2023

ENERGY ASSET TRANSFORMATION

PROJECT PORTFOLIO

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

DISCLAIMER

CONTENTS

INTRODUCTION

NETL's Energy Asset Transformation (EAT) program is developing a comprehensive strategy to expand the current portfolio of Office of Fossil Energy and Carbon Management (FECM) technologies and programs in order to better enable fossil power plants to maintain the electricity grid's stability and resilience while increasingly utilizing variable renewable power. Energy storage at the generation site will be essential to a resilient and flexible electricity network and NETL's EAT program aims to address the needs and challenges of site storage. The goal of this program is to leverage over a century of investment in fossil energy infrastructure, extend the useful lifetime of existing fossil energy assets, enhance the role of fossil assets as contributors to grid stability and reliability, and provide the nation with a reliable fossil-based option by leveraging and extending ongoing EAT technology development while smoothing the transition to an energy system with net-zero carbon emissions.

Looking forward to additions and retirements on the grid, fossil-fueled plants will continue to be added through 2050 and play a major role in generation. Due to the inherent challenges between intermittent and baseload power systems, energy storage is integral to guaranteeing a seamless transition between systems. Energy Asset Transformation will enable fossil-based systems to be more flexible and retain longer lifetimes of components, making the system more efficient and environmentally friendly.

The three core challenges that the Energy Asset Transformation program seeks to address are:

1. Developing a set of cost-competitive storage technologies that enable the economic use of our nation's underutilized plant capacity
2. Predicting with certainty the changes to today's energy environment when calculating program-specific economic and environmental benefits
3. Integrating storage solutions with a broad and diverse set of existing plants—each uniquely designed with characteristics that enable operation at high efficiency and low cost

The Energy Storage project portfolio is categorized into these research areas:

- Chemical Technologies
- Thermal Technologies
- Electrochemical Technologies
- Mechanical Technologies
- Energy Storage Integration

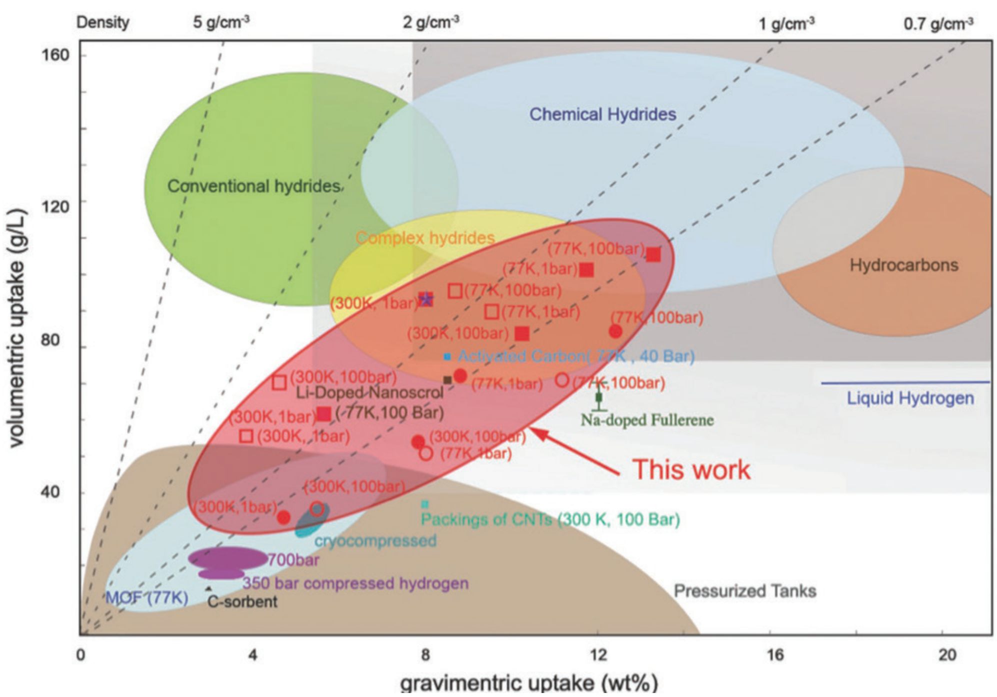
These new technologies are designed to create a more reliable and affordable energy supply, a cleaner environment, and a stronger energy infrastructure for the nation.

CHEMICAL TECHNOLOGIES

Low-Cost, Scalable Boron Nitride-Based Sorbents with Balanced Capacity-Kinetics-Thermodynamics for Hydrogen Storage in Fossil Fuel Power Plants

Performer	**C-Crete Technologies, LLC**
Award Number	FE0032010
Project Duration	03/01/2021 – 02/29/2024
Total Project Value	$ 312,500
Technology Area	Advanced Energy Storage

The overarching goal of this project is to demonstrate the feasibility of a new class of scalable, low-cost sorbents with an optimized balance of capacity-kinetics-thermodynamics for hydrogen storage and integration into fossil fuel power plants. The Phase I objective is to achieve full synthesis control over sorbent materials and their pore structure, and to fabricate a small module followed by optimization and various structural, chemical, and thermal property characterizations. The Phase II objective is to evaluate the performance of hydrogen energy storage at both the material and system levels followed by development of a conceptual process flow diagram, unit module, and performance models for integration into fossil fuel power plants. The technology may realize efficiencies of energy and time for the hydrogen-to-energy conversion, as only mild heat/pressure treatment will be required to rapidly desorb hydrogen for conversion to energy.

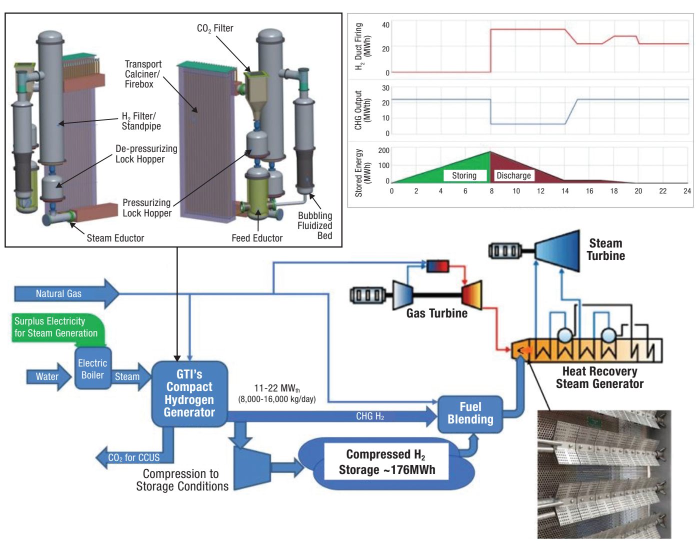


The proposed work in hydrogen storage technology leverages merger of energetic affinity and optimal geometry to impart both high gravimetric and volumetric hydrogen uptakes compared to other technologies.

