CROSSCUTTING RESEARCH

2022

ENERGY STORAGE

PROJECT PORTFOLIO

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

DISCLAIMER

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CROSSCUTTING RESEARCH

NETL's Crosscutting Research Program matures novel technologies that can enhance the efficient performance and eliminate or reduce the environmental impacts of fossil energy power plants. On behalf of the U.S. Department of Energy's Office of Fossil Energy and Carbon Management (FECM), NETL pursues crosscutting research and development (R&D) by collaborating with other government agencies, world-renowned national labs, entrepreneurs, industry, and academic institutions. Efforts are focused on five primary research areas: High Performance Materials; Sensors, Controls, and Novel Concepts; Simulation-Based Engineering; Energy Storage; and University Training and Research (UTR).

The goals are to create transformational technologies under a single research umbrella that improve plant efficiency, flexibility, and security; reduce water consumption; reduce costs; and better enable dependable fossil power systems to maintain the stability and resilience of the electricity grid while maximizing use of variable renewable power sources. The research is leading to enhancements to the fleet such as new ways to address the challenges of load following, better ways to counter cyber intrusions, and advancements in affordable, scalable technical solutions. Because of the broad scope of the Crosscutting Research Portfolio, its technologies often have applicability to other energy-related sectors such as renewable and nuclear power generation, oil and natural gas infrastructure, and aviation (both commercial and military).

Crosscutting Research efforts include sponsorship of two long-running university training programs that prepare the next generation of scientists and engineers to meet future energy challenges. These are the University Coal Research (UCR) program and the Historically Black Colleges and Universities and Other Minority Institutions (HBCU-OMI) program. By working with students on the university level, the efforts ensure that key technologies in areas including advanced manufacturing, cybersecurity, smart data analytics, and high-performance computing will be integrated into fossil plants of the future.

In combination, these investments in innovation, informed by private sector stakeholders, enable more comprehensive risk assessment and techno-economic analysis, increase the resiliency of the nation's energy infrastructure, and enable the adoption of cutting-edge data harnessing technologies for plant owners and operators.

High Performance Materials: The High Performance Materials program drives to characterize, produce, and certify cost-effective alloys and other high-performance materials suitable for the extreme environments found in fossil-based power-generation systems. NETL supports and catalyzes a robust domestic materials supply chain that prepares materials for advanced ultra-supercritical (AUSC) steam cycles and spinoff applications. The work also enables research in suitable materials for supercritical carbon dioxide (sCO_2) cycles that yield higher thermal efficiencies.

The Crosscutting Materials program works to accelerate the development of improved steels, superalloys, and other advanced alloys to address challenges of both the existing fleet and future power systems. Materials of interest are those that enable components and equipment to perform in the high-temperature, high-pressure, corrosive environments of an advanced energy system with specific emphasis on durability, availability, and cost both within and across each of four primary platforms: Advanced Manufacturing, Advanced Structural Materials for Harsh Environments, Computational Materials Design, and Functional Materials for Process Performance Improvements.

Sensors, Controls, and Novel Concepts: The Sensors, Controls, and Novel Concepts program is conducting research and development for technologies that will provide pivotal insights into optimizing performance, reliability, and availability of integrated energy and carbon management systems. NETL develops, tests, and matures novel sensor and control technologies that are operable in next-generation energy systems, including hybrid plants incorporating components such as hydrogen-powered turbines and fuel cells, renewables, and energy storage applications. These sensors enable responsiveness to varying conditions in real time, maintaining high efficiencies and reducing emissions.

The Crosscutting Sensors, Controls, and Novel Concepts program explores advances within and the integration of technologies across the following primary research areas: Harsh Environment Sensors, Advanced Controls and Cyber Physical Systems, and Novel Concepts.

Simulation-Based Engineering: Simulation-Based Engineering (SBE) focuses on developing and applying advanced computational tools at multiple scales: atomistic, device, process, grid, and market scales, to accelerate development and deployment of fossil fuel technologies. Research in this area provides the basis for the simulation of engineered devices and systems to better predict and optimize the performance of fossil fuel power generating systems.

Computational design methods and concepts are required to significantly improve performance, reduce the costs of existing fossil energy power systems, and enable the development of new systems and capabilities such as advanced ultrasupercritical combustion and hydrogen turbines.

This effort combines theory, computational modeling, advanced optimization, experiments, and industrial input to simulate complex advanced energy processes, resulting in virtual prototyping. The research conducted in the SBE R&D develops accurate and timely computational models of complex reacting flows and components relevant to advanced power systems. Model development and refinement is achieved through in-house research and partnerships to utilize expertise throughout the country.

Energy Storage: Energy Storage aims to develop a comprehensive strategy to expand FECM's current portfolio of 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 Energy Storage 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 energy storage technology development.

University Training and Research: University Training and Research supports two of the longest-running university training programs, the Historically Black Colleges and Universities and Other Minority Institutions (HBCU-OMI) and the University Coal Research (UCR) programs, to support the education of students in the area of coal science. Both programs are promoted through research grants to U.S. colleges and universities that emphasize FECM strategic goals. These training programs were designed to increase the competitiveness of universities in fossil energy research and discoveries. The student-led research programs advance energy technologies and allow for expansion of energy production while simultaneously facilitating energy sector job growth.

ENERGY STORAGE

Over the next several decades fossil-fuel plants will continue to satisfy much of our nation's electricity demand. As variable renewable energy penetration increases, energy storage at the generation site will be essential to a resilient and flexible electricity network. NETL's Energy Storage program as a part of the Crosscutting portfolio aims to address these needs and challenges.

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 Storage 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 Storage 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
- Electromagnetic Technologies
- Energy Storage Integration

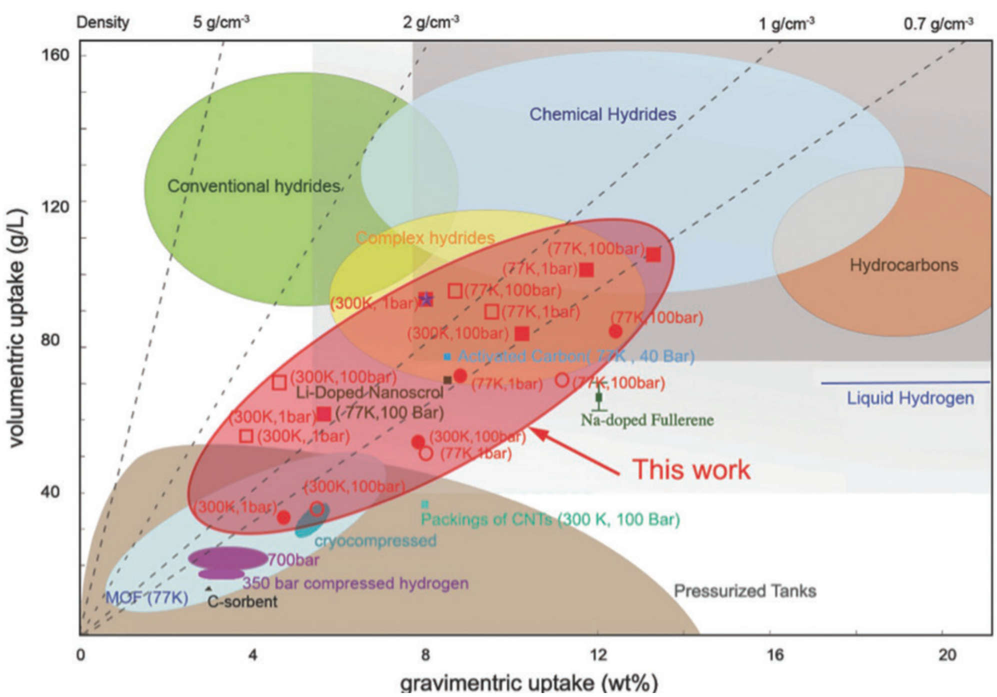
These new technologies are designed to create a more reliable and affordable energy supply, a cleaner environment, and a stronger energy infrastructure for the nation.

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 – 02/28/2023
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.

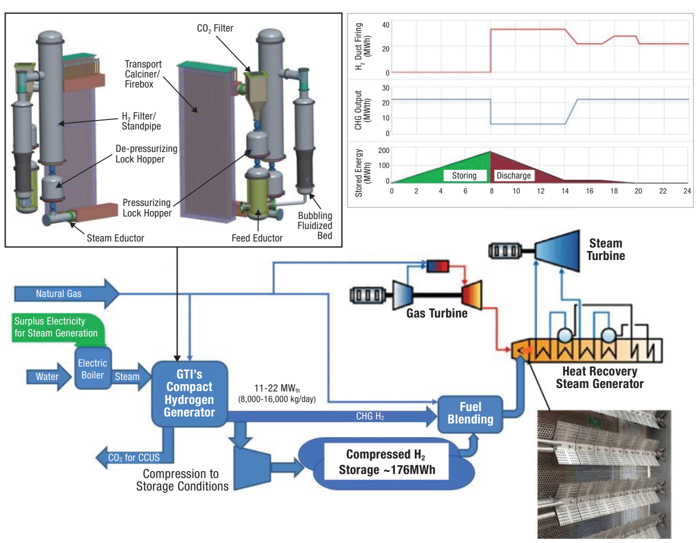


This work in hydrogen storage technology leverages a merger of energetic affinity and optimal geometry to impart high gravimetric and volumetric hydrogen uptake compared to other technologies.

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 – 02/28/2022
Total Project Value	$ 291,995
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 (MWh) 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 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.

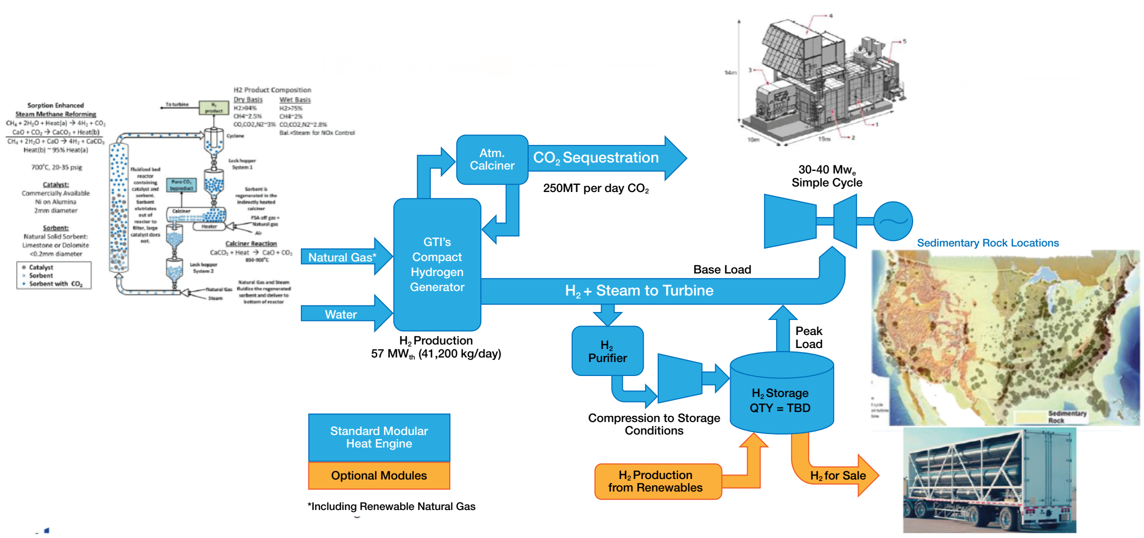


Hydrogen Storage for Load-Following and Clean Power.

