation in EPRI's Program 94 "Energy Storage and Distributed Generation" and Program 221 "Bulk Energy Storage."

[1] Energy Storage Technology Database (ESTD) v1.0. EPRI, Palo Alto, CA: 2023.

[2] EPRI Insights: Current Events, Industry Forecasts, and R&D to Inform Energy Strategy. EPRI, Palo Alto, CA: 2022. 3002025959.

[3] Long-Duration Energy Storage: Potential Use Cases and Technology. EPRI, Palo Alto, CA: 2021. 3002019019.

[4] Long-Duration Energy Storage Benefits. EPRI, Palo Alto, CA: 2021. 3002021099.

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Emerging LDES Technologies Overview

Electrochemical: Uses reversible chemical reactions to generate electricity, with lithium ion batteries being the principal technology. New electrochemical batteries represent a promising frontier in long-duration energy storage. These technologies use low-cost raw materials such as zinc and iron in the active materials that store energy. These batteries are scalable, with projected low marginal cost of energy, making them suitable for applications required sustained energy delivery, such as renewable integration and backup power.

Mechanical: Harnesses kinetic or potential energy to store and release energy. Potential energy systems, such as pumped hydro storage, use gravity and involve lifting mass when charging and lowering it to spin a generator to create power when discharging. Kinetic energy systems, such as compressed air energy storage (CAES), generally compress a working fluid when charging, storing it at pressure, then expanding it to drive a turbine when discharging. A wide array of emerging mechanical energy storage systems are being developed, which promise lower cost and higher round-trip efficiency (RTE), along with easier siting.

Thermal: Stores and releases energy in the form of heat. Heat can either be stored sensibly using media such as concrete, gravel, sand, or salt or using a phase-change material, which provides additional heat from phase transitions. When charging, the medium is either heated by a hot fluid or electrically, and when discharging, a working fluid is heated to either drive a power cycle, or to provide heat directly to a process. Thermal energy storage (TES) has the potential to be the lowest cost LDES system, balanced by lower efficiencies.

Chemical: Involves creating a low-carbon fuel or performing a reversible thermochemical reaction that can generate heat. Hydrogen is the primary low-carbon fuel candidate and can be generated using electrolysis, or chemically through reforming a fossil fuel, coupled with carbon capture and storage. Other candidate low-carbon fuels include ammonia and bio-fuels. Once created, these fuels can be stored for up to seasonal periods and burned in conventional power generators. Thermochemical systems use a compound that combined with air or water generates heat to drive a power cycle, that is then reformed to repeat the process.

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CMBlu (*Electrochemical*)

CMBlu's Organic SolidFlow battery is a redox (reduction-oxidation) flow battery (RFB) containing electrolytes in the solid and liquid form. Nearly all the energy is stored in a carbon-based solid. The liquid electrolyte acts as a shuttle, moving charged ions between positive and negative sides through the battery stack to charge and discharge. The separate tanks and stacks make it possible to scale power and capacity independently.

Technology Benefits

Long Lifetime: The separation of electrolytes in tanks eliminates some mechanisms of capacity degradation. The technology is projected to have a 20-year project life, capable of over 20,000 cycles, with minimal loss of capacity due to cycling.

Cost Effective: Abundant carbon-based molecules for the electrolyte have the potential to be low cost when manufactured at scale. This in combination with the long lifetime can make the technology cost competitive at scale.