Hydrogen Storage for Load-Following and Clean Power: Duct-Firing of Hydrogen to Improve the Capacity Factor of NGCC

Performer	**Gas Technology Institute**
Award Number	FE0032008
Project Duration	03/01/2021 – 05/31/2023
Total Project Value	$ 1,423,966
Collaborator	Southern Company, Pacific Gas & Electric, Electric Power Research Institute
Technology Area	Advanced Energy Storage

Gas Technology Institute, in partnership with Southern Company, Pacific Gas & Electric, and the Electric Power Research Institute, will perform a Phase I feasibility study on asset-integrated production and intermediate-duration storage of greater than 150 megawatt-hours of energy in the form of "blue" hydrogen (H_2). The H_2 will be produced from natural gas with integrated carbon dioxide (CO_2) capture using GTI's patented Compact Hydrogen Generator (CHG) technology. Stored H_2 will be used for load-following in an existing natural gas combined cycle (NGCC) plant within Southern Company's fleet. The objectives of the study are to: (1) perform a conceptual engineering assessment to define a system consisting of onsite H_2 production, storage, and integration within a Southern Company-owned NGCC plant, in which the stored H_2 will be injected into a duct burner within the heat recovery steam generator (HRSG) section; (2) perform the associated modeling to predict and quantify the load-following characteristics of the system; (3) obtain preliminary techno-economics and environmental performance of the system; (4) determine the risks and mitigation steps at the component/subsystem and integrated system levels; and (5) establish a project plan for conducting a potential preliminary front end engineering design (pre-FEED) study at a site that will be downselected from the 20 NGCC plants owned by Southern Company. Successful integration of energy stored as H_2 with an existing NGCC plant is expected to improve the capacity factor while reducing CO_2 emissions and improving system resiliency, dispatch, and reliability.



Hydrogen storage for load-following and clean power.

Development of an Advanced Hydrogen Energy Storage System Using Aerogel in a Cryogenic Flux Capacitor

Performer	Southwest Research Institute (SwRI)	John F Kennedy Space Center
Award Number	FE0032003	89243321SFE000019
Project Duration	03/01/2021 – 07/31/2023	03/01/2021 – 02/28/2023
Total Project Value	$ 575,680	$ 49,300
Collaborators	Air Liquide; University of Central Florida	
Technology Area	Advanced Energy Storage	

Southwest Research Institute, in collaboration with the University of Central Florida, NASA Kennedy Space Center, Air Liquide, and Turbine Technology Services, will develop a high-density cryogenic flux capacitor (CFC) for hydrogen energy storage. A key advantage of CFC modules is that they can accept gaseous hydrogen at ambient conditions, such as from an electrolyzer, and charge up over time. On the discharge step, controlling heat input into a CFC storage cell can pressurize the system and regulate the flow of the hydrogen gas as it is released from its physisorbed state. Simple auto-pressurization of the cell via heat input provides operational flexibility for the total system and allows a wide range of demand loads and duty cycles. The project will validate the prior work on the NASA test rig, demonstrate a CFC storage system working with an electrolyzer, and assess the inherent ramp times of the system. The work will also analyze and assess the required cell storage size to maintain flexibility and optimize costs. A commercial-scale study and development pathway of the technology will be produced in the form of a technology maturation plan, technology gap assessment, commercialization plan, and techno-economic assessment. Because a CFC module stores fluids with densities approximately equivalent to cryogenic liquid densities, it is competitive with cryogenic methods of fluid storage. One potential integration of this storage is to blend the hydrogen with retrofitted existing fossil fuel power generators, such as a combustion gas turbine. Further potential integration paths of this technology include steam methane reforming, which provides a stream of hydrogen gas from a fossil source for combustion or direct power production using hydrogen fuel cells. CFC stored gas could provide refrigeration power for cold-chain shipping of biological tissue and pharmaceuticals, cooling of sensors and electronics, and next-generation cryocoolers. Small storage units could provide healthcare applications with breathing air or oxygen packs. Diving, space, and aircraft life support would also benefit from this storage technology.

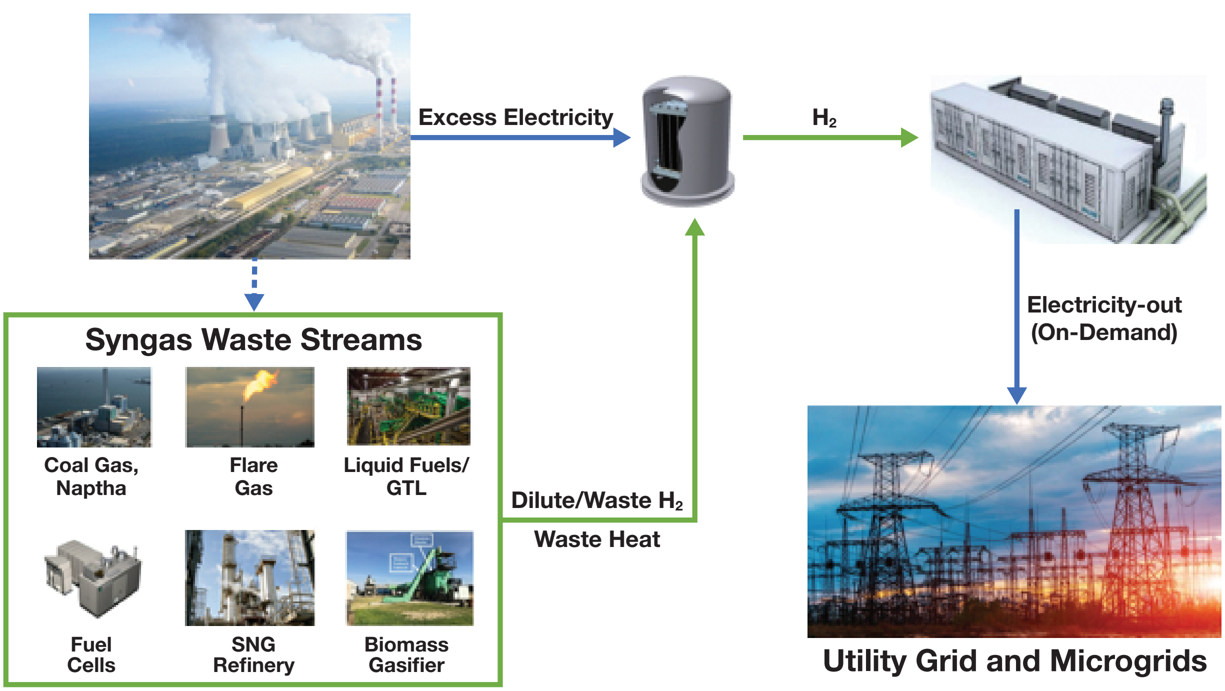
Various prototypes of CFC core modules (spiral configurations with different conductors).

Advanced Oxygen-Free Electrolyzer for Ultra-Low-Cost Hydrogen Storage for Fossil Plants

Performer	T2M Global, LLC
Award Number	FE0032023
Project Duration	04/12/2021 – 08/11/2023
Total Project Value	$ 625,000
Technology Area	Advanced Energy Storage

T2M Global will develop an advanced oxygen-free electrolyzer system (AES) to equip fossil plants with H_2 energy storage needed for load-following capability. T2M will scale up kilowatt (kW)-class AES technology to the 10-kW level for testing under simulated syngas conditions derived from a variety of fossil plants. T2M Global will obtain input from Hawaii Gas at various stages from identification of syngas streams to design and deployment strategy development for the megawatt (MW)-class modules.