Hydrogen Storage for Flexible Fossil Fuel Power Generation: Integration of Underground Hydrogen Storage with Gas Turbine

Performer	Gas Technology Institute
Award Number	FE0032012
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 316,046
Collaborator	University of Illinois Urbana-Champaign, Illinois State Geological Survey, Mitsubishi Heavy Industries, Ameren Illinois, Hexagon Purus
Technology Area	Advanced Energy Storage

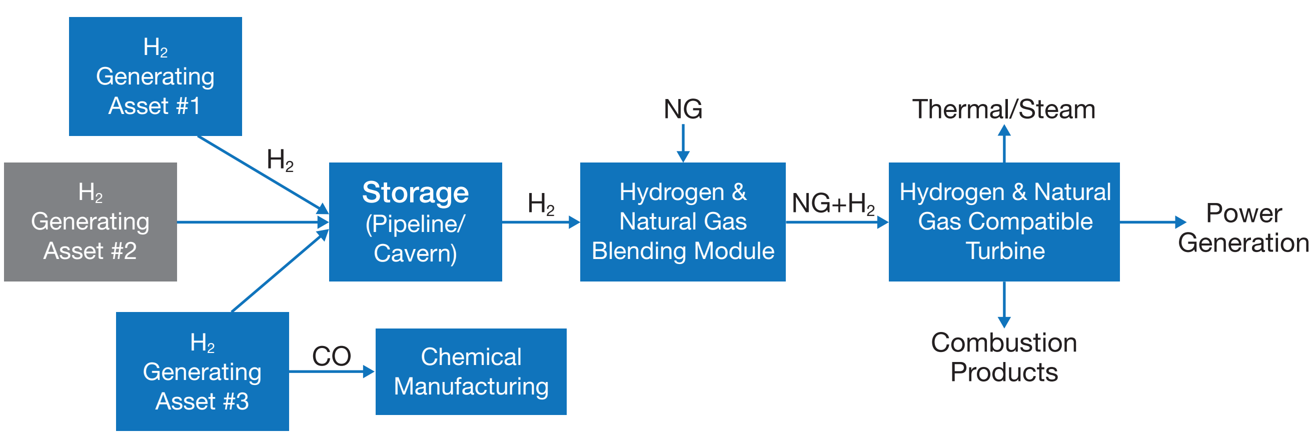
Gas Technology Institute (GTI) has put together a world-class group of companies and organizations to tackle the issue of producing low-carbon flexible power to address the increasing variability of the electric grid due to intermittent renewables, with the goal of a commercial-ready integrated power production system that has the ramping capability of turbines coupled with the lower-carbon attributes of renewable energy. This system is enabled through the use of subsurface and aboveground hydrogen storage. GTI, along with a project team consisting of University of Illinois Urbana-Champaign (UIUC), Illinois State Geological Survey, Mitsubishi Heavy Industries Group, Ameren Illinois, and Hexagon Purus, is performing a conceptual feasibility study for innovative H_2 energy storage and production as part of an integrated low-carbon, fossil-based power generation system located at UIUC. The project team will develop a platform with a goal of commercialization of an entire integrated low-carbon power system with energy storage. The commercial application of this system can address a market potential that encompasses much of North America. Both distributed and centralized deployments of this integrated system can address carbon emissions while utilizing low-cost domestically produced natural gas and provide flexible dispatchable electricity. Deploying and perfecting this suite of components and technologies into one integrated system can provide a low-cost, low carbon solution for electric power producers, businesses, and manufacturers across our nation.



Integrated Hydrogen Energy Storage System (IHESS) for Power Generation

Performer	**Gas Technology Institute**
Award Number	FE0032013
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 250,000
Technology Area	Advanced Energy Storage

The objective of the Phase I study is to determine the technical feasibility, economic viability, and environmental benefits of deploying an Integrated Hydrogen Energy Storage System (IHESS) to produce blended hydrogen/natural gas fuel mixtures for heat/power production "behind the fence" at a fossil-based power or cogeneration facility. To accomplish this study, the team will develop a process and technoeconomic model that evaluates the hydrogen generation and pipeline operating conditions required to provide the fossil-based power or cogeneration facility with access to at least 10 MWh of hydrogen energy storage. The data produced by this project will be important for understanding the risks and opportunities of and uncertainties about IHESS systems and in using hydrogen/natural gas mixtures to fuel power generation turbines. By exploring these challenges, this project will provide useful data that will de-risk economics and engineering uncertainty to promote near-/mid-term deployment of the hydrogen energy storage solution. The study aims to better understand the technical practicality, economic potential, and environmental benefits of delivering hydrogen to natural gas-based electricity generation units for low-emissions power production by IHESS in the near and mid terms.



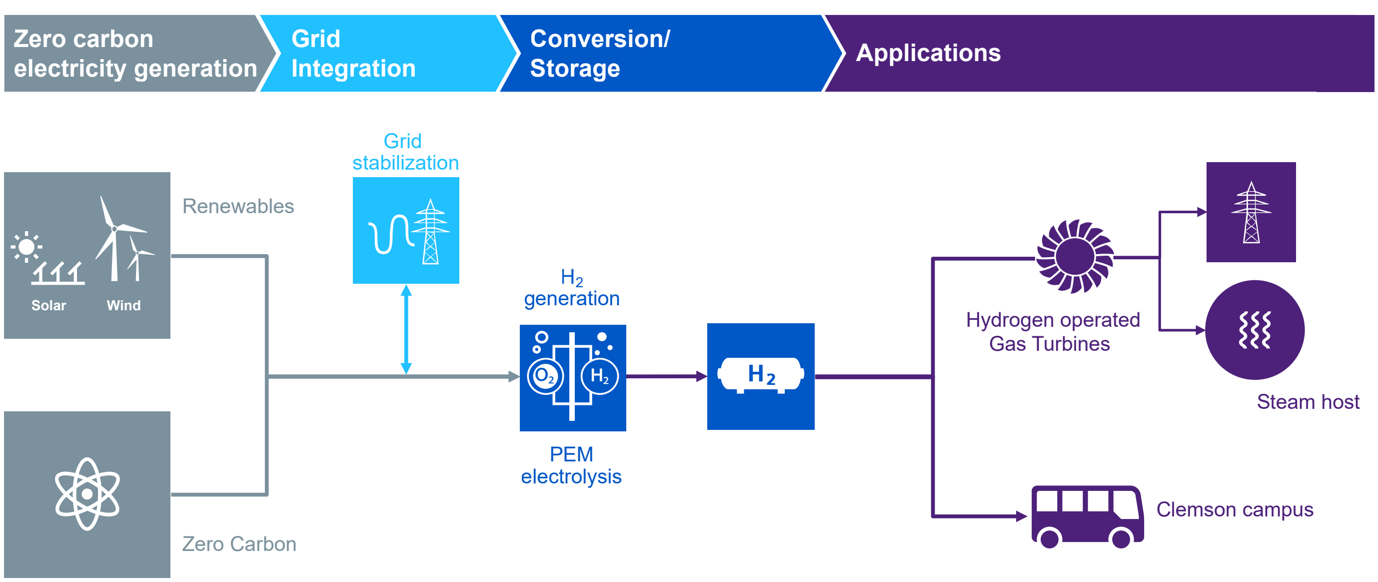
Integrated Hydrogen Energy Storage System (IHESS).

Clemson Hydrogen Combined Heat and Power Storage System

Performer	**Siemens Energy, Inc.**
Award Number	FE0032006
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 274,854
Technology Area	Advanced Energy Storage

Siemens Energy, Inc. will work toward the decarbonization of Clemson University's combined heat and power facility, located in Clemson, South Carolina. Siemens will perform a conceptual study to develop a >50 MWh hydrogen energy storage system. The study will compare various energy storage systems, considering the heat generation and grid requirements to maximize overall efficiency and reliability, thereby reducing the levelized cost of electricity. The advanced energy storage system will consist of hydrogen generation via a Siemens Silyzer electrolyzer, hydrogen storage, hydrogen co-firing of the existing SGT-400 gas turbine, and an integrated control system. The system will be designed and sized to ensure adequate supply for daily and or seasonal demand, as well as provide key grid support functions as an active electrical generator unit. The energy storage system would then be integrated into the Clemson University grid with controllable campus loads. As proposed, it has the potential to provide grid-forming and microgrid operations during outages while considering the steam demand and corresponding high-capacity factor of the gas turbine.

This project will help identify the technical requirements, costs and benefits of a hydrogen storage system sized around the actual fossil Combined Heat & Power Plant at Clemson. Project findings will enhance the understanding and enable further evaluation of the hydrogen storage system and re-electrification of the hydrogen at Clemson. These findings may also allow a broader evaluation of hydrogen storage and hydrogen re-electrification across the national fleet.

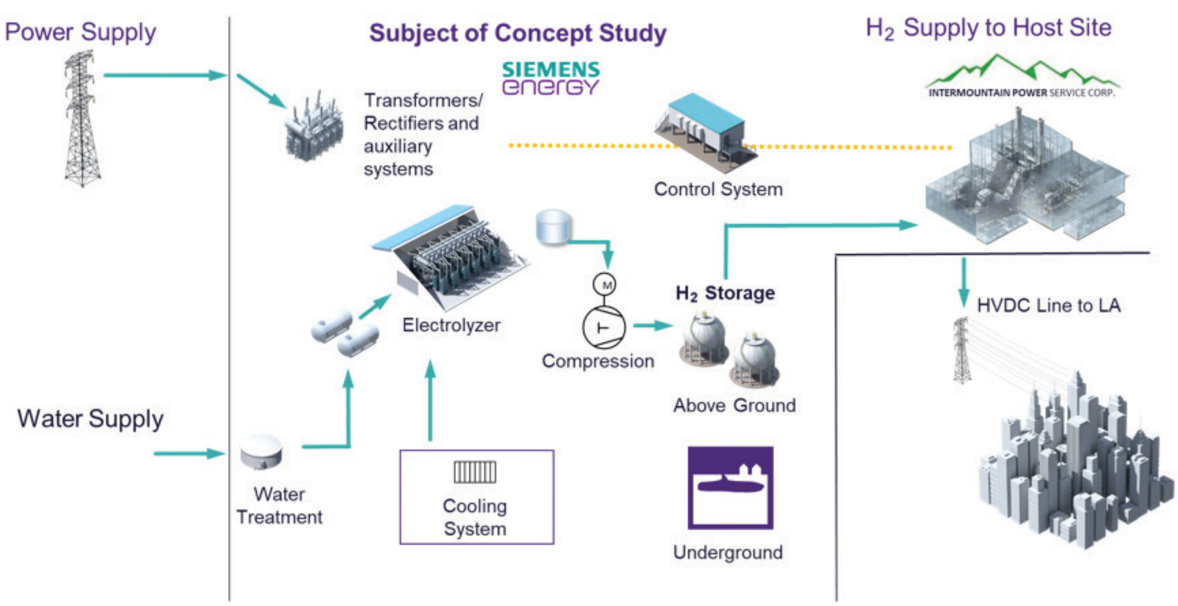


Hydrogen from zero emission resources enables long-term storage for industry, mobility, and energy.

Hydrogen Energy Storage Integrated with a Combined Cycle Plant

Performer	**Siemens Energy, Inc.**
Award Number	FE0032028
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 271,128
Collaborator	Intermountain Power Service Corporation
Technology Area	Advanced Energy Storage

Siemens Energy, Inc. and partner Intermountain Power Service Corporation are developing a concept design of a hydrogen energy storage system integrated into an advanced class combined cycle power plant (CCPP). The goal is to maximize efficiency and reliability of the CCPP, mitigating inefficient or off-design operation by complementing it with the dynamic response characteristics of the hydrogen energy storage system. The project aims to address underlying hydrogen energy storage system challenges in technology and economic design, and thoroughly analyze the intricacies of integrating the system into an existing power plant and transmission grid. The conceptual study will be based on Siemens's Silyzer PEM electrolyzer platform, hydrogen compression, hydrogen storage, and intelligent plant controls. A technoeconomic study using simulation and optimization software is planned to determine sizing, scheduling, and cost/benefit analyses. The study would include a thorough assessment of the H_2 system integration into a CCPP and how the dynamic response capabilities of the electrolyzer support grid stability, further promoting renewable penetration while avoiding off-design operation, thus improving overall efficiency and plant life. If successful, this project will help the power sector gain a thorough understanding of how the elements of an integrated H_2 production, storage, and power plant system interact and can be optimized and applied to advanced class power plants.



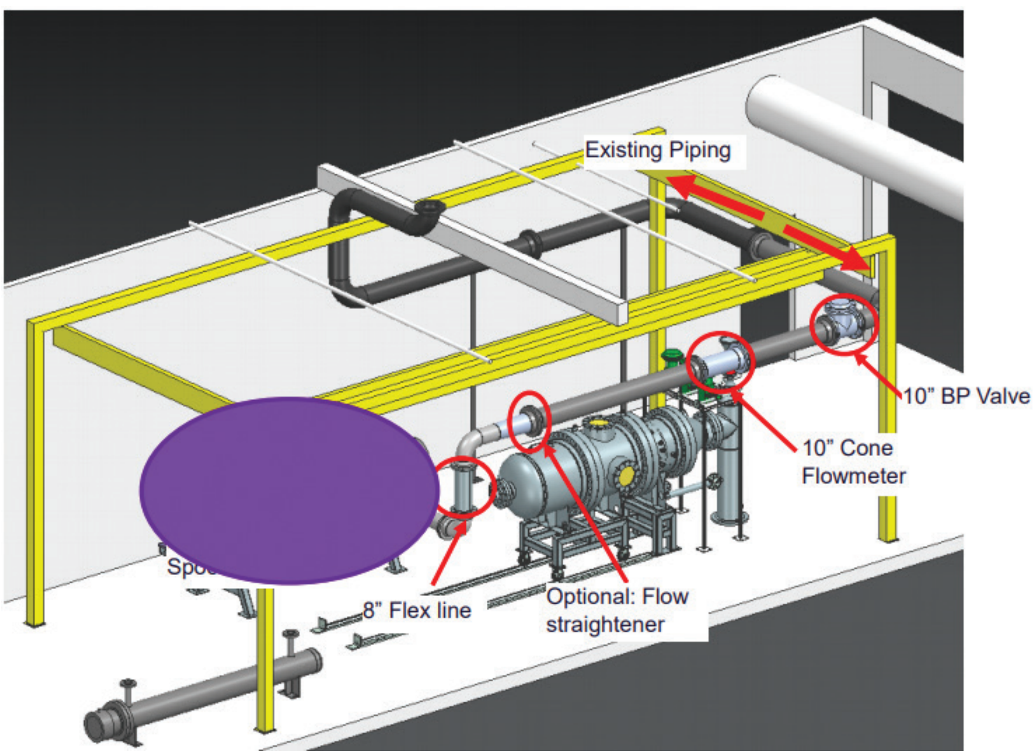
Technical approach – SE/IPSC.