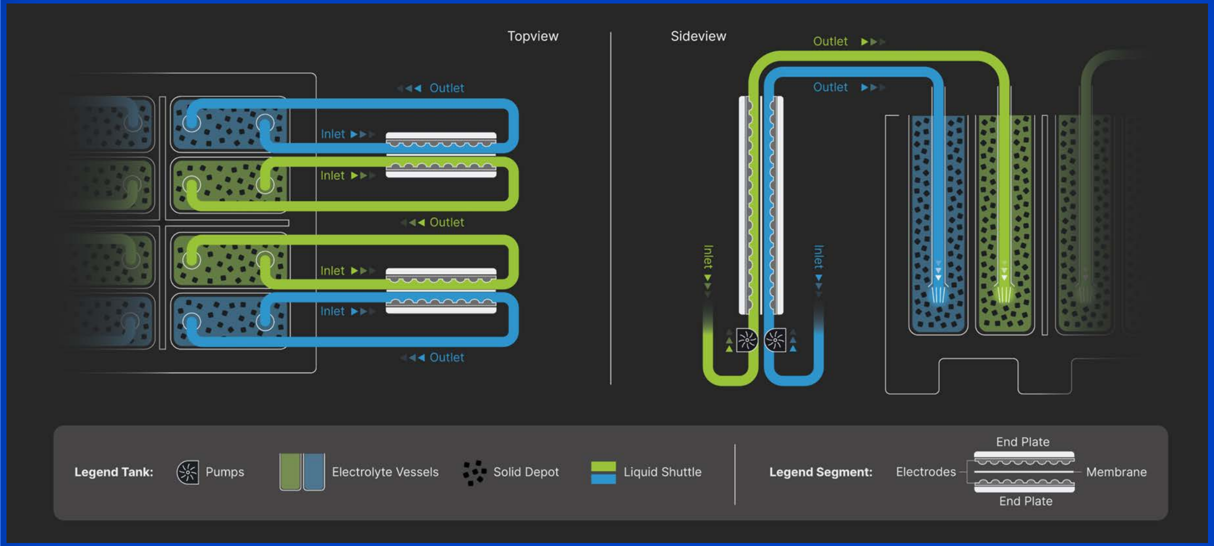

Figure 1. Schematic of the Organic SolidFlow Battery

Figure 1 shows the operation of CMBlu's SolidFlow battery. Two external tanks containing different electrolytes, one positively charged, and one negatively charged, are connected to the stack via pumps that deliver the electrolytes to the power module. They are prevented from mixing by a thin membrane and pass-over porous electrodes to cause either a charging or discharging. To charge, oxidation occurs at the anode causing a loss in electrons, which flow in the power module and to the cathode. The process is reversed to discharge, where the anode experiences reduction and the cathode experiences oxidation.

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CMBlu (*Electrochemical*)

Process

The Organic SolidFlow battery is made up of two external tanks, a battery stack and a power module connecting the battery to the grid. The external tanks contain either anolyte or a catholyte (positively or negatively charged electrolyte respectively). Each of the electrolytes are composed of an active solid and liquid material of matching potentials. The battery stack is made up of four components in a repeating order. The electrodes facilitate the redox reaction. The membrane is an insulator that selectively allows ion migration but prevents the different electrolytes from mixing. Current collectors facilitate the flow of electric charge and connect the stack to the grid. The end plates provide mechanical support and electrical interfaces to the power conversion system. The battery output is dependent on the material and surface area of electrodes, the stack size, and the kinetics of the redox process.

Pilot

CMBlu is collaborating with WEC Energy Group and EPRI to install a 1–2 MWh pilot project at Valley Power Plant in Milwaukee, WI to test the performance of the battery system, including discharge durations of five to ten hours.[5] Initial testing of a single DC module prototype was successful at the power plant in December 2023 with testing on-site initialization of the module, several charge and discharge rates and providing critical logistical experience with sea, rail, and truck transport. As part of the pilot project, WEC, EPRI, and CMBlu conducted a detailed hazard mitigation analysis (HMA) of the battery module, focusing on potential hazards to personnel. The HMA used the Energy Storage Integration Council Flow Battery HMA Guide and provided input to pilot test plans and safety checklists.

[5] "WEC Energy Group Announces Project to Demonstrate Long-duration Organic Flow Battery Storage," February 2, 2023. https://www.prnewswire.com/news-releases/wec-energy-group-announces-project-to-demonstrate-long-duration-organic-flow-battery-storage-301737840.html.

Figure 2. Modular Battery (used with permission from CMBlu)

CMBlu's Organic SolidFlow battery module is being designed to enable scalability. Figure 2 shows how the modules can be stacked to increase the system-level energy density. Each module has a targeted footprint of 21.5–26.9 ft^2 (2–2.5 m^2), depending on duration, and a 50 MW, 250 MWh system has a projected footprint of 33,906 ft^2 (3150 m^2) for the battery portion.