The MW-class AES module would use the excess electricity and waste heat from fossil plants to upgrade the dilute syngas streams to pure H_2 at higher pressures. The stored H_2 will be used to produce power on demand using a highly efficient hybrid power cycle. The AES targets a round-trip electrical efficiency of 80% and H_2 production at a cost of < $4/kg. Deployment of MW-class AES modules at fossil plants will reduce the greenhouse gas footprint and enhance their economic viability by generating additional revenue from currently stranded or underutilized resources.



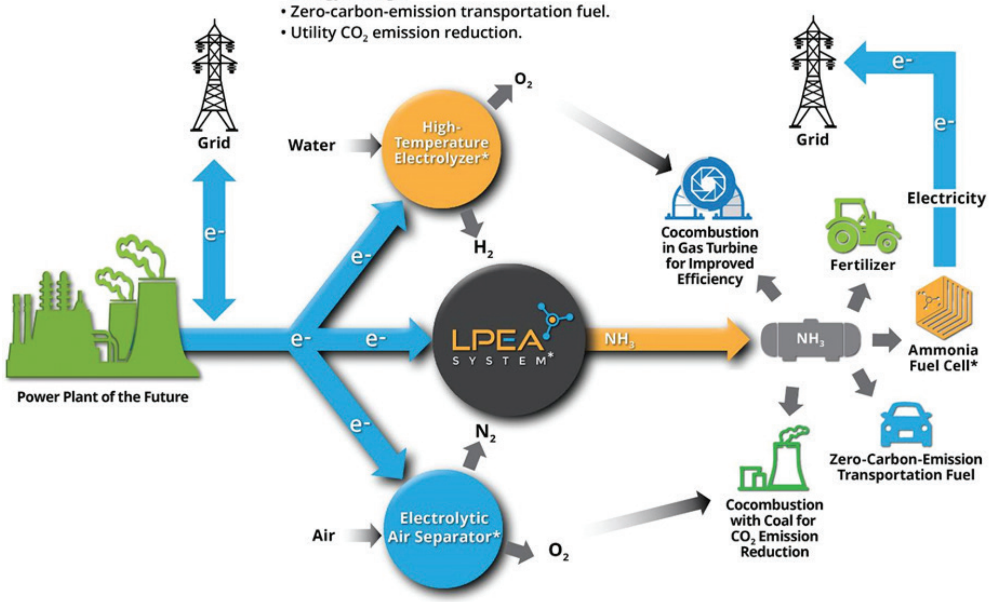
Use dilute syngas streams to produce higher value of H_2 and extend the life of fossil plants.

Ammonia-Based Energy Storage Technology (NH_3-Best)

Performer	University of North Dakota
Award Number	FE0032014
Project Duration	03/24/2021 – 12/23/2023
Total Project Value	$ 426,390
Technology Area	Advanced Energy Storage

Ammonia's unique set of chemical, physical, and economic properties make it the ideal energy storage medium for deployment at coal-fired power plants to reduce or eliminate the need for costly load following/cycling. In this project, the NH_3-BEST concept will be modeled, validated, and advanced from technology readiness level (TRL) 2 to TRL 3. This technology will enable electricity generation unit (EGU) accommodation of load fluctuations while operating within an optimal performance baseline output range, ensuring EGU operational efficiency and minimum degradation of materials, equipment, and performance due to load cycling-driven stresses. A basic model of the NH_3-BEST concept/subsystem, which comprises electrolytic ammonia production, storage, and conversion to electricity via a direct ammonia fuel cell, will be defined and built using operational data from coal-fired utility plants. The model will be utilized to evaluate and optimize NH_3-BEST performance when integrated with a power plant, establish NH_3-BEST round-trip energy storage efficiency, quantify power plant operational and economic benefits of NH_3- BEST integration, and establish NH_3-BEST performance requirements for commercial viability and deployment including storage capacity and operational ramp time. In addition to its carbon-free composition, high hydrogen content, low storage cost, and near-zero explosivity hazard, ammonia is a long-established globally fungible commodity. The highly developed ammonia industry represents an NH_3-BEST economic flexibility attribute, since it opens possibilities for selling and/or buying ammonia to capitalize on market conditions or address production or supply challenges.

Low-pressure electrolytic ammonia (LPEA) production technology as basis for current (fertilizer) and emerging ammonia applications, including:
- Energy storage.
- Zero-carbon-emission transportation fuel.
- Utility CO_2 emission reduction.



* Technology based on EERC–NDSU-developed polymer–inorganic composite (PIC) electrolytic membrane.

Economically Viable Intermediate to Long Duration Hydrogen Energy Storage Solutions for Fossil Fueled Assets

Performer	**We New Energy, Inc.**
Award Number	FE0032001
Project Duration	03/01/2021 – 12/31/2023
Total Project Value	$ 1,260,553
Technology Area	Advanced Energy Storage

The goal of this research is to explore and advance an innovative hydrogen (H_2) energy storage system – the Synergistically Integrated Hydrogen Energy Storage System (SIHES) – with existing or new coal- and gas-fueled electricity generating units (EGUs) that are best suited for the intermediate- to long-duration energy storage needs (i.e., from 12 hours to weeks). Such a storage system enables the EGUs to operate at optimal baseload operation conditions. The added round-trip electricity (E)-H_2-E cost is $5-10/MWh, or less than 10% of the levelized cost of energy (LCOE) of today's fossil plant for 30 years operation.

The prohibitive cost is the primary barrier to apply today's energy storage technologies such as battery-based solutions for long-duration storage in fossil power plants. By reducing the added energy storage cost to less than 10% of the baseline fossil power generation cost, the proposed technology would be an economically viable solution for existing and new fossil power generation assets. Furthermore, by operating the fossil EGU and the energy storage technologies at their optimal conditions, our technology will benefit the asset owners by offering high flexibility and reliability and extended operational life of fossil power plants. Improving the capacity factor of power plants could generate more revenues.

H_2 storage tank.

Durable Low-Cost Pressure Vessels for Bulk Hydrogen Storage

Performer	Wiretough Cylinders, LLC
Award Number	FE0032022
Project Duration	03/01/2021 – 08/31/2023
Total Project Value	$ 693,176
Technology Area	Advanced Energy Storage

The primary objectives of the project are (1) to design and build a prototype of an all steel, Type-IIs, low-cost, and durable pressure vessel with a capacity between 1,500 to 2,000 liters to safely store 50 to 60 kilograms (110 to 132 pounds) hydrogen at 500 bar (7,250 psi) for use in fossil power plants. WireTough will achieve this objective by designing the new cylinder that will fully comply with the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME-BPVC) Section VIII-Division 3 requirements including Article KD-10 for service in hydrogen, conduct a detailed finite element analyses of (a) the steel liner by itself and (b) the finished pressure vessel to determine the magnitude and distribution of stresses during service loading and ensure that the design is safe and it can be safely produced, and demonstrate that the design utilizes only commercially and widely available materials and is compatible with the needs of fossil power plants.