Advanced Hydrogen Compressor for Hydrogen Storage Integrated with a Powerplant

Performer	**Siemens Energy, Inc.**
Award Number	FE0032033
Project Duration	03/01/2021 – 03/31/2022
Total Project Value	$ 828,854
Technology Area	Advanced Energy Storage

Siemens Energy is pursuing an advanced compressor concept that significantly reduces the overall number of stages required for cost-effective hydrogen compression. The proposed project will include progressing the design of the compressor, manufacturing a prototype, and testing it to verify its performance in relevant operating conditions. Testing will aim to provide validation of the efficiency and operating range of the compressor stage and advance the technology readiness level (TRL) of the concept to 4.

Siemens also will develop a cost model and conduct a techno-economic analysis to evaluate the cost benefits provided by the advanced hydrogen compressor relative to current commercially available compression technologies. Successful completion of the test program would validate use of counter-rotating axial compressor technology to reduce the cost of compression required for hydrogen storage.

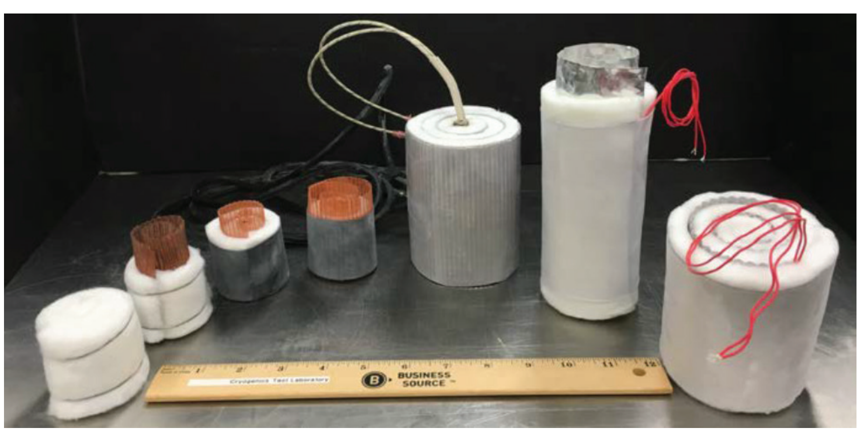


The advanced compressor stage test rig will be installed in 1 of 3 test bays in the Redmond, Washington facility.

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 – 02/28/2023	03/01/2021 – 02/28/2023
Total Project Value	$ 575,680	$ 49,300
Technology Area	Advanced Energy Storage	

Southwest Research Institute, in collaboration with the University of Central Florida, NASA Kennedy Space Center (NASA), 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.



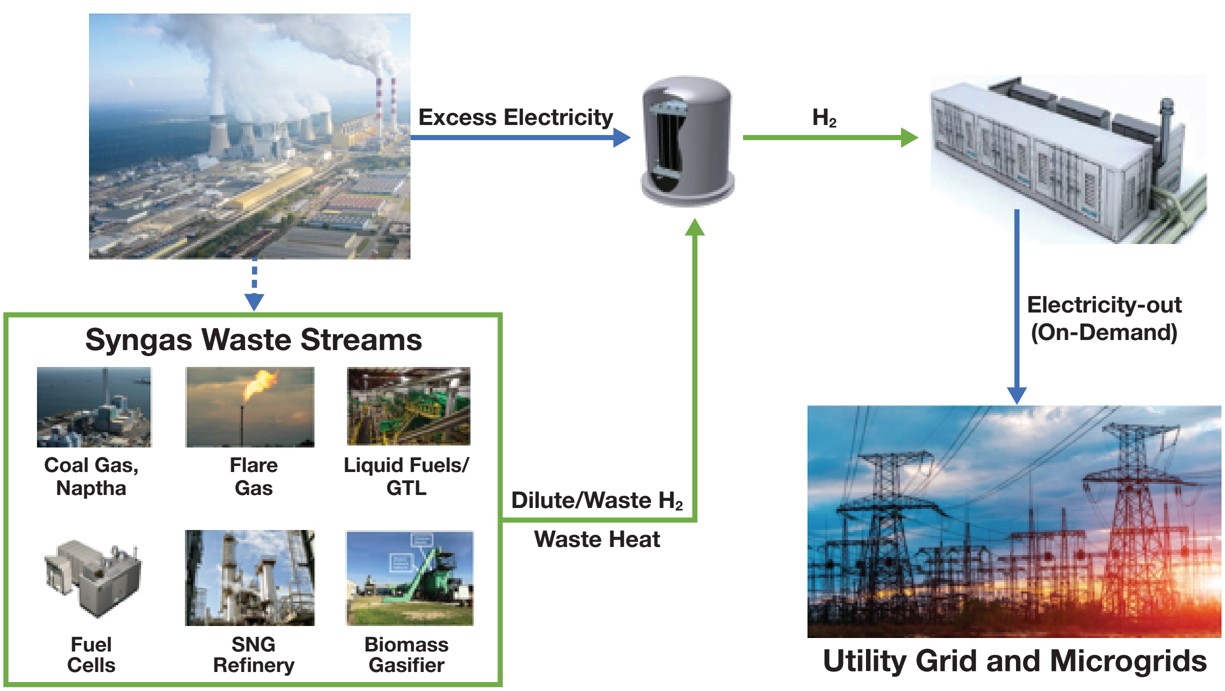
Various prototypes of CFC core modules (spiral configurations with different conductors).

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 – 04/11/2023
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.



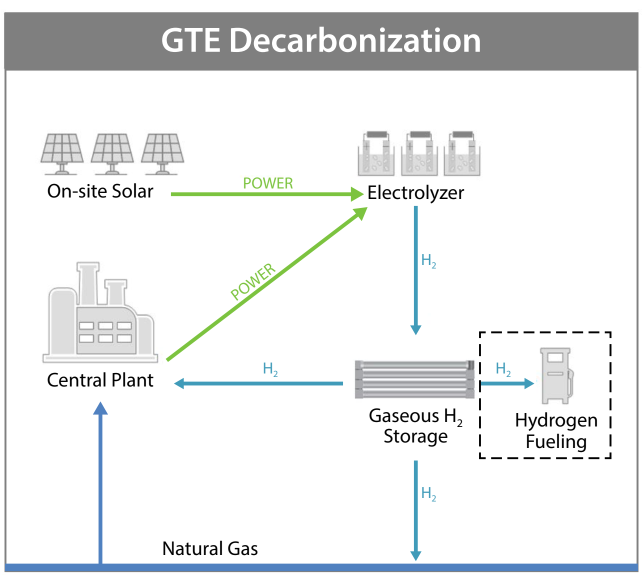
Use dilute syngas streams to produce higher value of H_2 and extend the life of fossil plants.

Hydrogen Based Energy Storage System for Integration with Dispatchable Power Generator: Phase I Feasibility Study

Performer	University of California - Irvine
Award Number	FE0032021
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 285,000
Technology Area	Advanced Energy Storage

The University of California–Irvine (UCI) will advance the capability of an existing fossil asset serving the campus microgrid to store energy in the form of hydrogen produced through electrolytic and/or micro-steam methane reforming and to consume hydrogen as fuel with the production and use cycles optimized based on market, operational, and demand conditions. The UCI central plant features a natural gas-fired 13 MW gas turbine, which is coupled with a heat exchanger that captures waste heat for use in either additional power generation via a steam turbine, chilling via an absorption chiller, or heating via steam use and exchange with a district heating system. The Phase I project will assess the optimal design of this integrated storage ecosystem that would feature turbine retrofit to enable operation on variable fractions of hydrogen up to 30%; integration of technology to utilize waste heat from the gas turbine for hydrogen production; physical interconnection via hydrogen pipe of the campus central plant and the campus hydrogen refueling station to allow joint use and co-optimization of electrolyzer, multi-frequency scanning microwave radiometer (mSMR), and storage resources to serve either power or transportation demand; and an integrated control system to allow dynamic dispatch of ecosystem components. In addition, a technoeconomic study to assess the generic implementation of the system to assess overall value and pricing models will be conducted.

The primary output is a feasibility study that will assess how the integrated resources can help reduce emissions impact and wear and tear on the existing fossil-fueled asset, and potentially lead to savings on utility and fuel costs. This project has potential for replicability at other institutions with a similar set of constraints relative to emissions and utility costs. As a result, the project could serve as a model for future integrated hydrogen-based energy storage.



H_2 Salt: Storing Fossil Energy as Hydrogen in Salt Caverns

Performer	**University of Kansas Center for Research**
Award Number	FE0032015
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 250,000
Technology Area	Advanced Energy Storage

This project supports the Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM) goal to advance near-term commercial deployment of fossil-fueled, asset-integrated energy storage solutions. The overall objective is to conduct an initial feasibility study for a power-to-hydrogen system "inside the fence" of a fossil fuel electricity generating plant in the state of Kansas. The scope of work will set the stage for subsequent site-specific projects integrating relatively mature combinations of energy storage technologies with particular fossil-fueled assets. The specific goals of the project are to complete a conceptual study of a hydrogen-based energy storage system at a specific site, conduct a technoeconomic study of a generic implementation in the midwestern electricity market, perform an assessment of the key risks including perceived technology gaps that could delay commercialization by 2030, create a project plan for a Phase 2 pre-FEED study, define a maturation plan that includes the work required to advance the technology to TRL 9, and prepare a commercialization plan to enable wide-scale deployment. The project team will leverage previous geologic assessments performed by the Kansas Geological Survey and Linde's industrial experience operating an underground salt cavern in the Gulf Coast area to facilitate attainment of the project objectives. Evergy, the energy asset partner, owns the two natural gas combustion turbine electricity generating units (EGUs) that are the designated sites for the study.

The proposed EGU is currently operated as a peaking plant, so having a storage system that can take advantage of arbitrage opportunities will improve the economics of the facility. In addition, the opportunity to deliver pure hydrogen using existing natural gas pipeline infrastructure for industrial and residential customers as well as local and regional customers will improve the economics of the plant and support the development of a hydrogen economy in the Midwest. There are approximately 20 other combination fossil EGUs that overlie the Hutchinson Salt in Kansas and about 20 other plants that overlie other salt beds further west in Kansas that can benefit if the project is successful.