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Energy Dome (*Mechanical*)

Energy Dome has developed a CO_2 Battery system for LDES, utilizing carbon dioxide as the storage medium. This system, which operates similarly to CAES but uses CO_2 stored above-ground instead of air stored below-ground. Key features include efficient heat capture during CO_2 compression and a flexible, above-ground CO_2 gas dome, allowing for diverse siting possibilities. The pilot project, a 2.5 MWe/4 MWhe grid-connected unit, has successfully demonstrated the technology's viability and was completed in two years despite global challenges. Energy Dome plans a larger-scale 20 MWe, 200 MWhe plant by late 2024. The technology is targeted for utilities and industries, including remote mining operations.

Technology Benefits

Energy Efficient: Energy Dome's CO_2 Battery, leveraging commercially available components, targets an 18-month development cycle and has a RTE of 75–80% with 100% depth of discharge. Designed for a lifespan exceeding 30 years, it operates without capacity or power degradation. The system's energy density is 1.9 kWh/ft³ (67 kWh/m³), surpassing conventional CAES systems. A 200 MWh installation requires a 10–12-acre (4–4.9 hectares) footprint or 17–20 MWhe/acre (42–49.4 MWhe/hectare).

Cost Effective: The capital costs are estimated at \$150–220/kWh, with the levelized cost of storage projected under \$100/MWh for early projects, with the potential to reduce to \$50–60/MWh. Challenges include siting due to visual impact of the dome. The dome is an inflatable structure that can be easily removed at the end of life of the project. The CO_2 Battery does not have any major environmental impacts as it only uses steel, water, and CO_2 in its functioning.

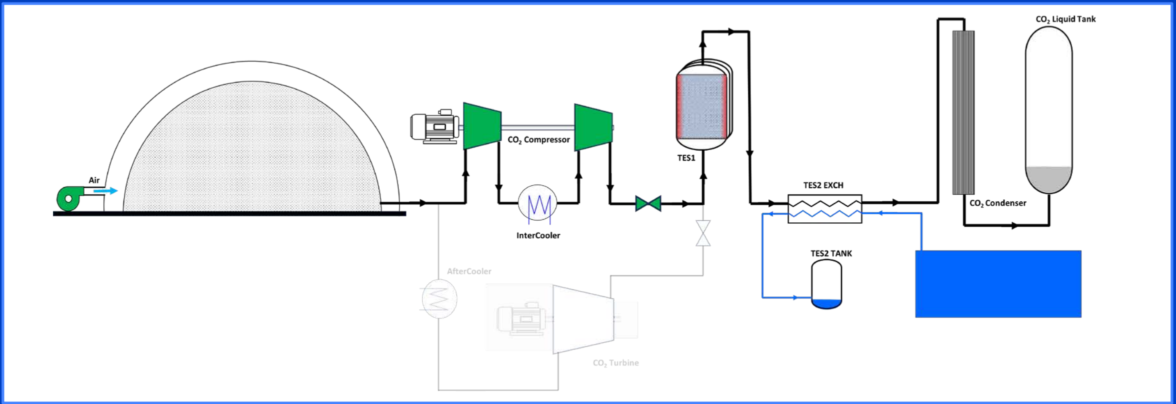

Figure 3. Charging Energy Dome's CO_2 Battery

In Figure 3, the CO_2 Battery's charging process involves a multi-stage compressor powered by an electric motor, compressing CO_2 to medium pressure. This process generates heat, which is stored in two types of **TES** systems: a primary pressurized packed particle-bed system for direct heat transfer, and a secondary tubular heat exchanger system that cools the CO_2 to a liquid/dense phase for storage in above-ground pressure vessels.