The vessel will have the ability to apply deep pressure cycles daily ranging from the maximum operating pressure to ambient with a design life of 30 years or longer. It can be tailored to the needs of fossil power stations and can store as little as 1,000 to 1,400 kWh electricity up to as much as 100 MWh or more, if necessary. WireTough will receive user design specifications that will lead to the preliminary cylinder design, followed by design analyses using finite element analysis. An appropriate liner will be selected and manufactured, followed by building of the prototype cylinder. Finally, a Manufacturing Design Report (MDR) will be prepared by a third party and the vessel will be ASME stamped/certified, a process that requires an ASME authorized inspector to witness the manufacturing process and assure compliance with the MDR.

This project's approach to utilize high-pressure hydrogen has several advantages over mature technologies and some other emerging technologies. Other approaches such as liquification of hydrogen require large amounts of energy initially to cool the gas and then to maintain the low temperatures during storage. Metal hydrides require considerable heat to discharge the stored hydrogen and the process is slow. Surface hydrogen storage systems such as C-nanotubes are currently not sufficiently mature. The compressed H_2 approach to energy storage competes favorably with non-hydrogen approaches such as batteries that degrade over time and create chemical waste, with pumped water that requires large amounts of land, and with thermal energy storage systems that are not efficient for this application.

WireTough cylinder.

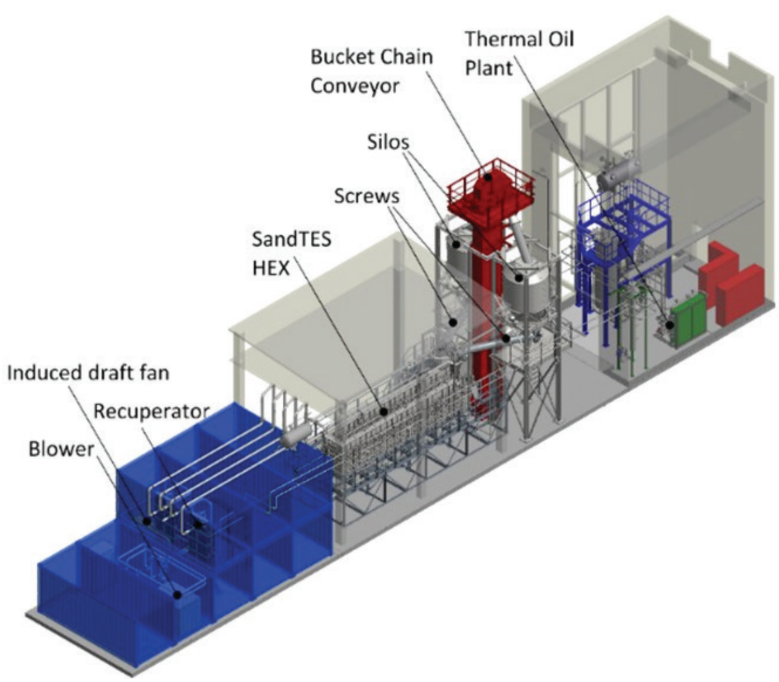
THERMAL TECHNOLOGIES

Sand Thermal Energy Storage Pilot Design

Performer	**Electric Power Research Institute**
Award Number	FE0032024
Project Duration	03/01/2021 – 07/31/2023
Total Project Value	$ 1,245,315
Technology Area	Advanced Energy Storage

The drive for a low-carbon future and the commensurate growth of variable renewable energy has led to a potential for grid instability and associated inability to provide dispatchable, synchronous power. Energy storage can alleviate these concerns. One promising vehicle for storage is sand-based thermal energy storage (SandTES) integrated with an operating fossil power plant. This strategy allows the plant to store energy in the system when less power is needed and provide power to the grid from both the operating fossil plant and the SandTES system when more is required. The objective is to perform a Phase I feasibility study on the integration of a 10-MWhe SandTES system to Southern Company's coal-fired Plant Gaston in preparation for a Phase II project in which a pre-front-end engineering and design (pre-FEED) will be performed. The scope of work for the Phase I feasibility study consists of a conceptual study, a techno-economic study, a technology gap assessment, a project plan for Phase II, a technology maturation plan, and a commercialization plan.

The ultimate goal of the proposed project is to accelerate SandTES and its ability to be integrated with fossil power plants at low cost and risk. Achieving this goal will provide a critical option for dispatchable, synchronous energy storage. Energy storage combined with fossil energy assets offers a suite of benefits to asset owners, the electricity grid, and society. These benefits include more reliable and affordable energy, a cleaner environment, and stronger power infrastructure.



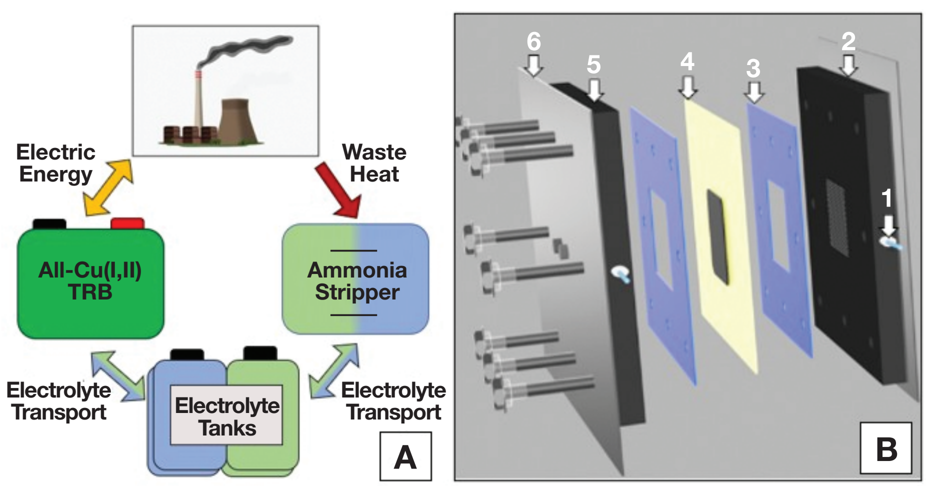
SandTES integrated system.

Development of an All-Aqueous Thermally Regenerative Redox Flow Battery to Support Fossil Fuel Assets

Performer	**Pennsylvania State University**
Award Number	FE0032030
Project Duration	03/01/2021 – 07/31/2023
Total Project Value	$ 312,881
Technology Area	Advanced Energy Storage

PSU will develop a basic model of the all-copper [Cu(I, II)] redox flow battery (TRB) to assess its performance as an energy storage technology. The numerical model will produce current-potential simulations of the TRB via a multi-physics computational program. Once developed, the model will provide insights into its preliminary energy storage, power output, and energy efficiency capabilities. The model will simulate fluid flow, mass transfer, and electrochemical transport in the battery reaction cell using the proposed chemistry. Simulation results will allow researchers to determine mass transport effects on cell power output, identify favorable flow cell designs, and determine the optimal combination of electrode and membrane materials for lab-scale prototype testing. Electrochemical and spectrochemical experimental data will be used to collect and validate model inputs. Model outputs will be validated and improved through laboratory-scale prototype testing.