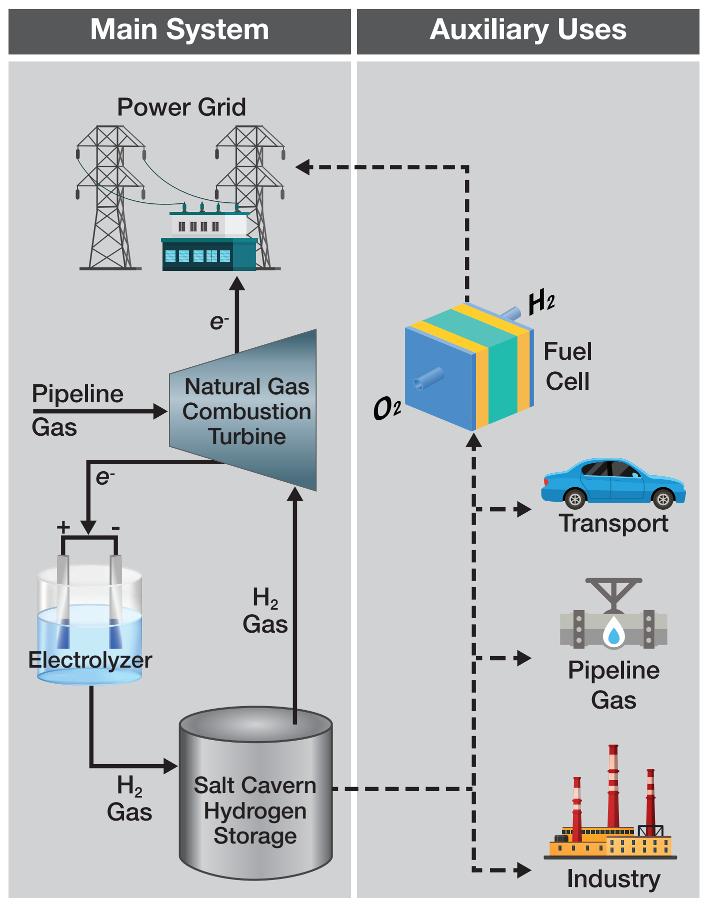
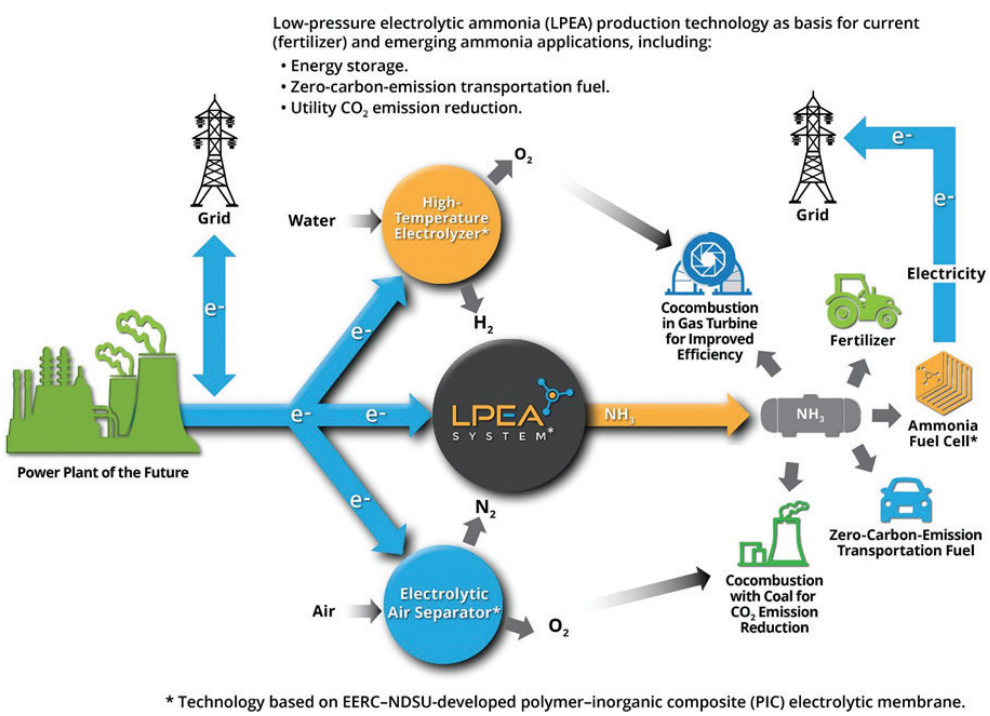


Diagram showing energy storage concept and auxiliary uses.

Ammonia-Based Energy Storage Technology (NH_3-Best)

Performer	**University of North Dakota**
Award Number	FE0032014
Project Duration	03/24/2021 – 03/23/2022
Total Project Value	$ 362,500
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.



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 – 02/28/2022
Total Project Value	$ 250,000
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 ones 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 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, reliability, and operational life of fossil power plants. By improving the capacity factors of power plants, more revenues could be generated.

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 – 02/28/2023
Total Project Value	$ 693,176
Technology Area	Advanced Energy Storage

The primary objective of the project is 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 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.

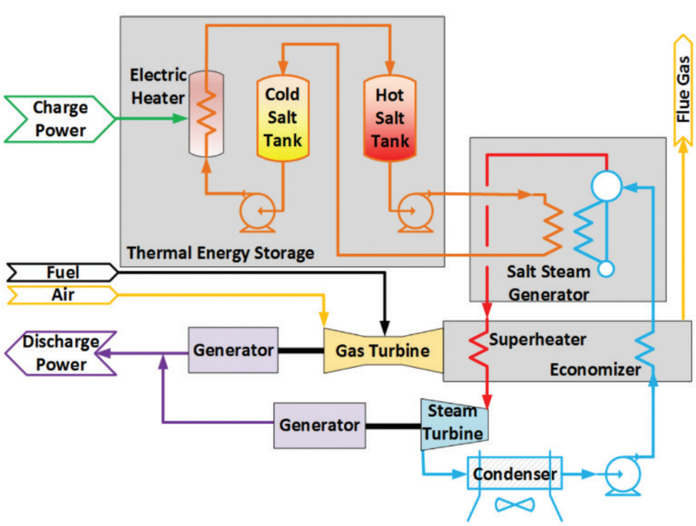
WireTough Cylinder.

THERMAL TECHNOLOGIES

Liquid Salt Combined-Cycle Pilot Plant Design

Performer	**Electric Power Research Institute**
Award Number	FE0032016
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 249,664
Collaborator	Pintail Power LLC, Nexant Inc., Southern Company
Technology Area	Advanced Energy Storage

Electric Power Research Institute, Inc. and partners Pintail Power LLC, Nexant, Inc., and Southern Company will perform a feasibility study—comprising a conceptual study, techno-economic study, technology gap assessment, Phase II project plan, technology maturation plan, and commercialization plan—to integrate a pilot scale (4MWe/20MWhe) liquid salt combined-cycle (LSCC) design into a gas turbine environment, evaluate system responsiveness in a real-time operating environment, and estimate the costs. Southern Company's Plant Rowan in North Carolina has been selected for this study. LSCC technology integrates thermal energy storage with fossil electric generation units to enable faster system startup to full load with less fuel burn and reduce fuel heat rate at full load via stored energy. The system combines two-tank molten salt storage with electric heating and a molten salt steam generator in a system integrated with gas turbine exhaust gas. By moving evaporative heating duty outside the exhaust heat recovery equipment, this arrangement removes pinch constraints by using high-temperature turbine exhaust for superheating, with 2.5 to 3 times more steam flow than with exhaust heating alone. Because the liquid salt combined-cycle system makes use of only commercially available equipment (molten nitrate salt, thermal energy storage, resistive electric heaters, and salt-to-steam heat exchangers), no novel equipment is needed to realize an effective energy storage system. By allowing an LSCC system to store energy when power is not needed and provide power to the grid when it is using synchronous generation, the overall grid can remain stable and balanced at far higher variable penetration levels than is achievable today.



Liquid Salt Combined Cycle (LSSC) Pilot Plant Design. Developed and patented by Pintail Power. Excess renewable power converted to thermal energy and stored in molten salt. When power is needed, gas turbine is started and LSCC steam system is activated when flue gas is available. Steam is generated in combination with salt steam generators and heat recovery exchangers.

Modular, Crushed-Rock Thermal Energy Storage Pilot Design

Performer	**Electric Power Research Institute**
Award Number	FE0032017
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 250,000
Technology Area	Advanced Energy Storage

The goal of this project is to design a next-step pilot to advance near-term energy storage integrated with a fossil plant, providing a facility capable of achieving viability and effectiveness in a market with growing penetration of variable renewable energy (VRE). Thermal energy storage (TES) represents an ideal technology for this purpose. A feasibility study to prepare for the Phase II pre-front-end engineering design (pre-FEED) for implementing a crushed-rock TES system integrated with a natural gas combined cycle (NGCC) plant will be performed. The crushed rock storage technology, which is being developed by Brenmiller, is a modular TES system termed bGen™, which can accommodate both thermal and electrical inputs, and output steam, hot water, or hot air. For this application, the estimated efficiency is 80% thermal to thermal. The Brenmiller technology will be designed to operate on a slipstream from NYPA's Eugene W. Zeltmann Power Project (Zeltmann) natural gas combined cycle (NGCC) plant or a similar plant in their portfolio. The projected size of the system will be up to 4 megawatt electric (MWe) with at least 4 hours of storage duration, or 16 megawatt-hours electric (MWh-e) total. Final sizing will be determined during the feasibility study. EPRI has reviewed Brenmiller's technology, which is being built in Dimona, Israel, to demonstrate bGen at 1.7 MWe on a solar plant (Rotem 1) and has been designed for an NGCC facility in Italy, assessing it at technology readiness level (TRL) 5. Brenmiller is also conducting a separate 1-megawatt thermal (MWth) pilot with Zeltman that pairs a bGen module with a microturbine for a combined heat and-power application to improve efficiency and provide flexibility. The next-step pilot being designed as part of the project will represent a 5-fold increase in scale versus Rotem 1 and will show the technology's ability to provide effective and economical energy storage, bringing the technology to TRL 6. This pilot at Zeltmann would be the next-to-last demonstration scale before bGen could be commercially ready at GWh-e scales in the 2030 timeframe. This project will provide the design for the critical next-step pilot to be undertaken in real-world operating conditions to determine the Brenmiller technology's ability to be integrated with an NGCC plant and assess degradation over transient cycling rates available at various marketplaces.

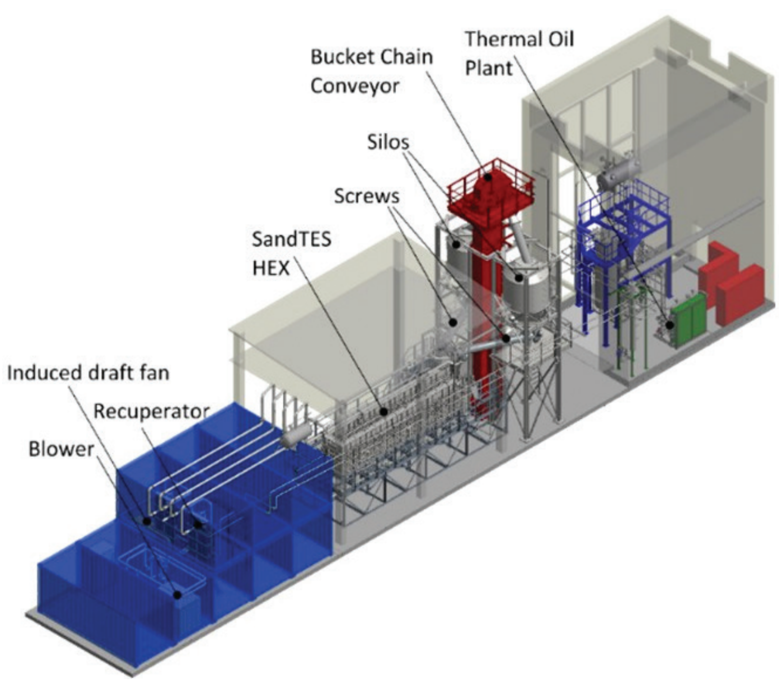
Multiple thermal and electrical inputs are supported for flexibility.

Sand Thermal Energy Storage Pilot Design

Performer	**Electric Power Research Institute**
Award Number	FE0032024
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 249,999
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-MWh-e 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 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.



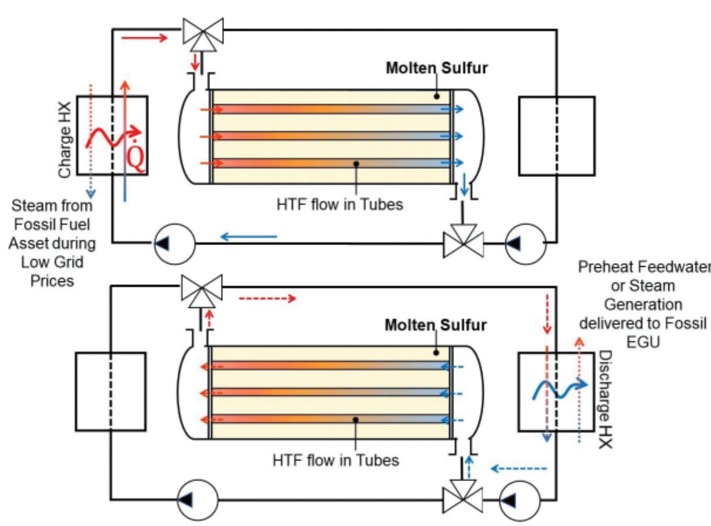
SandTES Integrated System.

Low Cost Sulfur Thermal Storage for Increased Flexibility and Improved Economics of Fossil-Fueled Electricity Generation Units

Performer	**Element 16 Technologies, Inc.**
Award Number	FE0032007
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 250,000
Technology Area	Advanced Energy Storage

Element 16 Technologies, Inc. will conduct a detailed feasibility study establishing the impact, cost, and performance of a molten sulfur thermal energy storage (TES) system integrated with fossil fuel assets. The molten sulfur TES performance model combined with cost model will be used to derive an optimal integration plan for increasing flexibility and improving economics of fossil-fueled electricity generating units. The planned activities include system performance and cost modeling for detailed techno-economic evaluation, and system design optimization to maximize the fossil fuel electricity generating unit's output capacity and to minimize the levelized cost of electricity/storage and emissions. The project also includes developing a commercialization plan and technology gap assessment plan that identifies future research and development required to commercialize the technology by 2030.

This project will establish the feasibility of integrating energy storage technology with fossil energy assets. Fossil energy assets, the electricity grid, and the nation would benefit from the application of energy storage technology. Fossil energy assets would benefit from reduced thermal cycling of critical components such as the boiler, which reduces maintenance costs and increases reliability. The electricity grid would benefit by maintaining power quality due to improved fossil generation dispatchability, which would ultimately benefit the grid utility consumers. Finally, the nation would benefit due to the electricity grid's ability to incorporate increased variable renewable energy capacity and the extended economic lifetime of existing electricity generating units, which would reduce emissions without increasing the cost of energy.