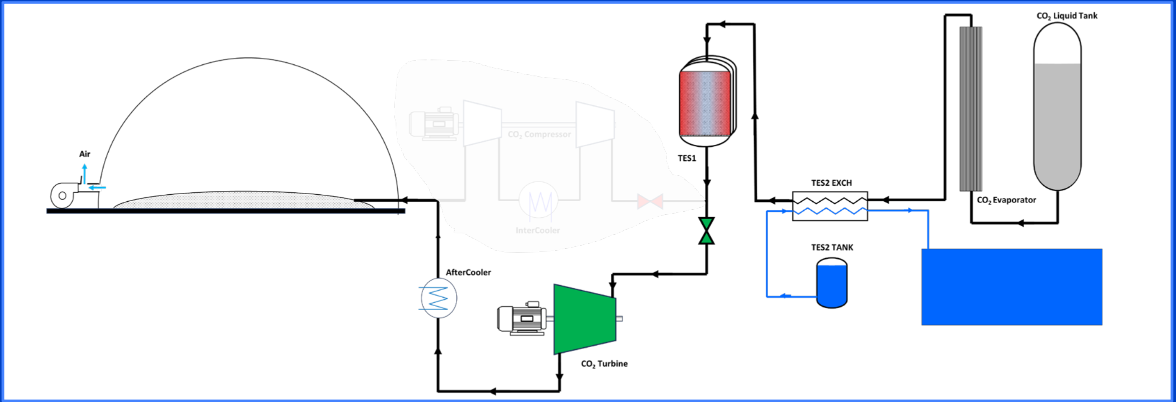

Figure 4. Discharging Energy Dome's CO_2 Battery

In Figure 4, the CO_2 Battery's discharging process involves reversing the charging cycle. High-pressure liquid/dense-phase CO_2 is vaporized and heated by passing through a water-tube heat exchanger, serving as an evaporator, and then through a TES packed particle bed. The hot gaseous CO_2 expands through a turbine connected to a generator, supplying electricity to the grid. After expansion, the CO_2 is cooled to ambient temperature for storage in the dome's bladder. This system is engineered for daily use over a 30+ year lifespan without degradation.

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Energy Dome (*Mechanical*)

Process

Energy Dome's CO_2 Battery system utilizes CO_2's unique property of transitioning to a liquid phase at ambient temperature under moderate pressure. The storage process compresses atmospheric CO_2 to medium pressure, efficiently capturing and storing the heat generated during compression in two TES systems. When electricity is needed, the stored CO_2 is reheated and expanded through a turbine to generate power. The system's architecture allows for consistent operation over 30 years with daily cycling and can accommodate charge/discharge cycles ranging from 4 to 24 hours. To house the required substantial quantities of CO_2, a dome storage structure is needed, which, despite its large footprint, remains cost-effective due to the use of economical materials and minimalistic site preparation requirements.

Pilot

The CO_2 Battery system's projected RTE of 75–80% hinges on the performance of the TES modules and the efficiency of the compressors and turbines. Achieving this RTE on a large scale would make the system especially suited for applications requiring high depth of discharge cycling while avoiding the degradation issues common in electrochemical batteries. The pilot plant in Sardinia, with a capacity of 2.5 MWe/4 MWhe, has demonstrated promising results, confirming the system's anticipated operational capabilities. These outcomes have placed Energy Dome's technology at Technology Readiness Level 7, reflecting its suitability for broader commercial application and signaling a significant step forward in sustainable energy storage solutions.

Figure 5. CO_2 Battery's Dome-Shaped Housing for the Inflatable Bladder Holding the CO_2 in Discharge Mode at Atmospheric Pressure (used with permission from Energy Dome

Figure 5 displays Energy Dome's 2.5 MW, 4 MWh CO_2 Battery unit in Sardinia, which has been operational since May 2022. It highlights the plant's real-world operational and grid-support capabilities. Energy Dome is also in advanced planning for a commercial-scale 20 MW, 200 MWh plant at the same location, and has several agreements for additional projects in Italy and beyond, including with Alliant Energy, which as prime won a United States Department of Energy award in 2023 to install a commercial-scale Energy Dome system in Wisconsin.

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Storworks Power (*Thermal*)

Storworks is developing systems to store energy using heat. They focus on thermal power plants, especially those using fossil fuels, solar concentration, or nuclear energy. Stackable blocks made of concrete material are used to store the heat. Using concrete has proven to be cost efficient and flexible. Charging occurs by passing either hot gas, steam, or hot air through steel tubes in the concrete blocks. To use the stored energy, a working fluid such as water or carbon dioxide is passed through separate tubes in the concrete blocks to recover the heat and deliver it to a power cycle.

Storworks makes three different designs; different system configurations offer solutions for industrial decarbonization.