The unique capabilities of this long-term energy storage solution provide a means for fossil fuel plants to mitigate the negative impacts of off-design operations with the added benefit of utilizing low-grade waste heat, an otherwise unused waste stream. Its expected performance, with power densities greater than 350 watts per square meter and energy storage densities greater than 30 watt-hours per liter, represent major milestones for TRBs and make them comparable to commercial flow batteries like the iron-chromium and all-vanadium redox flow batteries. If successful, this technology will be able to safely store large quantities of excess electric power generated by fossil fuel electricity generation units in aqueous electrolytes composed of materials that are inexpensive, readily accessible, and produced in large quantities.



All-Cu(I, II) TRB integration with fossil fuel assets [A] and schematic of the electrochemical cell [B]. (1) fluid inlet and outlet; (2) negative electrode current collector; (3) gasket; (4) membrane-electrode assembly; (5) positive electrode current collector; (6) steel endplate.

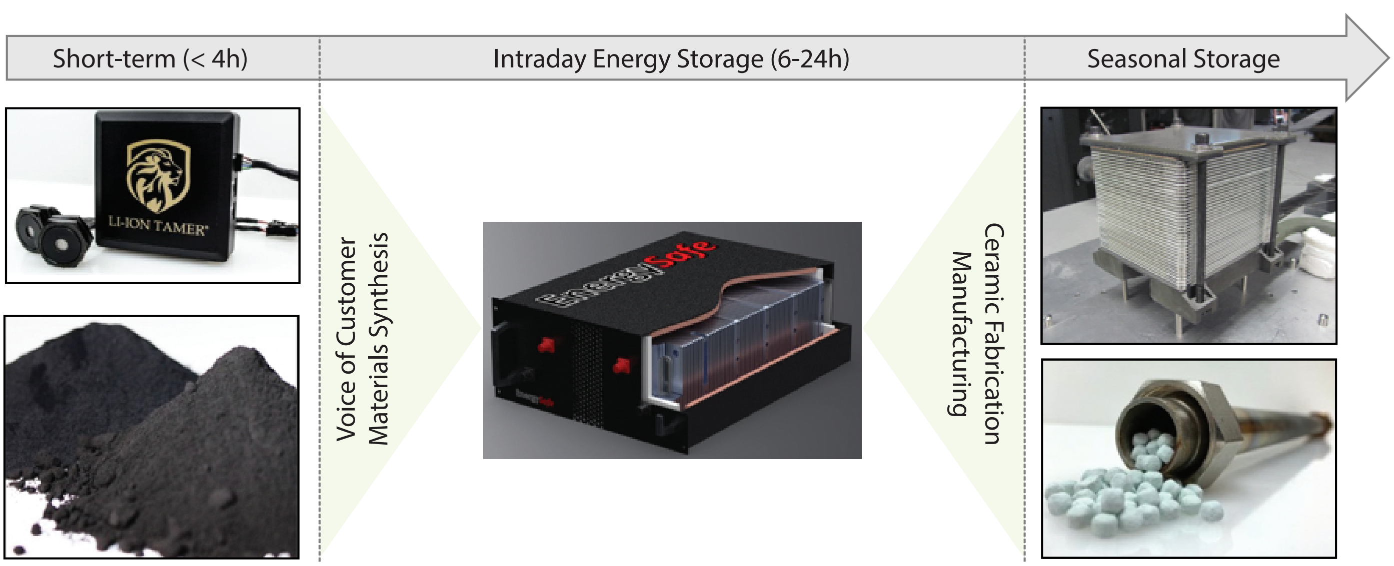
ELECTROCHEMICAL TECHNOLOGIES

Low-Cost Metal-Supported Metal Halide Energy Storage Technology

Performer	**Nexceris, LLC**
Award Number	SC0021566
Project Duration	02/22/2021 – 04/03/2024
Total Project Value	$ 1,356,500
Collaborator	Pacific Northwest National Laboratory and BRITE Energy Innovators
Technology Area	Advanced Energy Storage

Nexceris will advance the product readiness of EnergySafe™, a disruptive metal-halide energy storage technology that is ideally suited for fossil asset integration. EnergySafe systems can improve fossil asset utilization and environmental performance while improving grid stability and renewable integration. Nexceris advanced the maturity of the EnergySafe cell by tailoring its chemistry and design for EGU-integrated 6–24-hour storage, a critical unmet grid support need. In the Phase II project, Nexceris, in partnership with Pacific Northwest National Laboratory and BRITE Energy Innovators will accelerate the product readiness of EnergySafe culminating with independent testing and validation of a 5kWh module demonstration, to position EnergySafe for larger on-site demonstrations.

The EnergySafe cell design eliminates the high manufacturing costs associated with thick-walled, cylindrical electrolyte designs of the past that have prevented widespread adoption of the technology, while retaining the excellent safety and cycle life, insensitivity to ambient conditions, lower operation and maintenance costs, and supply chain based on low cost, recyclable, U.S.-sourced raw materials. Integrated with fossil EGUs, EnergySafe systems can use waste heat from the fossil asset to enhance overall efficiency.

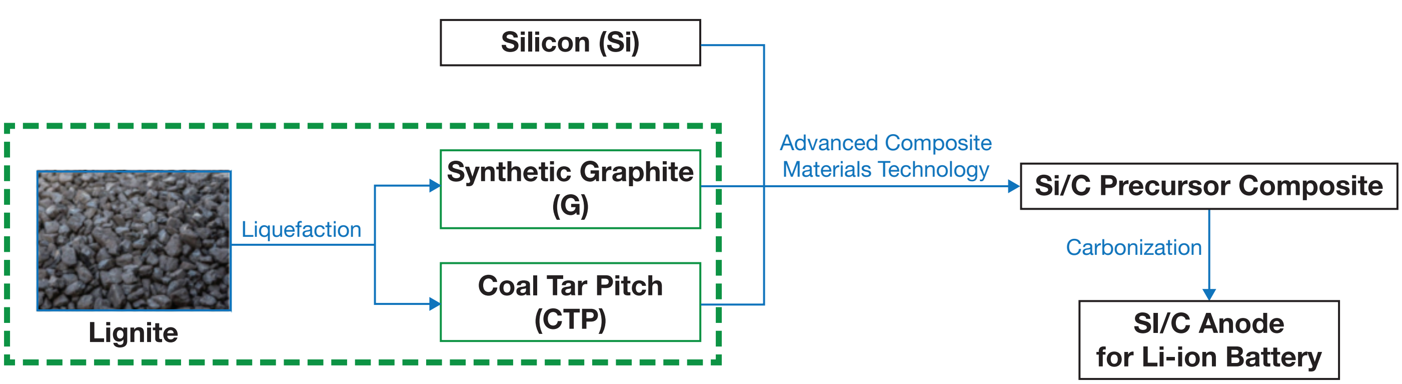


Nexceris is engaged in technology development throughout the energy storage spectrum.