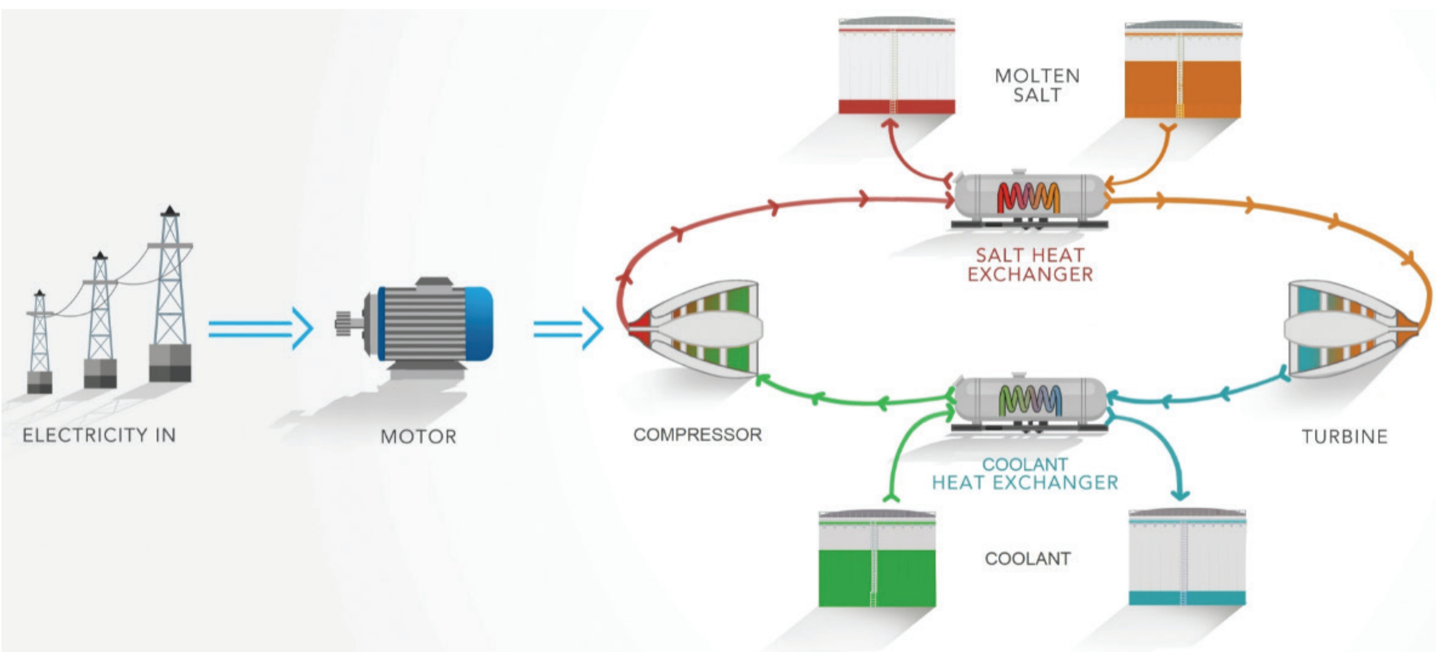
Schematic illustration of sulfur TES for generating steam or preheating feedwater in a fossil fuel electricity generating units (EGUs).

Repurposing Fossil-Fueled Assets for Energy Storage

Performer	**Malta, Inc.**
Award Number	FE0032004
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 312,500
Technology Area	Advanced Energy Storage

The overall objective of this project is to perform a conceptual design study of methods to integrate the Malta Pumped Heat Energy Storage System (MPHES) with an existing fossil energy (FE) power plant scheduled for partial or full retirement to identify opportunities to extend the useful economic life of the plant, maximize the asset owner's return on investment in the plant, and provide stored energy to help maintain electric grid stability. The objective will be achieved through engineering design and economic studies of various MPHES-FE power plant integration options and economic analyses that will identify the most favorable economic option. The minimum stored energy delivery capacity will be 100MW for 10 hours.

MPHES integrated with coal-fired electricity generating units (CF-EGUs) is expected to provide increased flexibility for the balance of the plant and portfolio, decreased acquisition costs for energy storage, and increased performance and decreased O&M costs for fossil-fueled assets. It is expected to improve the reliability of operation of the electrical grid by replacing essential grid functions lost to retiring CF-EGUs and firming variable renewable electricity. It is expected to address the impacts that CF-EGU retirements have on incumbent workforces and their communities and improve the environmental performance of fossil-fueled assets.



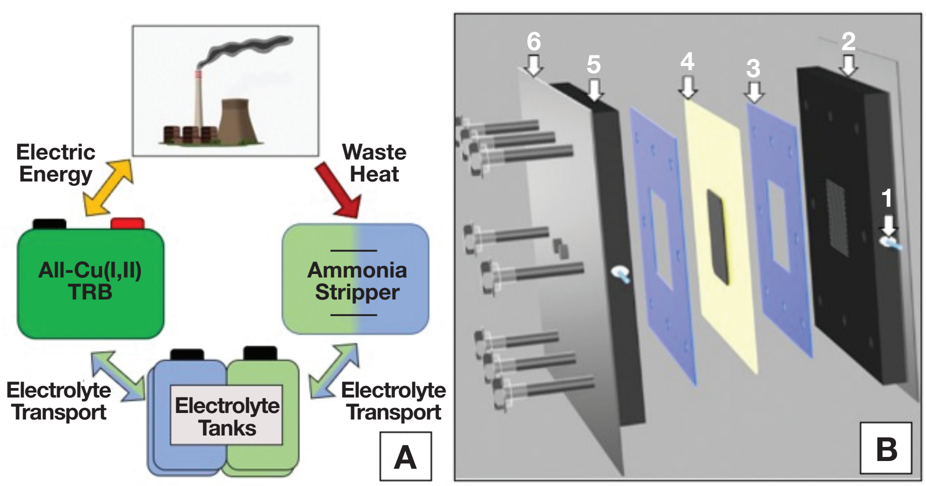
Malta Pumped Heat Energy Storage System.

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 – 02/28/2023
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 all-Cu(I, II) 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 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.

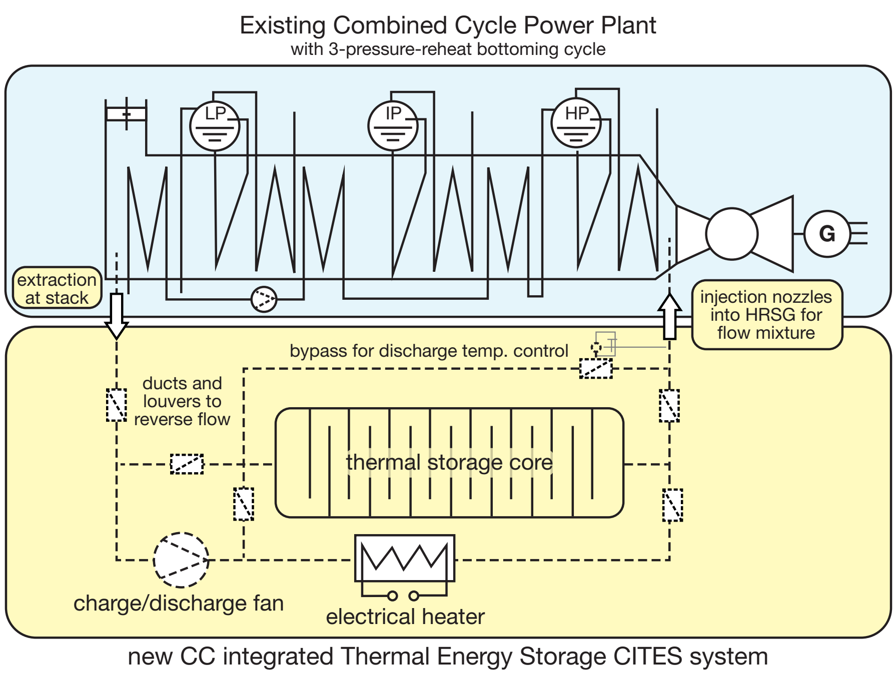


All-Cu(I, II) TRB integration with fossil fuel assets [A] and schematic of the electrochemical cell [B]. (1) fluid inlet and outlet; (2) negative electrode current collector; (3) gasket; (4) membrane-electrode assembly; (5) positive electrode current collector; (6) steel endplate.

Combined Cycle Integrated Thermal Energy Storage

Performer	**Siemens Energy, Inc.**
Award Number	FE0032029
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 250,668
Technology Area	Advanced Energy Storage

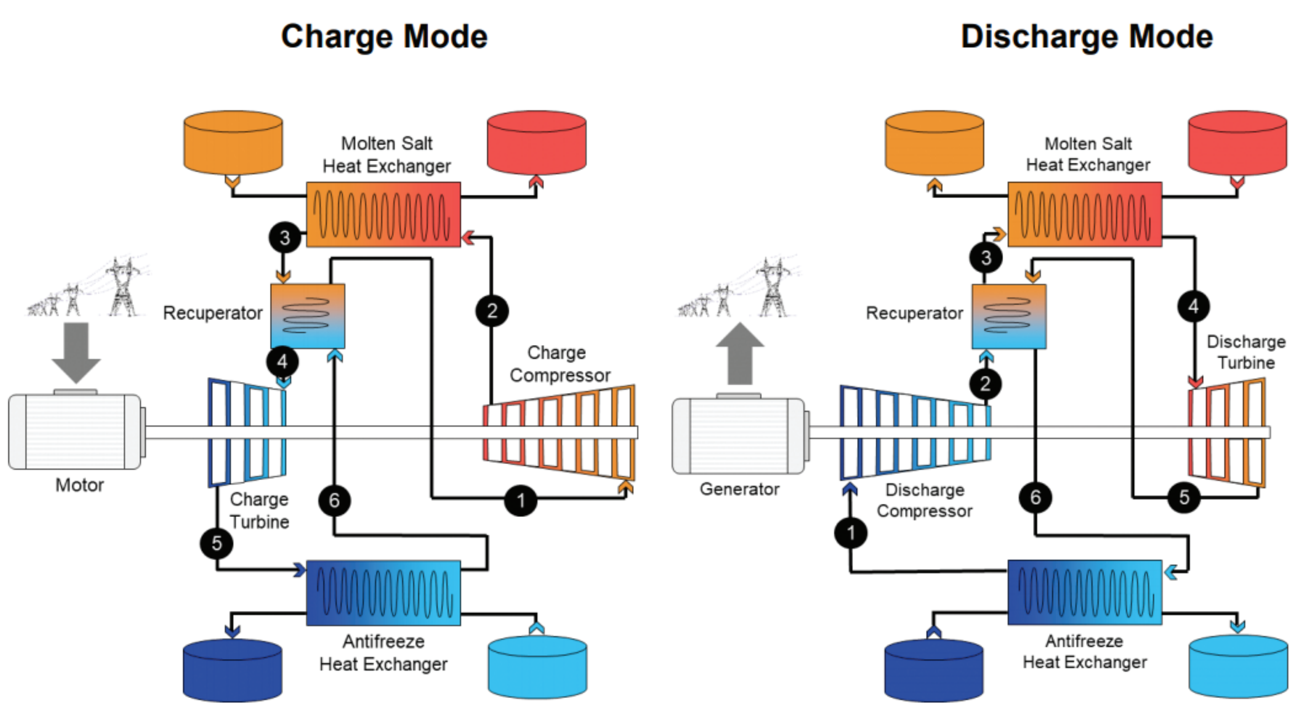
Siemens Energy, Inc. will conduct a feasibility study comprised of a conceptual study, techno-economic study, technology gap assessment, Phase II project plan, technology maturation plan, and commercialization plan to prove the technical and economic feasibility of integrating a combined cycle-integrated renewable energy storage (CiRES) system storing surplus renewable electricity as thermal energy into an existing gas-fired combined cycle power plant. A secondary objective is to use the stored thermal energy to increase the flexibility of the combined cycle power plant by pre-warming the heat recovery steam generator (HRSG) during plant start preparation. This transforms each start into a hot plant re-start regardless of the plant down time, thus avoiding low-load holds of the gas turbine during start, which improves the flexibility of the plant by shortening the start-up time. The CiRES system uses a thermal energy storage core with a pebble bed of inexpensive solid material with excellent thermal properties and durability. For charging, a blower pushes air through the electrical heater using surplus renewable energy to heat up the thermal storage. When energy is needed, the combined cycle power plant is started. For discharge of CiRES, the gas flow is reversed with a set of dampers. Cold gas is extracted at the stack, heated in the storage core, and injected into the exhaust gas of the gas turbine at the HRSG. The stored thermal energy is added to the exhaust energy of the gas turbine and converted into electricity in the bottoming cycle and steam turbine of the plant. A successful project will provide owners of gas-fired combined cycle plants with a tool—easily adaptable to different plant configurations and markets—that enables them to make investment decisions.