Technology Benefits

Energy Efficient: In a normal combined cycle plant, the gas turbines make about two-thirds of the total power with the remainder being from a steam-Rankine bottoming cycle. Using the concrete heat recovery steam generator (HRSG), the turbines can be sized smaller and run efficiently all day long, sending extra energy to the heat storage system when power is not needed and releasing this energy when needed. The RTE is 35–45% based on the capability of the power cycle the system is attached to.

Cost Effective: Unlike other energy storage systems that store heat using specialized materials and require proprietary power cycles to generate energy, the Storworks concrete modules utilize existing power plant hardware, including the steam turbine-generators, thereby reducing capital costs for deployment. Storworks anticipates the cost of a system exceeding 10 hours of duration retrofitted to an existing steam turbine asset would be \$60–105/kWhe.

Figure 6: Storworks BolderBlocs (used with permission from Storworks Power, Inc.)

The Storworks concrete modules, shown in Figure 6, are large, flat blocks with embedded pipes set into them. Each tube has about 2 inches (5 cm) of concrete surrounding the tube enabling conductive heat transfer. The modules, called "BolderBlocs," are about 40 feet (12 m) long, allowing them to be shipped on a regular flatbed truck. When installed, they are stacked and connected using a network of pipes and distribution manifolds. The final stacked assembly is covered with high-temperature rockwool insulation and clad with waterproof metal sheets for weather protection. The footprint is expected to be >500 MWhe/acre (1235 MWhe/hectare).

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Figure 7: Storworks Plant Gaston Pilot (used with permission from Southern Company)

The Concrete Thermal Energy Storage (CTES) pilot plant, shown in Figure 7, consists of 7 layers of BolderBlocs stacked in a brickwork-like pattern along with an additional cooling block layer at the bottom needed to insulate the foundations during operation. Supercritical steam from the host site enters the CTES during charging (top right), warming the CTES and thereby generating high-pressure condensate that is further cooled using the heat exchanger (bottom left) before being depressurized and stored in a local vessel (top left). This condensate is reused during discharge by pumping to high pressure and reversing the flow, entering the CTES at the bottom before becoming superheated steam, which is measured and vented to a safe location.

Storworks Power (*Thermal*)

Pilot

The CTES pilot plant, shown in Figure 7, is a 10-MWhe scale (2.5 MWe x 4 hours) system at Alabama Power's Plant Gaston in Wilsonville, AL. Lead by EPRI and funded by the U.S. Department of Energy, this facility is demonstrating the technology's performance for the steam-heated version by charging using supercritical steam at a pressure of 3500 psig (240 barg) from the host plant and discharging at various pressures and durations to quantify performance and flexibility of the system throughout the full charging and discharging cycles.

Process

For the electrical charging version, hot air is generated via thermal heating elements and is fed through the concrete blocks from the hot end to the cold end. This creates a "thermocline" effect within the concrete, forming a consistent temperature zone for heat transfer from the hot to the cold part. As the charging progresses, the temperature of the block material increases, approaching hot air inlet temperature. This allows hotter air to heat cooler concrete material further into the assembly. For discharge, the process is reversed with cool air being heated by the blocks before being passed to a heat recovery steam generator to raise steam for power generation.

Next Steps

Storworks has been developing several variants of the CTES system:

- **FlexJoule:** Designed to be charged using electricity from curtailed renewable sources, this design uses air as a heat transfer fluid to charge and discharge the BolderBlocs and a conventional HRSG to raise steam for heat and power.
- **FlexOps:** Steam-integrated BolderBlocs that charge from and discharge to a fossil plant to reduce plant cycling and limit the number of starts

Storworks is actively looking for commercial opportunities for these systems for stand-alone industrial decarbonization and fossil retrofitting applications.

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RedoxBlox (*Chemical*)

The RedoxBlox system, leveraging magnesium-oxide ($MgXO_3$) pellets, operates through two modes: charging and discharging.