Lignite-Derived Carbon Materials for Lithium-Ion Battery Anodes

Performer	**University of North Dakota Energy and Environmental Research Center**
Award Number	FE0031984
Project Duration	01/20/2021 – 09/30/2023
Total Project Value	$ 667,465
Technology Area	Advanced Energy Storage

The overall goal of this project is to develop advanced anode materials for lithium-ion batteries (LIB) from lignite-derived carbon feedstock. Specific objectives include (1) prepare silicon carbon (Si-C) composite anode materials for LIBs using lignite-derived pitch and synthetic graphite (SG) as the main feedstock; (2) identify the optimal pitch and SG for LIB anode applications from a variety of sources produced by a co-sponsor; (3) develop a low-cost and scalable process to make porous and spherical Si-C composite anode materials; (4) evaluate the battery performance of the new Si-C composite anodes and compare with a similar commercial anode as the benchmark; (5) investigate the feasibility of making the Si-C composite anodes at pilot scale; and (6) evaluate the economic and commercial potential of the technology. The anticipated benefits of this project are (1) the unique high-quality lignite-derived pitch and synthetic graphite will be suitable feedstocks for high-value carbon-based LIB anode materials such as Si–C composite anodes; (2) the current technology of preparing Si–C anode materials will be advanced toward a low-cost and high-performance product; (3) the project will accelerate the commercialization of production of high-quality lignite-derived pitch and SG through opening a high-value LIB market; and (4) the domestic and international marketability of U.S. coals and of domestic production of LIBs will be increased.



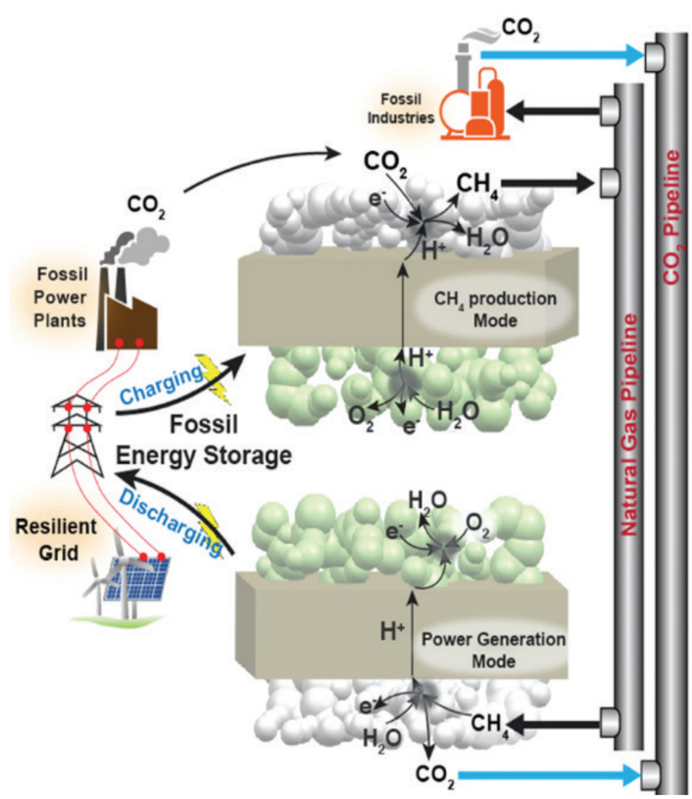
Simplified schematic for producing lithium ion battery anodes from North Dakota lignite.

Reversible Methane Electrochemical Reactors as Efficient Energy Storage for Fossil Fuel Power

Performer	University of Oklahoma
Award Number	FE0032005
Project Duration	03/01/2021 – 08/31/2023
Total Project Value	$ 312,504
Technology Area	Advanced Energy Storage

The University of Oklahoma will conduct research on the integration of reversible methane (CH_4) electrochemical reactors as an efficient energy storage technology in fossil fuel power plants. Protonic ceramic electrochemical reactors (PCERs) integrated with a fossil asset may offer efficient energy storage by operating and switching between fuel cell and electrolyzing modes. In fuel cell mode (power generation mode), the chemical energy in the CH_4-rich supply gas is converted to electrical energy as the fuel flows from the fuel tanks through the stack. In electrolyzing mode (fuel production mode), the polarity of the cell switches as surplus electrical energy from the fossil power plant or renewable resource is supplied to the stack. The carbon dioxide (CO_2)-rich gas captured from the fossil power plant (e.g., using a carbon capture system) is converted to a CH_4-rich gas which can be stored in fuel tanks, injected into a natural gas pipeline, or immediately used as feedstock for fossil industries. Fundamental processes and system models will be developed to conduct a preliminary conceptual study and identify power plant system integration requirements, performance requirements, and technology gaps for eventual implementation at a system level.

This project will help establish the feasibility of reversible CH_4 electrochemical reactors as efficient energy storage technologies that can be used with any size power plant. If commercialized, this technology could significantly change the energy storage market by its reversible operation at moderate temperatures, modular design, low contamination risks, low cost compared to other reversible fuel cells, and high round-trip efficiency.



Reversible CH_4 protonic ceramic electrochemical cells.

Titanium-Cerium Electrode-Decoupled Redox Flow Batteries Integrated with Fossil Fuel Assets for Load-Following, Long-Duration Energy Storage

Performer	Washington University
Award Number	FE0032011
Project Duration	03/01/2021 – 02/29/2024
Total Project Value	$ 626,215
Collaborator	Giner, Inc.
Technology Area	Advanced Energy Storage

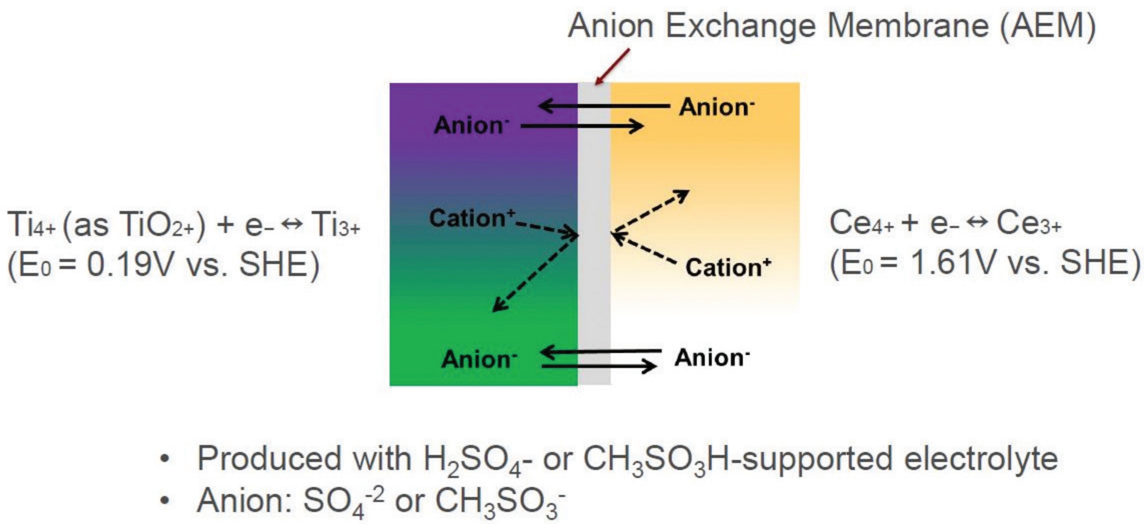
Operation of fossil plants at partial capacity with frequent cycling results in decreased efficiency and increased emissions, wear, and maintenance. The objective of this project is to advance the integration of a titanium-cerium electrode-decoupled redox flow battery (Ti-Ce ED-RFB) system with conventional fossil-fueled power plants through detailed technical and economic system-level studies, component scale-up, and research and development. The Ti-Ce chemistry has a clear pathway to meet the Department of Energy cost targets of $100/kWh and $0.05/kWh-cycle owing to the use of low-cost, earth abundant elemental actives and incorporation of inexpensive carbon felt electrodes and non-fluorinated anion exchange membrane separators. With assistance from Giner, Inc., the team will scale up Washington University's existing laboratory Ti-Ce flow battery system to a kW-scale 3-5-10 cell stack with a current density of 0.5 A/cm2, a cycle duration of 48 hours, and less than 5% capacity loss during 1-week standby.