Integration of Pumped Heat Energy Storage with Fossil-Fired Power Plant

Performer	**Southwest Research Institute (SwRI)**
Award Number	FE0032031
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 250,000
Technology Area	Advanced Energy Storage

Southwest Research Institute will perform a Phase I feasibility study for the integration of a 100 MW, 10-hour (100 MWh) Malta Pumped Heat Energy Storage (MPHES) system with one or more full-sized fossil-fired electricity generation units (EGUs). MPHES is a long-duration, molten salt energy storage technology that uses turbomachinery and heat exchangers to transfer energy to thermal storage media when charging and removes the heat in a similar fashion when discharging. This Phase I study will focus on determining the size and method of integration of the MPHES system with the natural-gas-fired EGU and grid, enabling the fossil asset owner to optimize the operation of the co-located assets, balance their portfolio of energy generation, and better respond to grid disturbances through the integration of MPHES on-site. With efficient operation and long lifespan, MPHES provides economic benefits to the fossil asset owners that can be scaled to integrate with assets across their portfolio. This technology uses hardware components, workforce personnel, and skill sets similar to those used by fossil EGUs, allowing for synergy when co-locating the two technologies.



MPHES charge (left) and discharge (right) cycles.

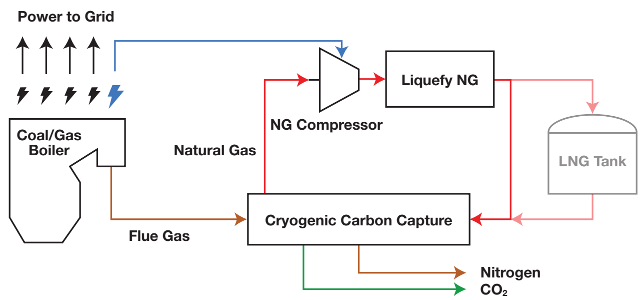
Energy-Storing Cryogenic Carbon Capture for Utility and Industrial-Scale Processes

Performer	**Sustainable Energy Solutions, Inc.**
Award Number	FE0032020
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 250,000
Technology Area	Advanced Energy Storage

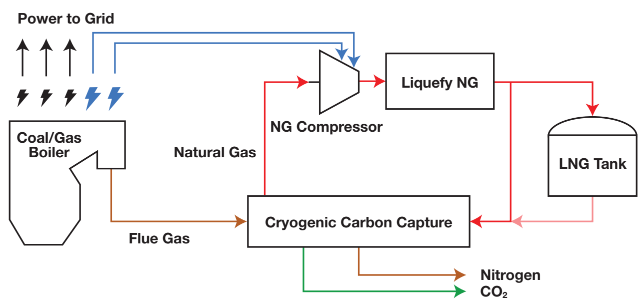
Sustainable Energy Solutions and Chart Industries will perform a quantitative assessment of an energy-storing version of their cryogenic carbon capture process. The Cryogenic Carbon Capture-Energy Storing (CCC-ES) technology will provide a minimum of 10 megawatt-hours (MWh) of energy storage. The technology uses liquefied natural gas as a refrigerant to store energy when power generation costs are low or when power is plentiful and recovers energy by drawing on stored refrigerant when power generation costs are high or when power is scarce. The project team will conduct design, engineering, and modeling of the energy-storage process and analyses of the associated costs and fuel prices based on a specific fossil energy host site and the value added from energy storage.

The energy storage process enables the fossil equipment to operate closer to steady state while enabling the plant to follow load. SES has already completed some prototype work and initial modeling to demonstrate the impact of the CCC-ES process. These analyses showed that the process could stabilize grid power demand swings of up to +/- 50% of the plant size, while allowing the coal plant to operate closer to steady state and provide a net value to the power producer of over $0.02/kWh. The economic benefit derives from the relative value of the power at low and high demand times and does not include the value of stored natural gas. The CCC-ES technology can operate at industrial and utility scales with continuously operating point sources of CO_2 to provide greater than 10 MWh of storage. The underlying CCC-ES technology has already been demonstrated at skid scale.

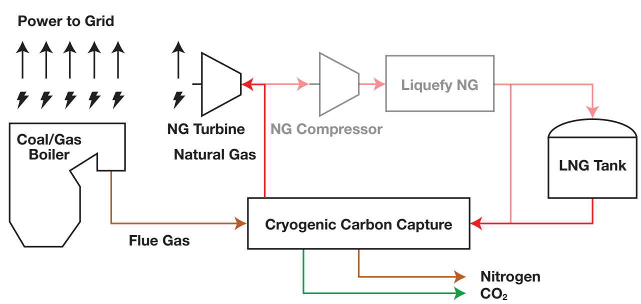
Normal Operation



Energy Storing



Energy Recovery



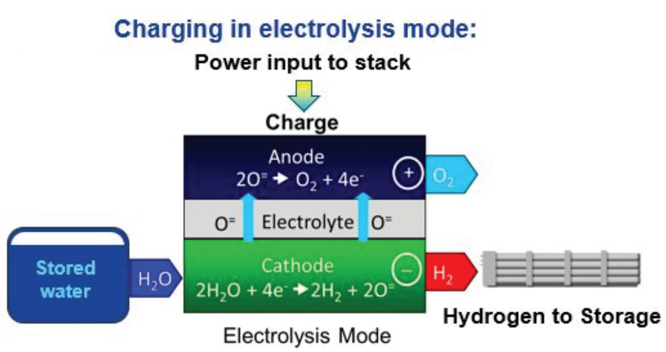
ELECTROCHEMICAL TECHNOLOGIES

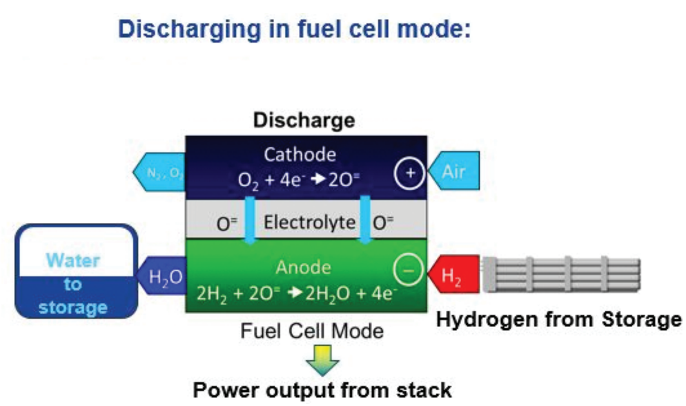
Reversible Solid Oxide Fuel Cell Systems for Energy Storage and Hydrogen Production

Performer	**FuelCell Energy, Inc.**
Award Number	FE0032032
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 249,999
Technology Area	Advanced Energy Storage

Fuel Cell Energy, Inc. (FCE) will complete a detailed feasibility study and technoeconomic analysis for MW-scale deployment of its reversible solid oxide fuel cell (RSOFC) energy storage technology, in combination with hydrogen production as an additional source of revenue and/or use in the power plant during peak periods. The RSOFC system will be designed for greater than 10 MWh capacity applications co-located with fossil-fueled electricity generating units (EGUs). The primary objective of Phase I of this project is to show the technical and economic benefits of FCE's RSOFC technology for a variety of fossil EGU applications, while also advancing the technology toward demonstration at Tri-State G&T's natural gas-fueled combined cycle J.M. Shafer Generating Station power plant in Colorado as a key enabler for future commercial deployment. Additionally, FCE and team members plan to look more broadly at RSOFC energy storage implementations with fossil assets and complete a technoeconomic study in specific market segments. The project includes creating a technology-to-market plan comprising a technology gap assessment, Phase II pre-FEED planning, technology maturation plan, and commercialization plan.

FCE's RSOFC has the potential to offer a highly efficient and affordable solution to energy storage. Successfully directing electricity generation to produce hydrogen that can be stored and used for power generation or sold as a commodity enables operators to buffer fossil plants from fast-changing electricity prices and offers parallel revenue streams, thus improving the overall economics of their assets.



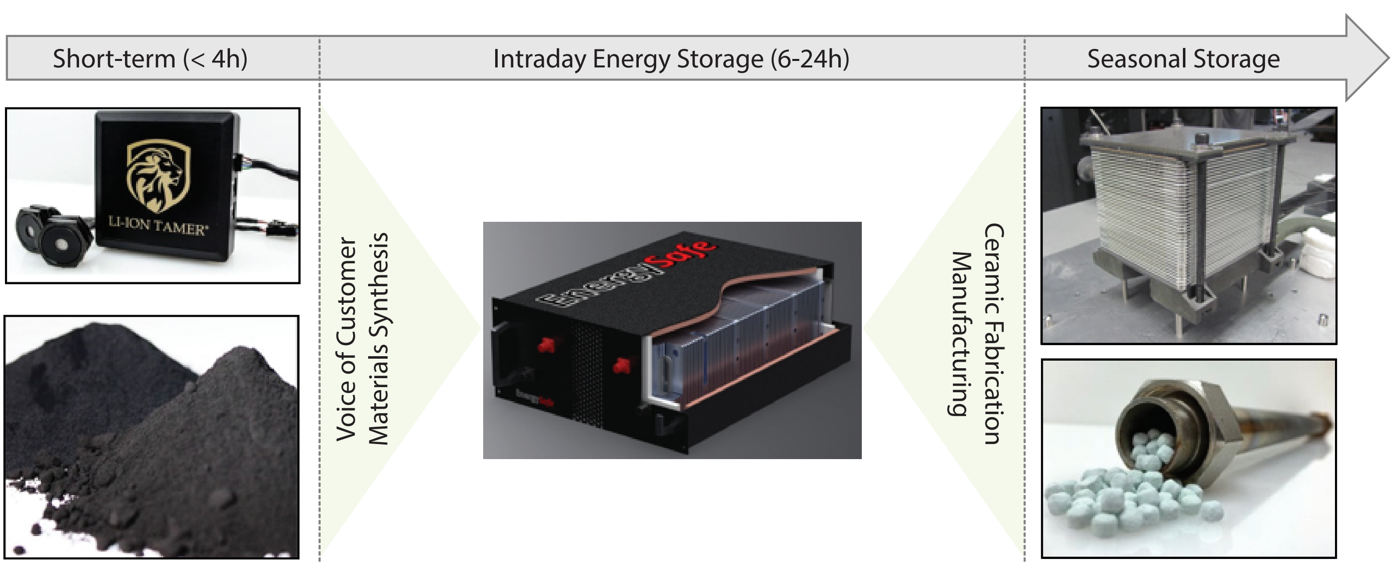


Low-Cost Metal-Supported Metal Halide Energy Storage Technology

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. In Phase, I Nexceris will advance 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. Phase I will culminate in a 20-cell, ~250 Wh pack 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.

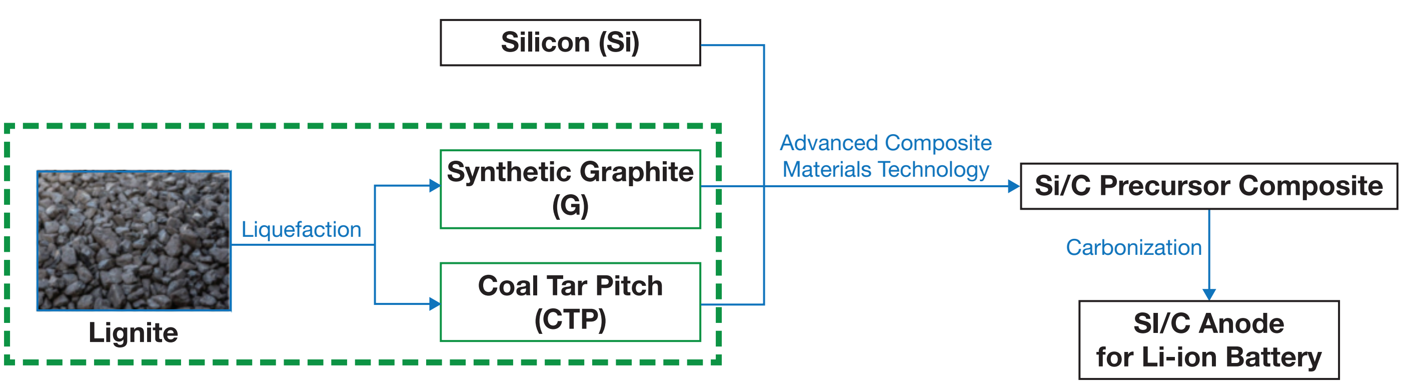


Nexceris is engaged in technology development throughout the energy storage spectrum.

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 – 01/19/2023
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.