Reduction (charge):	$MgXO_3(s)$ + heat → $MgXO_2(s) + ½ O_2(g)$
Oxidation (discharge):	$MgXO_2(s) + ½ O_2$(in air) → $MgXO_3(s)$ + heat

Charging: $MgXO_3$ pellets are heated from 1830°F (1000°C) to 2730°F (1450°C) within a pressure vessel, inducing an endothermic reduction reaction. This splits $MgXO_3$ into $MgXO_2$ and releases oxygen gas. This reaction stores energy in the system, with a capacity of approximately 64,000 Btu/ft³ (660 kWhth/m³). ***Discharging:*** Pressurized air introduced into the vessel reacts with $MgXO_2$, reversing the previous reaction and reforming $MgXO_3$. Heat generated during this reaction is used in a gas turbine (GT)-generator to produce electricity at 50-55 AC-AC% RTE when integrating with a combined-cycle GT. The system's design is compatible with standard GT-generators, enabling it to integrate into existing energy infrastructures. The storage system can also produce high temperature heat for industrial heating applications with 90-95 heat-heat% RTE.

Technology Benefits

High Energy Density and Low Pellet Cost: RedoxBlox achieves compact energy storage with high energy density – its footprint is 1500–1800 MWhe/acre (3704–4444 MWhe/hectare). The production cost of its $MgXO_3$ chemical pellets is anticipated to range from $600–800/ton (equivalent to $1.8–2.4/kWhth).

Commercially Compatible: RedoxBlox is working towards both industrial heating and electrical power generation. RedoxBlox is making its system directly compatible with commercial turbomachinery, by repurposing existing infrastructure, including a natural gas combined cycle plant's heat recovery steam generator, steam turbines, and electrical switchgear.