Cost and performance data from the RFB scale-up efforts will be incorporated into a detailed techno-economic assessment (TEA) of this storage technology situated within the fence lines of a fossil-fueled power plant to demonstrate the benefits of co-location to asset owners, grid operators, and the public. The TEA will consider both pulverized coal and gas fired power plants with and without carbon capture. The path to commercialization of this storage technology will be enabled through market research, gap assessment, and technology maturation and commercialization planning. The resulting TEA and performance data are expected to show reduction in risk and lowering of potential barriers to wide-scale deployment of integrated grid-scale storage; resulting in more secure, reliable, efficient, and cost-effective delivery of electricity with increased share of renewables.

One tangible product of the proposed work will be a new power system economic modeling tool that will be made available to power plant owners. This tool will allow users to determine the best battery technology and size for their location and the electricity market. The tool may be used by developers of large-scale battery technologies to identify market opportunities and attract investment. The development of the 3-5-10 cell stack will provide a prototype scaled-up RFB that is cost effective at the grid level. The project will also identify pathways to capital expenditure values of less than $500/kW (power) and less than $ 50/kWh (energy) for an annual production volume of less than 100 MW/yr and less than 1 GWh/yr, and a levelized cost of storage of less than $0.05/kWh-cycle, which will enable the widespread deployment of this technology solution.

For owners of fossil power plants, the addition of a cost-effective energy storage system will increase the value of the plant. Maintenance issues due to heavy cycling can be avoided, the life of the plant will be extended, fuel costs will be reduced because the plant will operate at higher capacity factor, and operators will have increased decision-making ability. For example, during periods of low demand, the operator can opt either to turn down plant capacity or maintain steady operation and store excess energy.

The addition of energy storage provides the plant owner with additional revenue opportunities through arbitrage (storing energy when electricity prices are low and discharging when high) and by providing other valuable grid services such as frequency regulation and capacity reserve. Electricity consumers will benefit from a more stable, flexible, and secure power grid with improved load-following capability. Stranded renewable energy can be eliminated and emissions can be reduced through plant efficiency improvement and delivery of additional renewable energy to the grid. In summary, the integrated approach is of great importance in that it can lead to increased acceptance of intermittent sources while simultaneously improving the value and effectiveness of the existing fossil fleet, resulting in optimal grid performance while minimizing costs to consumers.



Ti-Ce electrode decoupled Redox flow battery. SHE: Standard hydrogen electrode.

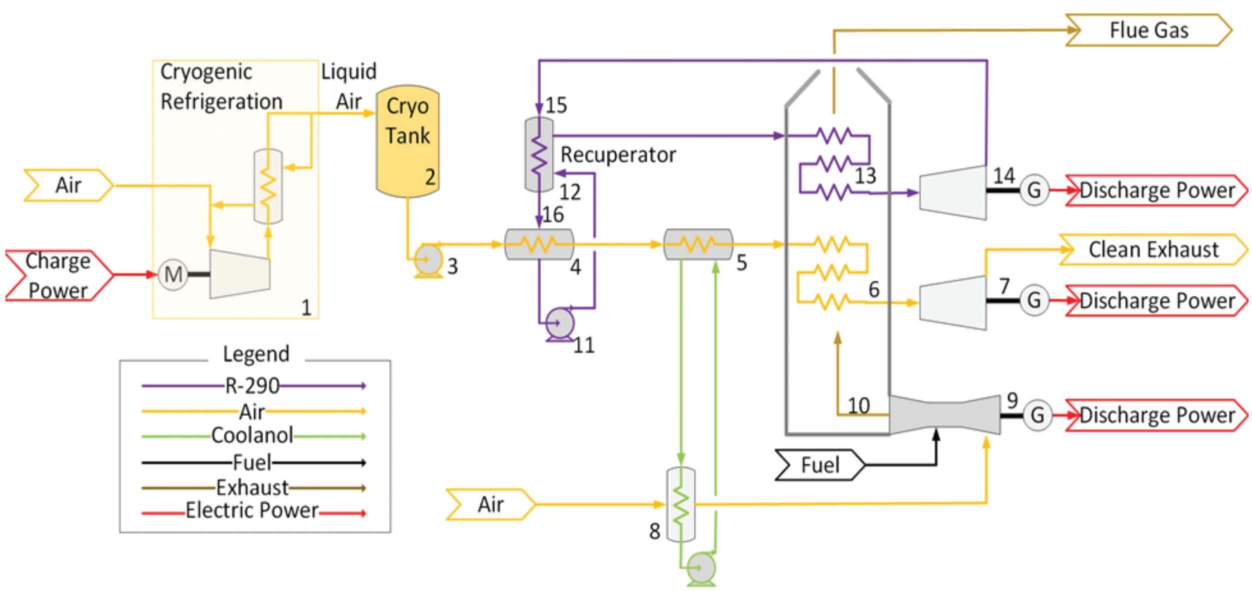
MECHANICAL TECHNOLOGIES

Liquid Air Combined Cycle (LACC) for Power and Storage

Performer	**Southwest Research Institute (SwRI)**
Award Number	FE0032002
Project Duration	03/01/2021 – 02/28/2023
Total Project Value	$ 319,120
Technology Area	Advanced Energy Storage

The research team will perform market analyses, cycle modeling and optimization studies, component specification and technology gap analysis, and techno-economic trade studies for variations of combustion turbine (CT) cycles augmented with liquid air energy storage. The studies and analyses will focus on a patent-pending Liquid Air Combined Cycle™ (LACC) that is expected to lead to the conceptual design and specification of a commercial-scale LACC. The commercial-scale LACC will also be adapted to a demonstration-scale LACC conceptual design specification based on a smaller, 10 MW-class CT. The primary technical objectives of the development effort are to (1) define cost and performance trades for charge and discharge cycle components, (2) perform system optimization of the charge and discharge cycles, and (3) develop an optimized commercial-scale LACC specification from techno-economic trade studies and incorporate technology gap analysis.