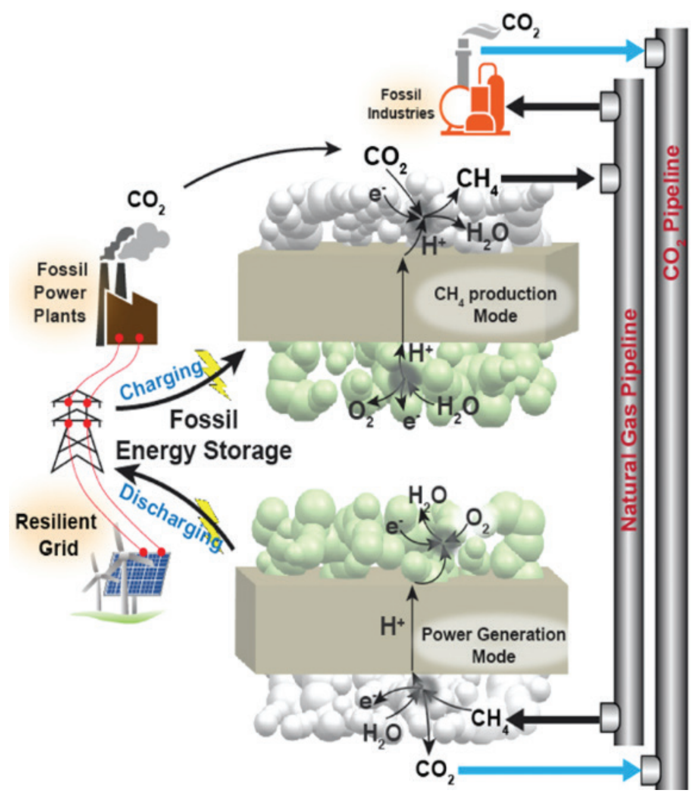
Simplified Schematic for Producing Lithium Ion Battery Anodes from North Dakota Lignite.

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

Performer	**University of Oklahoma**
Award Number	FE0032005
Project Duration	03/01/2021 – 02/28/2023
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 – 02/28/2023
Total Project Value	$ 626,215
Collaborator	Giner, Inc.
Technology Area	Advanced Energy Storage

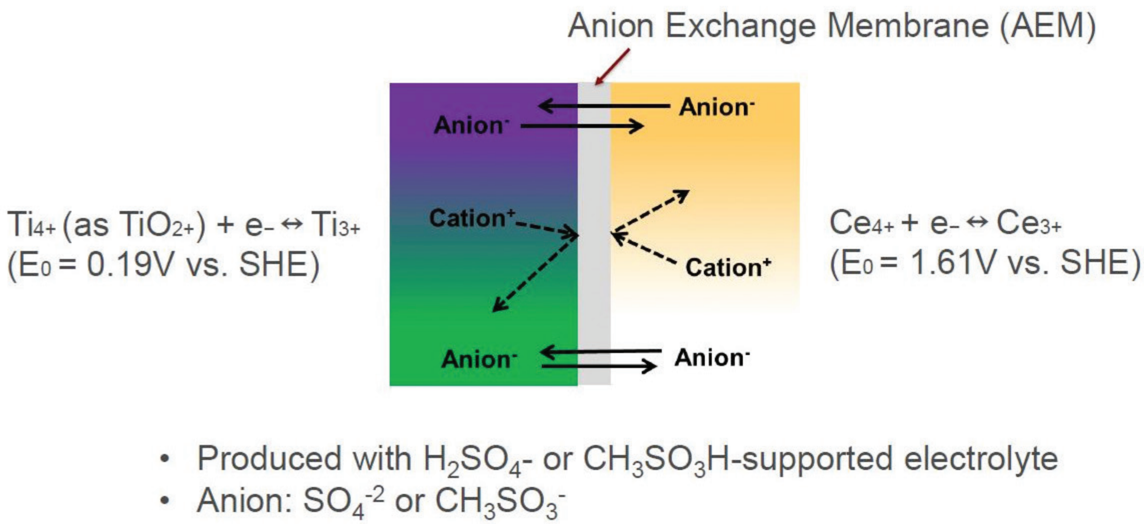
Operation of fossil plants at partial capacity with frequent cycling results in decreased efficiency and increased emissions, wear, and maintenance. The objective of this project is to advance the integration of a titanium-cerium electrode-decoupled redox flow battery (Ti-Ce ED-RFB) system with conventional 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 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 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 a 3-5-10 cell Ti-Ce ED-RFB cell stack with 400 cm2 cells at 0.5 A/cm2 current density, 48 h cycle duration, and less than 5% capacity loss in one week standby 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.

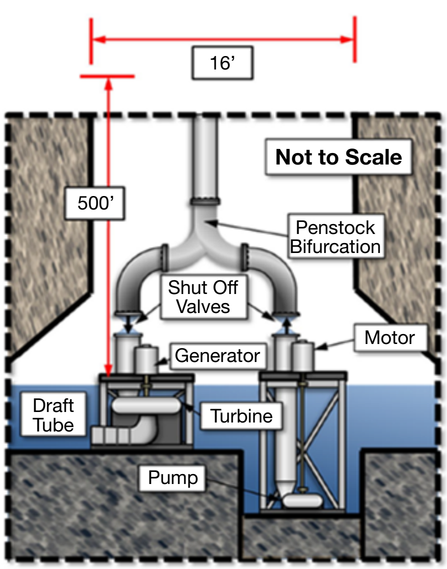
MECHANICAL TECHNOLOGIES

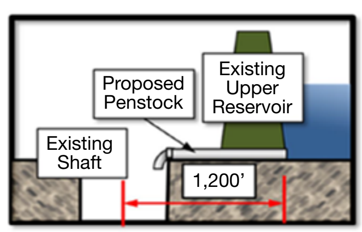
Pumped-Storage Hydropower using Abandoned Underground Mines as an Innovative Energy Storage Technology for Fossil-Integrated Systems

Performer	**Carbon Solutions, LLC**
Award Number	SC0021478
Project Duration	02/22/2021 – 11/21/2021
Total Project Value	$ 200,000
Technology Area	Advanced Energy Storage

Pumped-storage hydropower (PSH) accounts for around 95% of all utility-scale storage in the United States and globally. PSH is a proven, cost-effective technology that is poised for massive expansion throughout the U.S. if the "ΔH challenge" can be solved. The ΔH challenge refers to achieving a suitable difference in hydraulic head height between the upper and lower reservoirs in a PSH system to enable hundreds of megawatts of electricity generation power by turbines located at the lower reservoir. To date, PSH deployment has been constrained to locations throughout the United States for which natural topography provides suitable elevation relief between the upper and lower reservoirs. Carbon Solutions is investigating a solution to the ΔH challenge and facilitate the commercialization of a novel energy storage technology termed PSH-AUM—Pumped-Storage Hydropower using Abandoned Underground Mines.

The research will address DOE's goal of developing low-cost storage technologies for fossil-integrated systems by resolving key knowledge gaps in the PSH-AUM concept, including (1) subsurface reservoir performance, (2) integrated system design, operation, performance and cost metrics, and (3) optimal siting via detailed geospatial and technical screening analysis covering the lower 48-state region of the United States.





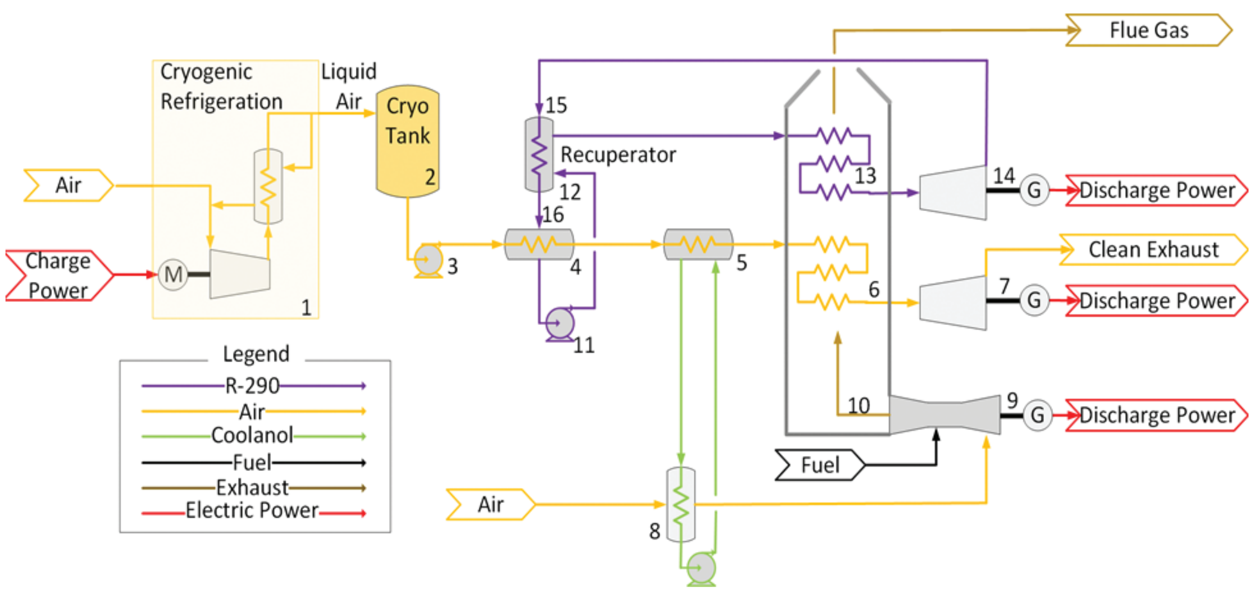
Concept for underground PSH using abandoned coal mine.

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.



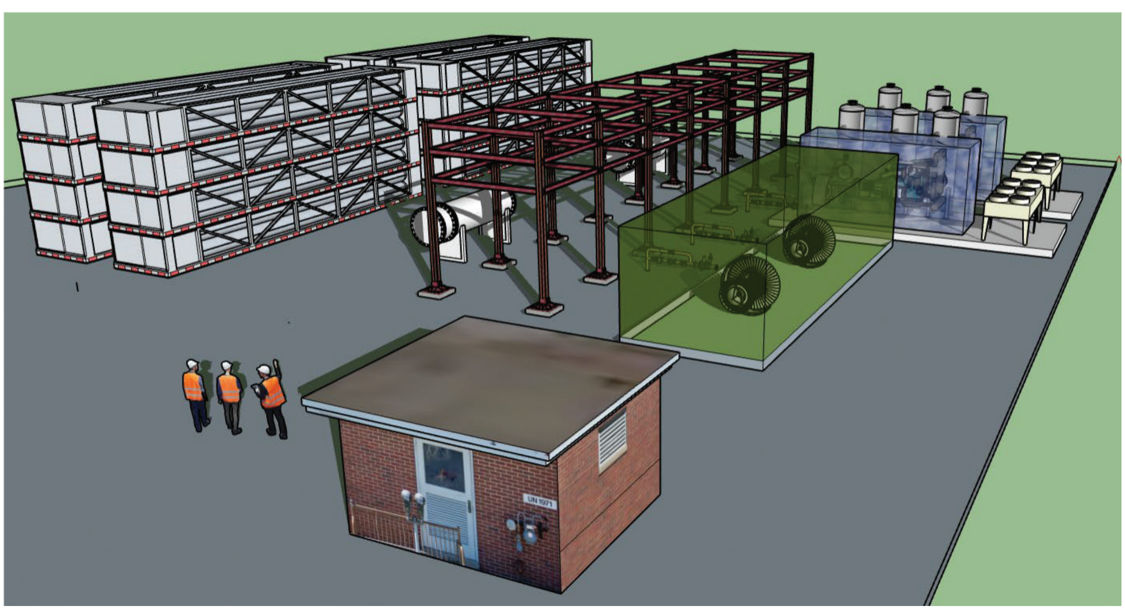
Schematic of a Liquid Air Combined Cycle (LACC).

Phase I: Natural Gas-Based Energy Storage at Abbott Power Plant

Performer	**University of Illinois**
Award Number	FE0032018
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 250,000
Technology Area	Advanced Energy Storage

Researchers at the University of Illinois will conduct a conceptual design study for integrating a 10 MWh compressed natural gas energy storage (CNGES) system with the Abbott Combined Heat and Power Plant at the University of Illinois at Urbana-Champaign. CNGES technology is analogous to commercial compressed air energy storage except natural gas is compressed during off-peak hours and discharged during peak hours. The project takes advantage of synergies at the Abbott plant where natural gas is its primary fuel. Co-locating energy storage with the plant will improve the short and long-term reliability delivery of electric power as the use of variable renewable power generation increases.

The technology includes control systems and algorithms to reliably adjust the energy generated to maintain a stable grid. This Phase I study will focus on a preliminary technical design that includes (1) identifying potential on-site locations for the CNGES; (2) projected utility requirements for CNGES from the fossil asset; (3) tie-in points; (4) permitting and regulatory considerations; and (5) technical challenges for integration of CNGES with the fossil asset. The impact of integration of CNGES into the campus grid, which already has renewables, will also be examined. Upon successful completion of the project, this new integrated technology would provide combined heat and power plants with improved energy efficiency, reduced fuel and maintenance costs, and reduced emissions (because efficient ramping uses less fuel).