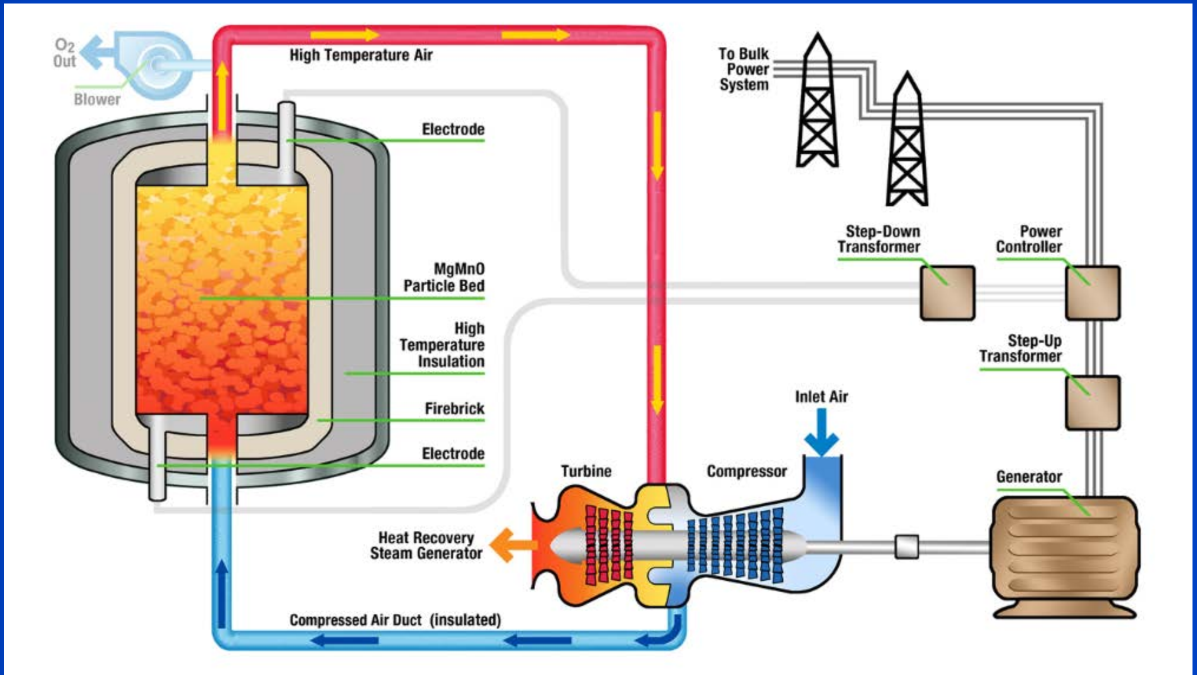

Figure 8. Schematic of the RedoxBlox Thermochemical Energy Storage System

Figure 8 details the process flow of the RedoxBlox thermochemical energy storage system. Charging mode starts with heating via electrodes passing electrical current through the particle bed, which raises the temperature of the $MgXO_3$ particle bed within a pressure vessel. This heat induces a chemical reaction that stores energy. Insulation by firebrick and high-temperature materials ensures minimal thermal loss. Oxygen produced during this mode is expelled by an O_2 blower. Discharge mode starts with compressed air fed to the particle bed. Oxygen in the air is absorbed and releases chemical energy as heat. The heated air from the particle bed drives a turbine, generating electricity for the grid. This diagram illustrates the energy storage process, from intake air to electricity generation, highlighting the system's key components and thermal management strategy.

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RedoxBlox (*Chemical*)

Figure 9. RedoxBlox Energy Storage Modules (a) and (b) (used with permission from RedoxBlox)

Figure 9 underscores the progression of RedoxBlox's technology from initial concept to larger-scale prototypes, each step validating and refining the system's capabilities. The successful operation of earlier prototypes laid the groundwork for the development of a small-scale pilot, driving the technology's potential toward practical application.

(a) **Sub-Scale Prototype (pictured on the left):** Features the advanced 10 kWhth capacity prototype, which underwent over 1400 hours of charge-discharge cycling in 2021, highlighting the system's chemical stability.

(b) **Small-Scale Pilot (pictured on the right):** Features commercial-designed temperatures and pressures with simulated charge and discharge modes at 100 kWhth capacity, validating control strategies and capabilities.

Pilot Design Characteristics

- Nominal storage capacity: 100 kWhth
- Two-thirds ratio of chemical-sensible heat storage
- Power input: 15 kWe (electrically resistive heaters)
- Thermal power output: 10–20 kWth
- Core operating temperature: 1832–2642°F (1000–1450°C)
- Pressure range: 2.4–72.5 psia (0.2–5 bara)
- Surface temperature: <185°F (85°C)
- Bed pressure drop: <0.15 psi (1 kPa)

System controls were developed to establish pressure control loops, set a combined power input to the system, hold a constant temperature overnight, and prevent pressure or temperature in the reactor from surpassing safe limits.[6]

Next Steps

Moving forward for the electrical power application, RedoxBlox was recently awarded $9M from the California Energy Commission for a 10 MWhth, 100 kWe project to start operation in 2026. The system will be more optimized for heat transfer and the prevention of heat loss, and it will reduce assembly and maintenance issues experienced by the pilot system. As a follow up, RedoxBlox is developing options to demonstrate the next scale with 2 MWe power capacity.

RedoxBlox is also developing its technology for industrial heating applications. For scale-up, RedoxBlox will progress from a 2 MWhth unit producing heat for cardboard drying with Ganahl in 2024, to a 10 MWhth unit producing heat to generate steam with DOW Chemical as part of a grant under the United States Department of Energy and a 10 MWhth unit producing heat for steam with Arrabawn (an Irish dairy). The 10 MWhth systems are expected to come online in 2025/2026, followed by commercial sales of the 10 MWhth system. Industrial heat units will continue to be scaled to address larger processes with capacities in the hundreds of MWhth.6

[6] Bulk Energy Storage Field Studies: RedoxBlox Thermochemical Energy Storage. EPRI, Palo Alto, CA: 2023. 3002026935.

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EPRI Edge in LDES Innovation

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EPRI as a neutral third-party research institute with deep industry subject matter expertise can evaluate new LDES technologies by assessing their technical capabilities and providing EPRI members with impartial insights on their efficacy and value. This ensures that the utilities are better informed by a credible analysis as they navigate the evolving energy landscape.

Synergy in Cost-Effective Demonstration Projects

EPRI fosters a collaborative environment where utilities can collectively engage in demonstration projects, allowing them to mitigate costs and maximize learning outcomes. This joint venture approach not only reduces financial outlays for individual members but also taps into EPRI's strategic evaluation, giving life to cost-effective and forward-thinking energy solutions.

Pioneering Sustainable Energy Innovations Together

Joining forces with EPRI is an investment in a sustainable energy future. Members gain the advantage of spearheading transformative industry advancements, leveraging EPRI's objective research and a networked innovation ecosystem.

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Acknowledgments

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