The combination of very large-scale energy storage (10 GWh or more) with a CT in the novel LACC system can provide game-changing capabilities to integrate and time-shift excess renewable energy while improving the economics and reliability of fossil-fueled generating units. Because LACC technology can be integrated with existing fossil assets, it can reduce capital costs and prevent fossil and renewable assets from becoming stranded due to over-generation of variable renewable energy. Pintail's LACC approach facilitates lower capital cost of the storage system and higher net revenue for the overall fossil-hybrid energy storage system, and its systems approach is largely vendor-neutral, which could facilitate broader and more-rapid commercial adoption by engineering, procurement, and construction firms and suppliers of turbines, compressors, and heat transfer equipment.



Schematic of a Liquid Air Combined Cycle (LACC).

ENERGY STORAGE INTEGRATION

Energy Storage Accessibility for Public Power Utilities

Performer	**American Public Power Association (APPA)**
Award Number	FE0032026
Project Duration	09/01/2021 – 08/31/2026
Total Project Value	$ 625,000
Technology Area	Advanced Energy Storage

The objective of this project is for American Public Power Association (APPA) to employ its unique capabilities and position as a convener of community-owned electric utilities (public power utilities) to evaluate opportunities to integrate energy storage technologies with fossil power plants. APPA will consult with partner utilities to identify their needs and motivations in relation to integrating energy storage with fossil power plants and use the findings to create a storage project maturity framework showing specific knowledge gaps by project stage. APPA will use this framework to create both educational resources and publications tailored to public power utilities and technical tools that build utilities' capacity for situation-specific project analysis (such as where to place storage units). APPA will also plan and/or host educational events such as conference sessions, workshops, and webinars. These events will be designed to allow experts in the field to engage with associated members on topics relevant to various maturity stages over project period, advancing in maturity and complexity.

This approach will increase accessibility to energy storage projects and offers benefits to community-owned utilities of all sizes. Public power utilities that own and operate fossil-fueled assets, along with those that rely on them to ensure regional grid stability, will experience direct benefits from this work, while the development of optimal strategies and frameworks for implementing energy storage at community-owned electric utilities will assure mutual benefits for everyone connected to the electric grid. Adopting energy storage will improve the flexibility of fossil assets to contribute to grid reliability and resiliency while reducing damage from cycling and will result in enhanced environmental performance by enabling low-cost approaches to decarbonization.

AMERICAN PUBLIC POWER ASSOCIATION

Energy Storage

Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022469
Project Duration	07/01/2020 – 03/31/2024
Total Project Value	$ 1,568,311
Technology Area	Advanced Energy Storage

Cost-effective energy storage technologies are needed to provide reliable and low-cost energy services to U.S. industries and the public. More broadly, there is a need for baseload power generation with increased flexibility to assure short- and long-term reliability in the delivery of electric power as the use of intermittent renewable power generation increases. Fossil fuel plants have historically provided most of the baseload power on the U.S. electric grid. With a higher penetration of variable renewable power generation, coal power plants must adjust their power output as demand for electricity fluctuates throughout the day. These cycling operations reduce the efficiency and lifetimes of the plants and increase harmful emissions. Energy storage technologies offer a potential solution to these problems. However, energy storage technologies for fossil plants are not yet developed and deployed at any meaningful scale in the United States. To accelerate impactful deployments, there is a need to better define energy storage use cases which use fossil energy and establish metrics for evaluating technologies and reducing the risk associated with newly adopted technologies.

This project will develop and disseminate energy storage knowledge and develop new metrics for energy storage when coupled to fossil energy assets. Both near- and long-term energy storage use cases and technologies will be assessed. Market and regulatory issues associated with integrating energy storage with fossil plants will also be assessed in this project.

Outreach for Advanced Storage Integration and Support (OASIS)

Performer	**National Rural Electric Cooperative Association (NRECA)**
Award Number	FE0032027
Project Duration	10/01/2021 – 09/30/2026
Total Project Value	$ 625,000
Technology Area	Advanced Energy Storage

The objective of the OASIS project is to assist in providing educational resources, outreach, training, workshops, and other means to electric cooperatives to empower them to integrate energy storage technologies with their generation systems. NRECA will also conduct coordination and outreach with its smaller electric generation utility members to facilitate awareness, transfer technology, and share best practices, lessons learned, and partnering on fossil energy projects. NRECA will enlist educational resources, available staff, case studies, guidelines, best practices, and training on common strategies for integrating energy technologies with fossil power plants and enhancing organizational capacities at utilities. NRECA will facilitate and convene meetings and events with cooperative utilities to define barriers to energy storage deployment and work with DOE and other stakeholders to overcome these barriers.

This project will result in better-informed electric utilities that will be positioned to participate in FECM's Advanced Energy Storage program as host sites for integrated testing at power plants as well as to adopt commercialized technology. Adopting energy storage will improve the flexibility and environmental performance of assets while reducing damage from cycling. It will also provide a pathway to decarbonization and contribute to grid reliability and resiliency.

ABBREVIATIONS

AEM ....anion exchange membrane

AES ....Advanced Oxygen-free Electrolyzer System

APPA.. .... American Public Power Association

ASME-BPVC .... American Society of Mechanical Engineers Boiler and Pressure Vessel Code

CFC..cryogenic flux capacitor

CH_4...methane

CHG .... Compact Hydrogen Generator

CO_2 ....carbon dioxide

CT ....combustion turbine

DOE...Department of Energy

E ....electricity

EAT........................ Energy Asset Transformation (NETL)

EGU.................................... electricity generating units

FECM.. ... Office of Fossil Energy and Carbon Management

GTI ....Gas Technology Institute

GTL ....gas to liquids

GWh .... gigawatt-hours

H_2..hydrogen

HRSG ....heat recovery steam generator

Kg .... kilogram

kW.. kilowatt

kWh...kilowatt-hours

LACC..................................Liquid Air Combined Cycle

LCOE.......................................levelized cost of energy

LIB..lithium ion batteries

MDR .... Manufacturing Design Report

MW... megawatt

MWe.. megawatt electric

MWh.. megawatt-hours

MWhe.....................................megawatt-hour equivalent

NASA....................................... The National Aeronautics and Space Administration

NGCC...................................natural gas combined cycle

NH_3 .... ammonia

NH_3-BEST.......................ammonia-based energy storage

NRECA ..... National Rural Electric Cooperative Association

OASIS............................. Outreach for Advanced Storage Integration and Support

PCERs............. protonic ceramic electrochemical reactors

pre-FEED............preliminary front-end engineering design

psi .... pounds per square inch

RFB ....redox flow battery

SandTES .... sand-based thermal energy storage

SG.. synthetic graphite

Si-C...silicon carbon

SHE.................................. standard hydrogen electrode

SIHES..................................... Synergistically Integrated Hydrogen Energy Storage System

SNG ....synthetic natural gas

TEA .... techno-economic assessment

Ti-Ce ED-RFB..........titanium-cerium electrode-decoupled redox flow battery

TRB ....all-Cu(I, II) redox flow battery

TRL .... technology readiness level

U.S. ....United States

yr...year

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ACKNOWLEDGMENTS

The Energy Asset Transformation Project Portfolio was developed with the support of many individuals. Key roles were played by principal investigators, federal project managers, the technology manager, the supervisor, and National Energy Technology Laboratory site-support contractors.

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April 2023