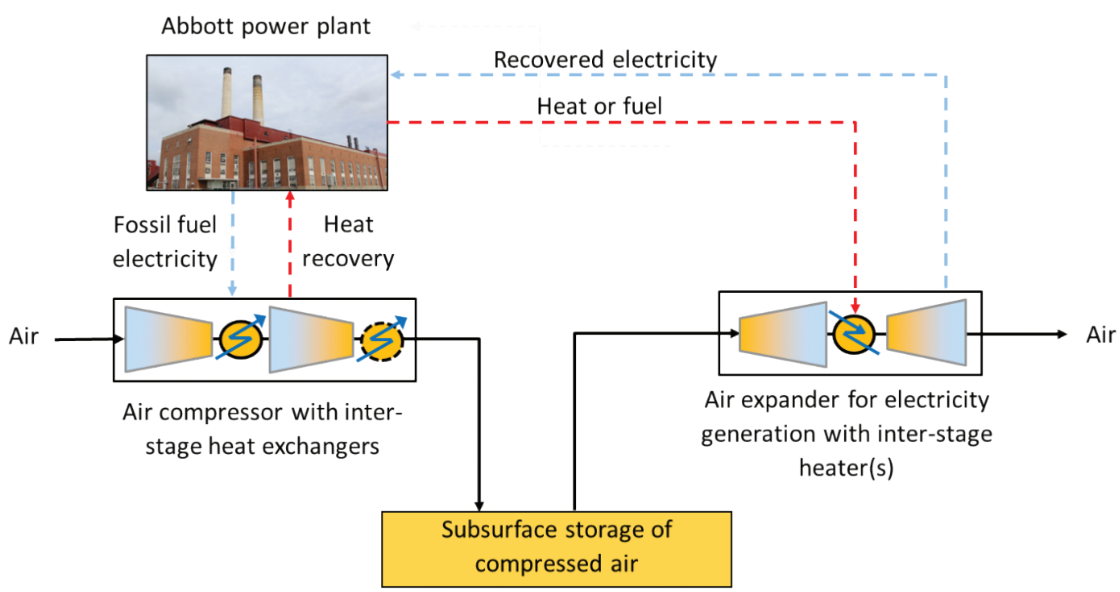


Natural Gas Energy Storage 3D Rendering.

Illinois Compressed Air Energy Storage

Performer	**University of Illinois**
Award Number	FE0032019
Project Duration	03/01/2021 – 02/28/2022
Total Project Value	$ 250,022
Technology Area	Advanced Energy Storage

Researchers at the University of Illinois will conduct a conceptual design study to determine the ability of Compressed Air Energy Storage (CAES) to capture and store compressed air in subsurface sedimentary strata when off-peak power is available or there is a need for grid balancing, as well as evaluate the feasibility of capturing surplus electrical energy from renewable sources and off-peak energy at the Abbott Power Plant on the University of Illinois Urbana – Champaign campus. The project team will design an integrated system to (1) capture surplus electrical energy from fossil-fuel and renewable sources and the Abbott Power Plant using a CAES system, (2) store both the compressed air and the thermal heat generated by compression in the subsurface as part of an adiabatic system, (3) simulate the movement of air and heat in the subsurface, (4) recover the compressed air and stored thermal heat to rotate turbine generators when additional electricity is needed during sustained interruption due to weather events or fossil fuel disruptions, and (5) remove or treat subsurface formation water that was recovered with the compressed air. The project will be organized into three research goals: (1) develop a geologic model and conduct numerical simulation of injection of heated air into the subsurface and the movement of air, temperature, and pressures in the subsurface; (2) develop preliminary technical designs for surface facilities including compressor, turbine, well facilities, pipeline, and thermal energy collection; and (3) create preliminary technical designs of the power plant facilities. This research, if successful, would enable large areas of the United States to better integrate older fossil-fuel energy systems with variable renewable energy sources and use natural gas as a backup during supply interruptions.



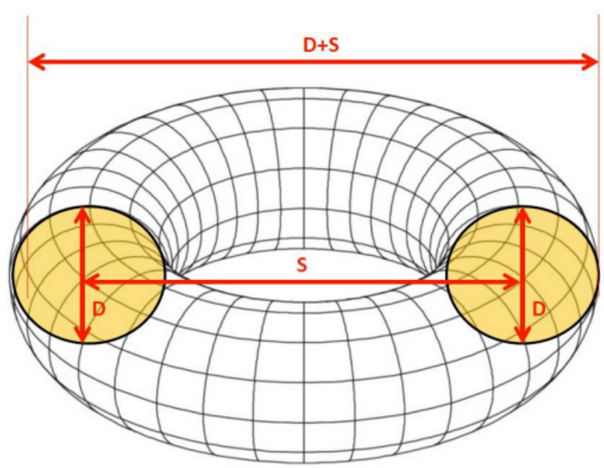
Conceptual Diagram of Surface Infrastructure.

ELECTROMAGNETIC TECHNOLOGIES

Integration of Superconducting Magnetic Energy Storage (SMES) Systems Optimized with Second-Generation, High-Temperature Superconducting (2G-HTS) Technology with a Major Fossil-Fueled Asset

Performer	**American Maglev Technology of Florida, Inc.**
Award Number	SC0021489
Project Duration	02/22/2021 – 02/21/2022
Total Project Value	$ 199,912
Collaborator	University of Houston, NRG Energy
Technology Area	Advanced Energy Storage

The objective of the project is to scale up low-cost, high-efficiency, second-generation high-temperature superconducting (2G-HTS) technology for deployment across several markets, with a primary focus on the commercial development of superconducting magnetic energy storage (SMES) systems. SMES is a transformative, disruptive energy-storage technology in the form of a "magnetic battery." The geometry of the device creates a highly contained electromagnetic field, and the energy is released by discharging the coils. Due to the zero electrical resistance and infinite conductivity of a superconductor, the stored energy remains constant in the coil without any degradation until it is discharged. This ensures instant charging and access capabilities, with unparalleled efficiency exceeding 95%. The goal of the program is to confirm whether the novel SMES design can meet the performance and financial requirements of the fossil asset industry, while exhibiting continuous grid-voltage regulation; cost-effective peak-hour energy storage with long duration; increased input/output efficiency; and the capability to undergo millions of charging cycles, representing a significant improvement over lithium-ion and other conventional storage technologies. If successful, this project would be integral in the long-term commercialization and widespread deployment of disruptive technology that can spawn a new worldwide supply chain and create domestic high-tech manufacturing jobs in the green industry.



Toroid Approach for the SMES Geometry & Design.

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 – 03/31/2022
Total Project Value	$ 883,877
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.

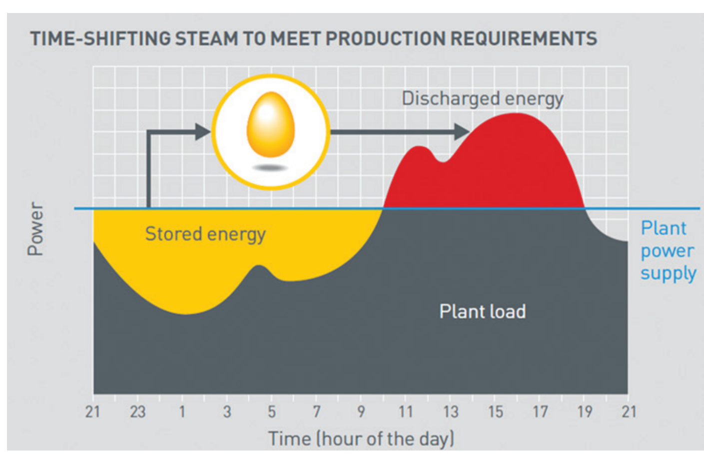
Techno-Economic and Deployment Analysis of Fossil Fuel-Based Power Generation with Integrated Energy Storage

Performer	**University of North Carolina at Charlotte**
Award Number	FE0031903
Project Duration	09/01/2020 – 08/31/2022
Total Project Value	$ 499,998
Technology Area	Advanced Energy Storage

Improving the flexibility of conventional power plants is a key challenge in transforming the current energy system to a high share of renewable energy in electricity generation. In the current energy system, mainly dispatchable coal- and gas-fired power plants compensate for fluctuating renewable power generation to ensure the stability and reliability of the electrical grid. Considering the expected capacity growth of renewable energy resources and corresponding reduction in the capacity of conventional power plants, the remaining dispatchable power plant fleet has to meet increasingly higher flexibility and reliability requirements. Energy storage integrated with a power plant partially decouples plant power output and boiler (steam generator) firing rate, thus improving flexibility of the plant (lowering minimum load, providing peak power when needed, time-shifting peak power generation, and allowing load changes at constant or nearly constant firing rate), reducing cycling damage, reducing emissions, and improving plant economic performance.

This project will analyze four energy storage technology options and six sub-options, and determine their impact on the operation and economics of a representative (reference) coal-fired power plant. A coal-fired steam plant was selected for the analysis because it may provide the greatest benefits from the integration of energy storage and can be used as a foundation for other fossil fuel facilities. The savings due to the integrated energy storage resulting from improved plant operating efficiency, improved system reliability, reduced CO_2 and other pollutant emissions, lower operating costs, more efficient plant participation in frequency control, and increased participation in the ancillary services market will be considered. As the penetration of renewables increase over the next decades, the efficient, flexible, and reliable operation of existing fossil power generating plants is critical for a smooth cost-effective decarbonization of the power generation sector.

Results obtained from this project will be highly relevant for future advances of energy storage implementation and integration with the power generation assets. Technical analysis performed using high-fidelity plant models will be verified against actual operating data and augmented with deep understanding of the power plant operation, resulting in a realistic incremental cost curve for the plant. An economic analysis will be performed using actual grid data and market prices to simulate operation of the reference plant with and without integrated energy storage to determine the actual value of storage under realistic grid operating conditions. Revenues due to increase in energy output (achieved by reducing inefficiencies caused by variable load operation and improved performance) and increased participation in the ancillary services market will be documented.



Visual representation of the energy storage concept.

ABBREVIATIONS

APPA.. .... American Public Power Association

2G-HTS ....second-generation high-temperature superconducting

AES ....Advanced Oxygen-free Electrolyzer System

CAES............................compressed air energy storage

CCC-ES.......... cryogenic carbon capture-energy storing

CCPP .... combined cycle power plant

CFC...cryogenic flux capacitor

CF-EGUs .... coal-fired electricity generating units

CH_4.. methane

CHG .... compact hydrogen generator

CiRES...................combined cycle integrated renewable energy storage

CNGES. ....compressed natural gas energy storage

CO_2 ....carbon dioxide

CT ....combustion turbine

DOE...Department of Energy

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

FCE .... Fuel Cell Energy, Inc.

FE... fossil energy

FECM ... Office of Fossil Energy and Carbon Management

GTI ....Gas Technology Institute

H_2... hydrogen

HRSG ....heat recovery steam generator

IHESS....... Integrated Hydrogen Energy Storage System

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

LAES ....liquid air energy storage

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

LCOS......................................levelized cost of storage

LIB... lithium-ion batteries

LSCC....................................liquid salt combined-cycle

MDR ....Manufacturing Design Report

MPHES......... Malta Pumped Heat Energy Storage System

MW.. megawatt

MWe... megawatt electric

MWh.. megawatt-hours

MWh-e .... megawatt-hours electric

MWth...megawatt thermal

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

NRECA ..... National Rural Electric Cooperative Association

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

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

PSH................................... pumped-storage hydropower

PSH-AUM .... pumped-storage hydropower using abandoned underground mines

RSOFC .... reversible solid oxide fuel cell

SandTES .... sand-based thermal energy storage

SG... synthetic graphite

Si-C... silicon carbon

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

SMES ....Superconducting Magnetic Energy Storage

TEA .... techno-economic assessment

TES .... thermal energy storage

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

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

TRL .... technology readiness level

UCI ....The University of California – Irvine

UIUC.....................University of Illinois Urbana-Champaign

VRE ....variable renewable energy

Zeltmann ....Eugene W. Zeltmann Power Project

NOTES

NOTES

CONTACTS

Richard Dennis
Technology Manager
Crosscutting Research

304-285-4515

richard.dennis@netl.doe.gov

Jason Hissam
Technical Project Coordinator
Integrated Carbon Management Team

304-285-0286

jason.hissam@netl.doe.gov

Mary Sullivan
Supervisor
Integrated Carbon Management Team

412-386-7484

mary.sullivan@netl.doe.gov

WEBSITES:

https://netl.doe.gov/carbon-management/crosscutting/energy-storage

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NATIONAL ENERGY TECHNOLOGY LABORATORY

1450 Queen Avenue SW
Albany, OR 97321-2198
541-967-5892

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

Program staff are also located in
Houston, TX and Anchorage, AK.

Visit us: www.NETL.DOE.gov

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